Climate Policy Design:
Interactions among Carbon Dioxide, Methane, and Urban Air Pollution Constraints

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ABSTRACT

Limiting anthropogenic climate change over the next century will require controlling multiple substances. The Kyoto Protocol structure constrains the major greenhouse gases and allows trading among them, but there exist other possible regime architectures which may be more efficient. Tradeoffs between the market efficiency of all-inclusive policies and the benefits of policies targeted to the unique characteristics of each substance are investigated using an integrated assessment approach, using the MIT Emissions Prediction and Policy Analysis model, the Integrated Global Systems Model, and political analysis methods.

The thesis explores three cases. The first case addresses stabilization, the ultimate objective of Article 2 of the UN Framework Convention on Climate Change. We highlight the implications of imprecision in the definition of stabilization, the importance of non-CO_2 substances, and the problems of excessive focus on long-term targets. The results of the stabilization analysis suggest that methane reduction will be especially valuable because of its importance in low-cost mitigation policies that are effective on timescales up to three centuries. Therefore in the second case we examine methane, demonstrating that methane constraints alone can account for a 15% reduction in temperature rise over the 21st century. In contrast to conventional wisdom, we show that Global Warming Potential based trading between methane reductions and fossil CO_2 reductions is flawed because of the differences in their atmospheric characteristics, the uncertainty in methane inventories, the negative interactions of CO_2 constraints with underlying taxes, and higher political barriers to constraining CO_2. The third case examines the benefits of increased policy coordination between air pollution constraints and climate policies. We calculate the direct effects of air pollution constraints to be less than 8% of temperature rise over the century, but ancillary reductions of GHGs lead to an additional 17% decrease. Furthermore, current policies have not had success coordinating air pollution constraints and CO_2 constraints, potentially leading to a 20% welfare cost penalty resulting from separate implementation.

Our results lead us to recommend enacting near term multinational CH_4 constraints independently from CO_2 policies as well as supporting air pollution policies in developing nations that include an emphasis on climate friendly projects.

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1 Stabilization in a Multi-Gas World

1.1 Introduction: An unresolved need for action

Anthropogenic climate change is likely to be one of the most important issues that humanity will need to address in the 21st century. While attribution is sometimes difficult, we are likely already seeing impacts of climate change in everything from the die off of Alaskan forests to increases in hurricane intensity to unprecedented European heat waves. As the planet continues to warm due to the radiative effects of greenhouse gases, more changes will be seen both on the short term (less than a century) and long term (multiple century) timescales. Addressing this issue will require both adaptation (as the Earth is already committed to some minimum amount of warming) and mitigation, and possibly even geo-engineering. This thesis concerns itself only with mitigation: adaptation is a worthy topic of study but outside the scope of this work, and geo-engineering should be considered a solution of last resort[1]. In terms of mitigation, we would ideally enact policies that will reduce both the short-term rate of change and the long-term temperature achieved. We especially would like to avoid any "tipping points" should they exist as such. However, we would like to achieve this mitigation for as little expense as possible.

Despite the growing recognition of the issue, there has been significant policy inertia in enacting mitigation strategies. The global nature of the climate change problem dissuades action, as the atmosphere is a global commons and therefore free rider, collective action, and similar issues inhibit enacting stringent policies. The long time scale of the problem similarly retards movement: politicians think on a the timescale of the electoral cycle, the general populace rarely accept sacrifices today for improvements tomorrow, and unborn generations have no ability to influence current events. The uncertainty in impacts adds confusion to the determination of optimal measures, and furthermore serves as a lever useful to those who wish to delay the passage of any significant measures. The cost of

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[1] As in the tale of the old woman who swallowed the fly, to solve one crisis precipitated by what is in effect a global scale experiment by enacting another global scale experiment is a very risky notion, to be undertaken only in the most dire circumstances.

reductions is similarly uncertain, and likely to be spread across most of the economy, and this uncertainty also adds to policy paralysis.

CO_2 is individually the most significant of the anthropogenic greenhouse gases. However, it is also perhaps the most difficult to abate due to its relationship with energy production. Governments are leery of accepting constraints that they perceive will put them at a competitive disadvantage with other nations, which may slow down their economic growth, which will impede politically powerful industrial lobbies in the energy, transport, and energy intensive production sectors, or which will be unpopular with the electorate who would see increased prices at the pump and in monthly energy bills.

Due to these economic and political implications of non-voluntary constraints on CO_2, emissions controls have been slow to be enacted, have not included some major players (such as the United States and China), and, according to some analyses, are not much more stringent than business as usual. The two most prominent such non-voluntary policies are the Kyoto Protocol and the European Union Emissions Trading System. Standard environmental economic wisdom dictates that efficient policies should be as comprehensive as possible in order to capture all low cost abatement opportunities, which in the case of greenhouse gases means as many nations as possible. In addition, given the existence of a metric such as Global Warming Potentials (GWPs) that allows direct comparison of greenhouse gases (GHGs) on a single axis, such efficient policies should also be comprehensive in terms of gas coverage. And indeed, the Kyoto Protocol was designed to cover the major gases and as many industrialized nations as possible. This theoretically enables the invisible hand of market forces to find the most efficient solutions to a given constraint. There are three major trading structures: trading between regions allows "where" flexibility, banking and borrowing (e.g., trading between time periods) allow "when" flexibility, and trading between gases allows "what" flexibility. Ceteris paribus, where, when, and what flexibility are all desirable features, and this fact has indeed been highlighted by research to which this author has contributed (Reilly et al., 2003a).

However, there are reasons to believe that some aspects of this flexibility may have negative consequences. First, gases with different lifetimes and source characteristics have properties that are sufficiently different that allowing reductions of one gas to compensate for increases in another may be ill-advised. Second, the inclusion of CO_2 in the comprehensive approach may be the primary issue that has slowed effective policy creation, and therefore a separate approach for individual gases might be politically more effective. We are not the first to note that there are issues with “what flexibility” (Goulder and Pizer, 2006), but we state it more firmly than we have previously seen. There are also substances that are not included in the Kyoto basket, and it is possible that these pollutants (namely ozone precursors and aerosols) deserve a more prominent role. We note that even inter-regional trading is not always optimal, both due to interaction effects between local taxes and reduction policies, and also because of differences between market equivalent prices and actual local purchasing power. In any case, there are tradeoffs between the benefits of coordination between abatement of multiple substances, and the benefits of crafting policy to optimally address the unique characteristics of each substance.

Therefore, this thesis uses multiple approaches to address the potential role of non-CO_2 gas policies in a global context. We first examine the standard approaches to climate policy in this chapter. The role of Article 2 of the UNFCCC and the emphasis on stabilization of greenhouse gases are important because of the lack of definition of stabilization itself, and because this emphasis on stabilization leads to a focus on CO_2 and long term targets. We then delve in more depth into methane policies in chapter two and air pollution policies in chapter three. Computational modeling plays a significant role in this thesis in order to determine the potential carried in reduction of these substances and the interaction between different policies. The capability of the MIT IGSM to handle the chemistry of the atmosphere is of vital importance for understanding the lifecycles of methane and ozone. The MIT Emissions Prediction and Policy Analysis model (EPPA, detailed in Appendix A) provides emissions scenarios for the 21st century, as well as the capability of determining economic costs of emission constraint policies in various configurations. We introduced new functionality into the EPPA model so that it could be used to analyze air pollution policies in a similar fashion to various GHG policies. These computations are then embedded in a deeper policy context in order to fully understand their implications.

This chapter demonstrates the importance of not being limited to addressing stabilization as a concept, and the necessity of looking beyond CO_2 for low cost and effective temperature change reduction on the century timescale. The conclusion of our work is that methane reduction in particular, and perhaps also black carbon reduction, should play important roles in future climate actions. However, in contrast to much other research in this area, this thesis suggests that greenhouse gas policies should not allow methane reductions to be traded for CO_2 reductions for reasons political, economic, and chemical. This separate approach will enable policies to be designed in such a way as to be best suited to the characteristics of each substance, taking into account the appropriate uncertainties, source partitioning between OECD and developing nations, and other aspects. We believe that the advantages in this separation outweigh the loss of "what flexibility".

However, there do exist advantages of coordination, even in the absence of actual trading. This coordination potential is especially prevalent in air pollution reductions, because fossil fuel combustion is a major source of both CO_2 and air pollutants and therefore reductions or modifications of the fossil fuel combustion process can lead to improvements in climate and air quality. So while we show that NOx, CO, and VOC reductions will play little role in direct climate impacts (though inclusion of ozone impact on agriculture may change this conclusion slightly), we can also show the magnitude of the the interaction of climate and air pollution policy. Therefore we see that the same analysis methodology leads to a suggestion of policy fragmentation in the case of methane, but policy coordination in the case of air pollution.

1.2 Article 2 philosophy and limitations: The stabilization question

1.2.1 The Role of Article 2 of the UNFCCC

Article 2 of the UN Framework Convention on Climate Change:

> The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the

> climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner.

Any discussion of climate change policy needs to address the centerpiece of international cooperation for addressing global climate change: the UN Framework Convention on Climate Change. Signed by heads of state in 1992 at the UN Conference for the Environment and Development summit in Rio de Janeiro the Convention entered into force in 1994. The UNFCCC coordinates various international climate change actions such as national inventories, and partners with other organizations such as the Global Environmental Facility and the IPCC to further research and create policy. While the Convention itself has no binding reduction commitments it is meant to serve as a framework for further climate treaties such as the Kyoto Protocol. As such, the text of the UNFCCC has significant influence on the framing of worldwide goals, studies, and actions in the climate change realm. Article 2, as the Ultimate Objective of the Convention, is therefore extremely important in considerations of global climate policy.

The language of Article 2 (perhaps deliberately) leaves significant room for interpretation. Specifically, the goal of stabilizing greenhouse gases does not specify a partitioning between gases or a timetable of reductions. Rhetoric and academic studies have concentrated in large part on carbon dioxide, and on long term solutions. Actual policies have mostly followed the suggestions of environmental economists in including all GHGs and as many nations as possible in a single comprehensive policy with trading both between gases and between regions in order to allow the market to take advantage of the lowest marginal cost solutions. However implementation of these policies has moved slowly, and fourteen years after the Framework Convention was negotiated only two such policies (the EU ETS and the Kyoto Protocol) have taken effect, and neither policy includes the US, China, nor India, nor, by many estimates, does either policy impose significant constraints[2].

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[2] Acknowledging, of course, that both policies are meant to be first steps and may therefore be worthwhile despite not being tight constraints in their early periods.

1.2.2 The Definition of Stabilization

There is disagreement about what stabilization actually entails, but despite attempts to put other gases on the agenda the discussion of stabilization tends to trend towards carbon dioxide. The 1997 Technical Paper III of the Intergovernmental Panel on Climate Change (IPCC) attempted to clarify the Convention's stabilization goal (Schimel et al., 1997). Sensitivity to small deviations in other GHG emissions was evaluated and the study revealed that in the short term these deviations could have significant impact. The Technical Paper also noted that since pre-industrial times, the contribution of these 'other' substances to radiative forcing is comparable to that of CO_2. But in academic papers, control of other gases is at best usually relegated to footnotes or asides (Arnell et al., 2002; Dai et al., 2001a; Hoffert et al., 2002; Nordhaus, 2001; O'Neill and Oppenheimer, 2002). Question 6 of the Synthesis Report to the IPCC Third Assessment Report (TAR) asks what the consequences are of stabilizing concentrations in carbon dioxide equivalents, but the text then only addresses CO_2, and the stabilization scenarios are analyzed with only one projection of other greenhouse gases, namely the unconstrained SRES A1B scenario (Watson and Core Writing Team, 2001). The U.S. National Assessment Report on Climate Change Impacts relies heavily on the CGCM1 and HADCM2 models, both of which use CO_2 as a surrogate for other greenhouse gases (National Assessment Synthesis Team, 2001). The fact that forcing changes are often measured in CO_2 equivalents rather than a more precise term such as W/m^2 is yet another piece of evidence that points towards the importance of CO_2 in academic studies and in political rhetoric.[3]

Other studies, such as a Hadley Centre analysis (Mitchell et al., 2000), equate a CO_2 stabilization level with a forcing value. These studies model varying CO_2 concentrations and assume the concentrations of all other gases stay constant, but acknowledge that, in reality, society might choose a different allocation between other GHGs and CO_2 that add up to the same total forcing level. For a given CO_2 equivalent stabilization target, the actual level at which CO_2 will need to be stabilized is therefore likely to be significantly lower than the target concentration and, moreover, such studies provide no direct guidance

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[3] W/m^2, or watts per meter squared, are used as a measure of the average global radiative forcing change at the tropopause resulting from an increase in the concentration of a given greenhouse gas from some baseline (usually present concentrations, or preindustrial concentrations).

on the emissions paths that would be consistent with stabilization of radiative forcing. The question of stabilization of multiple greenhouse gases is inevitably linked to how to compare greenhouse gases, and thus the inadequacy of GWPs (Reilly et al., 1999). GWPs are defined and discussed at more length in Appendix D. One approach is to set a specific climate or radiative forcing target and endogenously estimate the optimal control path of different gases (Manne and Richels, 2001a) . Work in this vein has relied on unrealistically simplified climate and atmospheric chemistry relationships, so it does not provide assurance that a single optimal path exists and that it is numerically feasible to solve for it. Absent in these efforts are important relationships among methane, the hydroxyl radical, tropospheric ozone and its precursors, nonlinearities and thresholds in climate dynamics, and issues involving aerosols and other climatically important substances. In addition, if the constraint is limited to stabilization rather than including additional tolerable rates of radiative forcing change constraints, the model will yield solutions that have little methane control until the decade prior to the constraint taking effect. In early periods, only the long lived gases – and mainly carbon dioxide – are expected to be controlled. Recently, more academic work has begun to have more emphasis on these other gases: they are especially prominent in the EMF-21 special issue of the Energy Journal (Weyant et al., 2006).

On the political side, we note that Kyoto's ratification was dependent on the signatures of 55 Annex I Parties accounting for 55% of total carbon dioxide emissions – not GHG emissions – from those parties. Similarly, though the European Union has set a target of 2° C above preindustrial, in several documents they have gone on to state that the target can be met by achieving a 550 ppm CO_2 target (European Parliament and the Council, 2002). The Ministerial Declaration of the UNFCCC COP in 1996 stated a goal of "stabilization of atmospheric concentrations at twice pre-industrial levels". It is likely that they set that goal with a doubling of CO_2 in mind. And of course, emissions of gases are often measured in *carbon* equivalent by multiplying by their GWPs. Finally, the European ETS is indeed a CO_2 only policy.

Despite the big picture emphasis on stabilization and CO_2, shorter term climate policies do often include the possibility of trading among greenhouse gases by using the global warming potentials (GWPs) established by the IPCC in order to reach more economically efficient solutions than relying on CO_2 reduction alone. Indeed, the Kyoto

Protocol allows for precisely this sort of trading across greenhouse gases, using a 100-year GWP as the ‘exchange rate’. However, there is an inconsistency between the concept of stabilization and the use of these trading schemes. We note that trading schemes that rely on constant GWPs will not generate stabilization of concentrations or radiative forcing, because trading a reduction of a gas with a short lifetime for an increase of a long-lived gas will inherently lead to reductions in radiative forcing in the near term and increases in radiative forcing in the long term (and vice versa). Stabilizing radiative forcing would require trading concentration levels of one GHG for another, which would imply that in terms of emissions, emissions paths for each GHG be specified over at least the lifetime of the longest lived of the two. This can be seen logically if we consider the case where we allow a trade between a one time increase in CO_2 emissions and a corresponding decrease in CH_4 emissions. A one time trade based on GWP weighting would lead to an initial decrease in forcing, as the radiative forcing effects of a given mass of methane is larger than that of the GWP equivalent mass of CO_2. However, within a few decades, methane concentrations would have returned to their equilibrium concentrations while CO_2 concentrations would still exhibit an increase, leading to a net increase in forcing.

Alternatively, we demonstrate the effects of a sustained change in emissions levels in Figure 1-1, using a highly simplified system where methane and CO_2 are assumed to decay in the atmosphere with a constant lifetime. The simulation starts in 2100 with CO_2 and CH_4 concentrations both stable at 550 ppm and 1.8 ppm respectively. In 2110 methane emissions are decreased and CO_2 emissions are increased. Again, the decrease in methane leads to a short term decrease in forcing. In this case, methane concentrations quickly stabilize at a lower level. CO_2 concentrations, however, take hundreds of years to reach a higher concentration, and this increase in CO_2 concentration will eventually lead to a net increase in forcing in the system, despite the GWP weighted sum of emissions remaining constant during the entire simulation. In the simulated case shown in the figure, the point at which the total forcing in the trading case exceeds the original forcing is reached within 70 years, and by the time CO_2 concentrations finally stabilize, there has been an increase in total radiative forcing of more than 0.7 W/m^2 (the diamond represents the total forcing reached in the year 3000).

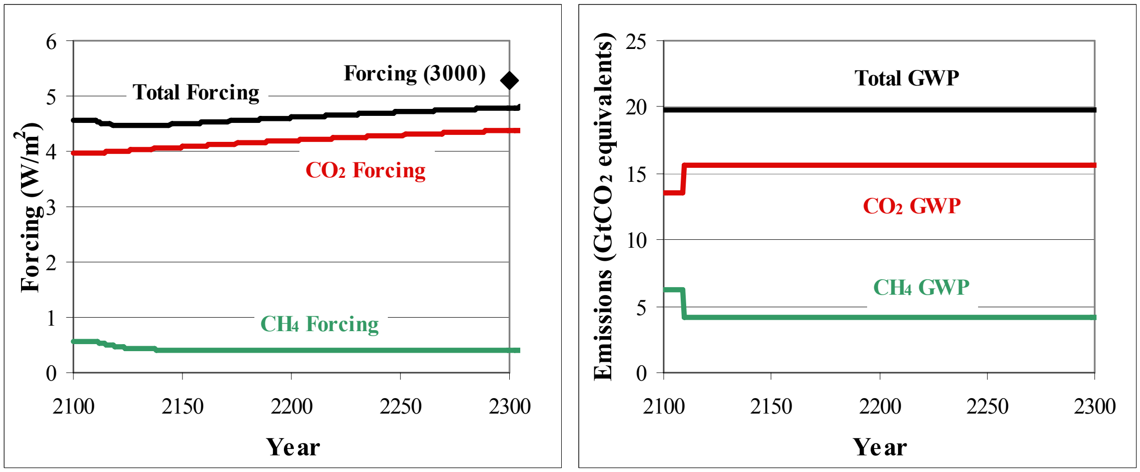

Figure 1-1: The impact on radiative forcing (left panel) and emissions (right panel) of trading CH_4 and CO_2 by constant GWP values in a simplified analysis

An interesting question can be raised as to what interests led the negotiators to adopt the precise language of the Article. Oppenheimer and Petsonk (2005) cite Reinstein, one of the US negotiators, as saying that some negotiators lobbied for language that would have defined danger in economic terms, which would have naturally led to a consideration of economic costs of policies being considered simultaneously with damages. We can hypothesize that it might have been in the interests of some negotiators to word a policy such that it would not encourage the adoption of early, near term constraints, and ironically, that these hypothetical negotiators might have found natural allies with ecologists who often think naturally about long time scales. In addition to the issue that Article 2 does not encourage short term action, it also limits some approaches to long-term solutions. In Oppenheimer and Petsonk's analysis of the historical origin of Article 2 they note that there exist alternative frameworks for long-term objectives "that are not consistent with the language of Article 2" such as technology-based approaches (Metz et al., 2002; Oppenheimer and Petsonk, 2005).

1.2.3 Avoiding Dangerous Anthropogenic Interference: The Ultimate Objective

Stabilization of greenhouse gases may be the means enshrined in Article 2, but the ultimate objective is prevention of dangerous anthropogenic interference in the climate system. Article 2 raises the question of temporal issues by noting that stabilization levels should be achieved within a time frame that allows adaptation by ecosystems. In a way, this is an implicit acknowledgment that stabilization by itself is not sufficient: that the path taken to achieve stabilization matters. One question is whether in fact this concept of a "path" which avoids dangerous anthropogenic interference might have been a more appropriate goal than stabilization.

Article 2 also makes a nod to economic realities by stating that the stabilization levels should be achieved in a manner consistent with sustainable economic development. It does not give any guidelines for resolving a potential conflict where stabilization cannot be achieved without impeding economic development, or considering possible tradeoffs between interference and development. It might be the case that the authors of Article 2 felt that economic costs would be taken into account regardless of inclusion in this statement – certainly economic interests have trumped environmental interests in the climate debate until now.

In any case, avoidance of dangerous anthropogenic interference in general refers to avoiding negative impacts on both human activities and ecosystems. These impacts presumably scale with the magnitude of climate changes, and these climate changes should be related in some way to global mean temperature rise. Temperature rise itself is a nonlinear function of radiative forcing in the atmosphere, and radiative forcing is a function of greenhouse gas concentrations. Therefore the idea that it is possible to limit anthropogenic interference by controlling greenhouse gas concentrations does have validity. Figure 1-2 demonstrates one way to think about the stabilization cause-effect chain[4]. It is possible to design polices and/or goals attempting to control any one of the points on this chain: emissions, concentrations, forcings, temperature, or impacts, and there have been suggestions addressing all these possibilities. Economists tend to concentrate on emissions, where there exists the most immediate link between policy and effect. Scientists usually use radiative forcing as a measure of choice, as a natural metric that is easily adapted for use in climate modeling.

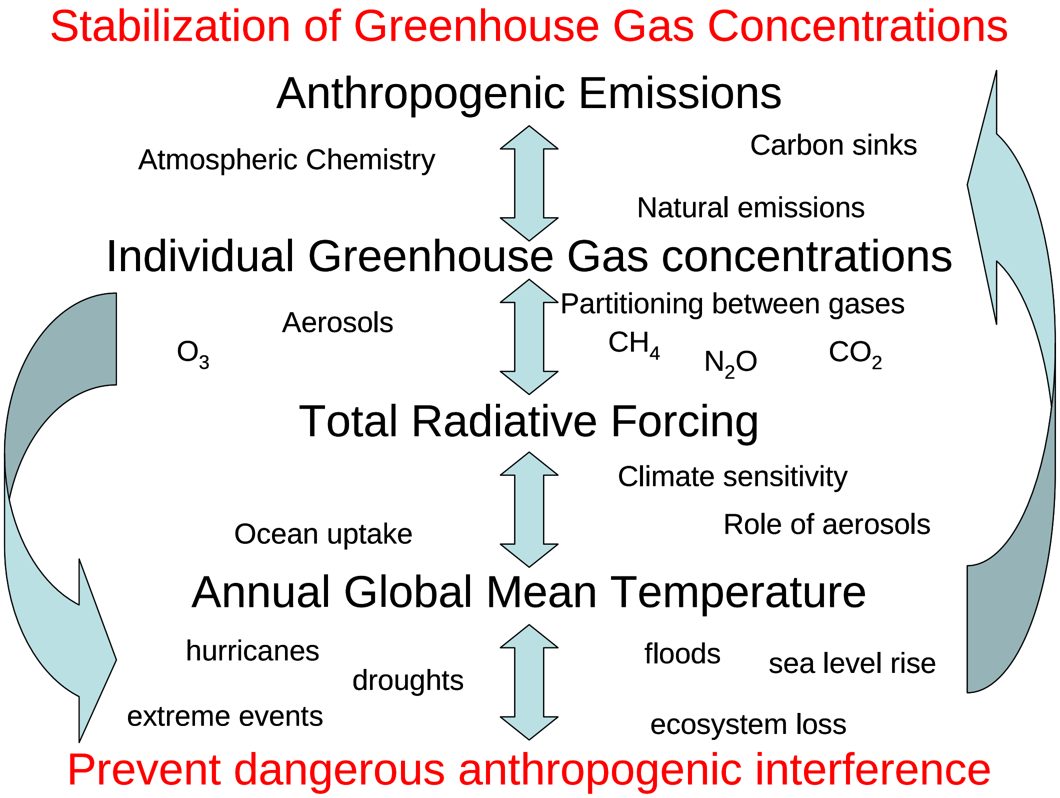

Figure 1-2: The Stabilization Cause-Effect Chain

The concept of stabilization clearly targets concentrations as a goal. There are some advantages to addressing concentration for the purposes of making policy rather than impacts or temperature. First is that there is significantly less uncertainty in what

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[4] . Note that a similar figure exists in Corfee-Morlot & Hohne (2003) but this figure was developed completely independently.

concentration will be achieved with a given emissions pathway than in what temperature will be achieved with the same pathway – most of the uncertainty in the climate system comes in terms of what temperature change results from a given forcing change, with this uncertainty mainly being a result of uncertainty in the magnitudes (or sometimes even signs) of various feedbacks and the rate of oceanic heat uptake. Second is that due to the inertia of the climate system there is a lag between reaching a given concentration and realizing the full impact of that concentration. Of course, one could use the same argument to imply that emissions should be the target rather than concentrations, especially given that regulations can more directly effect emissions. In general, moving up this cause-effect chain increases the ability to design policies to reach a given target with certainty, and therefore to understand the economic impacts of the policy.

The argument for moving *down* the chain is that if the final goal of policy is to actually reduce impacts, would impacts be a more relevant target? This is important not only because we care about the impacts specifically, but also to allow greater flexibility in how we achieve the goal. If we take emissions or concentrations as a goal, we need to determine an appropriate partitioning between gases (or an appropriate trading measure). Well-mixed gases in the atmosphere are effectively interchangeable as far as a climate model is concerned, and therefore the use of radiative forcing as a measure allows flexibility in determining gas concentrations. Targeting temperature or actual welfare impacts in unfortunately not only difficult for reasons of uncertainty mentioned above, but also because the variety in types of impacts and regions where the impacts occur make it difficult to even agree on a given target.

However there are, of course, some substances which have both climate and non-climate effects. Ozone, black carbon, NOx, and SOx all have direct health and ecosystem impacts as well as radiative forcing effects. Some substances change climate in complex ways that may not result in mean temperature change - black carbon can effect the hydrological cycle by warming the air column at high altitudes, and even in cases where this does not impact temperature it may change rainfall, cloud cover, and other important climatic attributes. It can be difficult to project concentrations from emissions due to uncertainties in atmospheric chemistry, natural emissions, or carbon sinks. Local differences of concentrations for substances such as ozone or black carbon make it hard to compare the global mean temperature impact of a given mean radiative forcing to that of well-mixed gases. There can be impacts on temperature due to albedo changes from land use change or urban expansion. CO_2 itself has direct impacts, both positive in terms of increased agricultural yields and plant growth, and negative such as increased ocean acidity (Ruttimann, 2006) and increased growth of C3 weeds in competition with C4 crops such as maize and sugarcane. There are also feedbacks in the other direction, as climate changes impact the carbon cycle, atmospheric chemistry, the hydrologic cycle, and the economy. These, and a host of other potential complications, make the link between stabilization and dangerous interference less straightforward than might be hoped.

Examples of the kinds of dangerous interference that are to be avoided can include global sea level rise, increases in hurricane intensity or frequency (Emanuel, 2005; Webster et al., 2005), changes in precipitation patterns impacting agriculture, melting of permafrost, increases in heat wave frequency, loss of especially fragile ecosystems that have limited migration capabilities such as coral reefs, alpine ecosystems, and tundra, change of surface insolation impacting plant growth, changes of air quality, or a host of other impacts. It is unlikely that there could ever be an agreement as to what combination of these impacts might constitute the threshold of “dangerous anthropogenic interference”. There are some possible events, such as the total melting of the Greenland ice sheet leading to 7 meters of sea level rise or collapse of the thermohaline circulation leading to likely disruption of weather patterns around the North Atlantic and the loss of a major sink for heat and carbon, that are outcomes widely considered to be avoided at any cost.

However, given the ability of ecosystems and economies to adapt, it is an open question whether even such drastic events would be a problem given a long enough time scale. The current climate is not inherently superior to a world several degrees warmer or cooler. However, there is significant human and ecological capital invested under the current system which might need to shift for any new climate, and it is not obvious what a safe rate would be to allow such shifts to occur without excess disruption – indeed, current rates of change may already exceed this “safe rate” for the most sensitive ecosystems. In fact, before Article 2 was written, the WMO in 1988 produced a report with a rate of warming target (a “tolerable rate”) that was proposed as a long term objective that would have led to a very different emphasis in thinking (Oppenheimer and Petsonk, 2005), in a similar fashion to UNEP and the AGGG in the 1980s (Corfee-Morlot and Hohne, 2003). The original proposed rate was 1/10th degree C per decade. The Dutch and US governments apparently were proponents of the long term stabilization approach that became the UNFCCC objective, rather than, for example, the Enquete Commission goal of a reduction of fossil fuel use by 2050 to avoid 1 to 2 degrees C rise in that time frame (Enquete Commission, 1989).

A potential problem is that even with a fairly slow rate of change, there may be tipping points where a rapid change is triggered. Is there a critical temperature at which the interior of the Greenland ice sheet will start melting, leading to total loss of the ice sheet on the time scale of decades? Or a threshold that will cause methane release from tundra or clathrates at a scale that will cause further rapid temperature increase? Is the Amazonian rainforest in danger of entering a dangerous cycle where, rather than "rain following the plow" as in the hopes of Western settlers in the 19th century, drought will follow the loss of vegetation yielding a rapid transformation from rainforest to savannah or desert? If we should pass any of these poorly understood thresholds it will become impossible to turn back without resorting to geo-engineering solutions which may prove as dangerous as the problem which they were meant to solve.

Not only is there no agreement on what constitutes dangerous anthropogenic interference, but global warming will certainly have very different impacts on different regions, and for some temperature changes some sectors in some regions may be positively effected by climate change. Vulnerability comes into play here, with developed nations more able to adapt by shifting infrastructure and using technologically (and often energy) intensive solutions to weather changes. Examples include air conditioning for heat waves, irrigation for droughts, dikes and levees for sea level rise, and so forth. However, recent events such as hurricane Katrina and the 2006 heatwave in California in the US, and the 2003 heatwave in Europe, show that even in very rich nations these potential solutions are not always well implemented. Less developed nations have less ability to adapt, and will therefore suffer more from climatic change. This implies that, perversely, those nations which are the most vulnerable are often those with the weakest economies, and therefore the fewest emissions. Meanwhile, the nations with the most emissions and therefore greatest impact on climate change have less incentive to reduce future warming and would bear more of the cost of reducing emissions, and therefore would be likely to set a threshold for dangerous anthropogenic interference at a much higher level than the vulnerable, poorer nations.

But the most important question for any ultimate objective is the impact that the goal has on near term policy. And all the uncertainty and complications involved in defining "dangerous anthropogenic interference" may serve to only delay action rather than promote actual solutions.

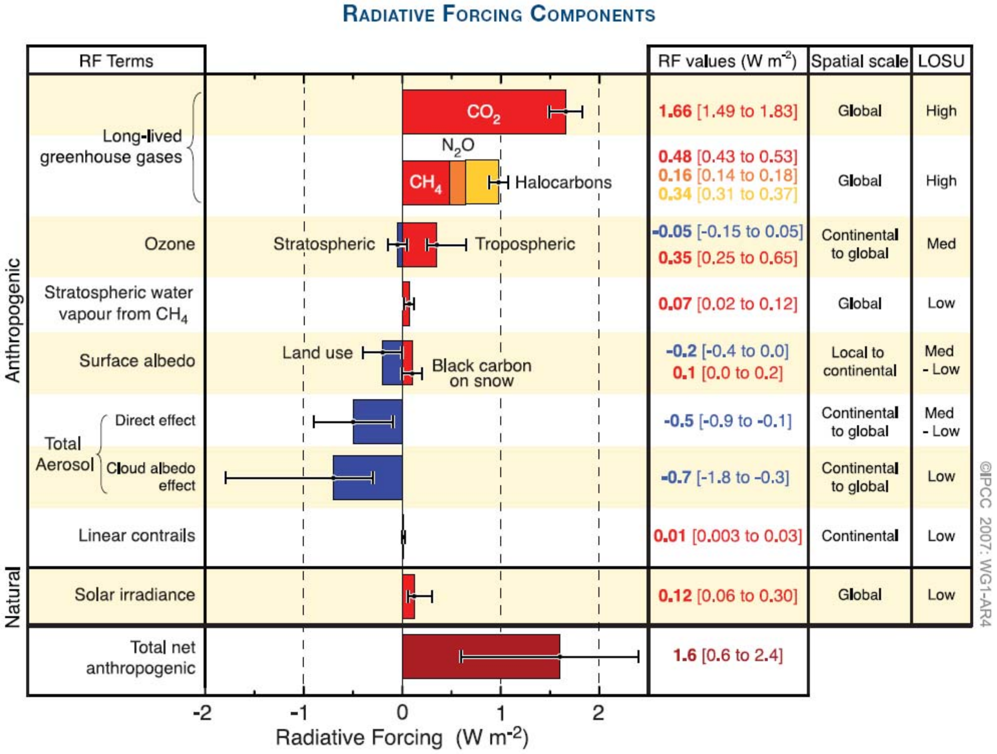

Figure 1-3: Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. Figure SPM-2 in the AR4 Summary for Policymakers (Alley et al., 2007)

1.3 Key Gases

1.3.1 The Emphasis on CO_2

Carbon dioxide is widely acknowledged to be the largest anthropogenic contributor to greenhouse forcing. CO_2 has been recognized as a GHG since the times of Tyndall and Arrhenius. The recognition of the primacy of CO_2[5] is demonstrated by Arrhenius's statement that the absorption of the atmosphere was "not exerted by the chief mass of the air, but in a high degree by aqueous vapour and carbonic acid, which are present in the air in small quantities." (Arrhenius, 1896) He even calculated the temperature change that would result from increases in carbon dioxide concentrations, estimating that a doubling of CO_2 would yield about 5° Celsius warming. And today climate sensitivity, a common metric for the equilibrium temperature response to a forcing change, is in fact defined based on forcing resulting from doubled CO_2 concentrations – despite the fact that the concept "climate sensitivity to forcings" exists (Hansen and Sato, 2004). The IPCC Fourth Assessment Report Summary for Policymakers (Alley et al., 2007) shows forcing contributions of increases in greenhouse gases beyond their preindustrial levels in their standard chart (Figure 1-3), with CO_2 contributing 60% of well-mixed gas forcing. This matches estimates from the MIT Integrated Global Systems Model (IGSM, discussed in more detail in the Appendix B). Similarly, using 100-year GWP weighted emissions[6] (Figure 1-4) from EPPA in 2000, CO_2 accounts for more than 60% of anthropogenic greenhouse gas emissions. Fossil carbon dioxide emissions are estimated in the AR4 Summary for Policmakers to be 6.0 to 6.8 GtC (Alley et al., 2007). And given a reference forecast of emissions, by 2100 CO_2 may contribute 75% of GWP weighted emissions and almost 75% of forcing increase from preindustrial times (Figure 1-4 and Figure 1-5).

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[5] Along with water vapor, but as the quantity of water in the atmosphere is a function of the climate system and not direct emissions, water vapor is always treated as a feedback rather than as a direct GHG.

[6] GWP weighting is still perhaps the best simple way to compare emissions of different gases, for all the limitations of the methodology. It is certainly the most widespread and widely accepted. Therefore, while we will attempt to include more direct measures such as radiative forcing or temperature impacts where possible, GWP measures will be used throughout this thesis.

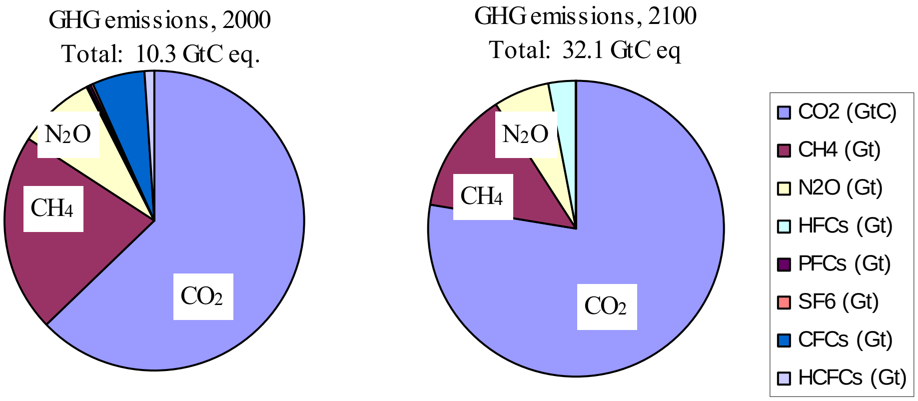

Figure 1-4: EPPA reference scenario emissions weighted by 100 year GWPs

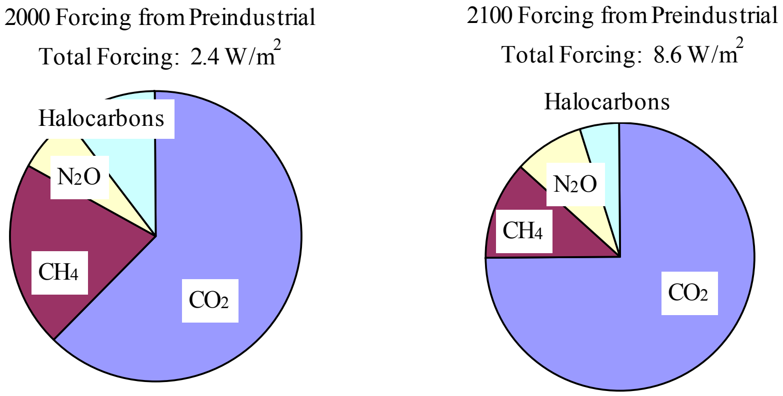

Figure 1-5: EPPA reference scenario, forcing from preindustrial

As has been pointed out by (Hansen et al., 2000), much of the forcing resulting from historical CO_2 emissions has been partially balanced by the sulfate aerosols that were produced concurrently – however, with the advent of pollution control equipment, the ratio of CO_2 to sulfate emissions has increased greatly, and in any case the century scale lifetime of CO_2 means that carbon dioxide is a stock problem whereas aerosols have a lifetime measured in weeks (Andreae et al., 2005; Novakov et al., 2003).

Carbon dioxide concentrations have risen from approximately 278 ppm preindustrial (Ramaswamy et al., 2001) to 377 ppm in 2004 (Keeling and Whorf, 2005). Atmospheric increases during the 1990s averaged 3.2 PgC/yr (IPCC) or about 1.5 ppm/year. Because increases in CO_2 concentrations are responsible for 60% of well-mixed gas forcing increases from preindustrial, it can be argued that CO_2 has been historically been the most important of the greenhouse gases. CO_2 is an inherent product of fossil fuel combustion, and emissions are likely to grow significantly because in the absence of strong policy action fossil fuels are likely to provide the majority of worldwide energy for the foreseeable future, and energy use is projected to continue to grow as economies grow. Therefore, CO_2 is likely to continue to be the largest contributor to anthropogenic greenhouse gas forcing in the future. Unlike other pollutants, CO_2 is very difficult to eliminate with the use of end-of-pipe technologies. The closest approximations to end-of-pipe control involve controversial[7], expensive, and energy intensive solutions such as capturing CO_2 and depositing it into oceanic or geological reservoirs, or novel but largely untested approaches such as using flue gases to grow algae (Schwartz, 2004). This lack of accepted end-of-pipe measures means that CO_2 may also be the most difficult of the greenhouse gases to abate. 86% of energy production in 2004 came from fossil fuel sources (U.S. Department of Energy, 2004), and energy use is projected to continue rising rapidly. The US DOE and EPPA both project a 50% increase in global energy use in the next 20 years (U.S. Department of Energy, 2006), and EPPA furthermore projects a fourfold increase in energy production by the end of the century (Figure 1-6).

Implementation of international greenhouse gas reduction policies such as the Kyoto Protocol has been slow, and was only ratified after last minute concessions and the withdrawal of the United States and Australia. Analysis suggests that the Protocol may now be non-binding if full use is made of available “hot air”. The pace of the Kyoto Protocol’s implementation is a contrast to the implementation of chlorofluorocarbon controls in the Montreal Protocol. This difference is likely due in large part to the difficulty of reducing CO_2 emissions. Because of the linkage between CO_2 intensive energy production and economic growth there is a fear that CO_2 constraints will lead to an economic competitive disadvantage between nations adopting CO_2 emissions restraints and unconstrained nations. In addition, the fossil fuel industry is politically powerful. The influence of the fossil industry is especially strong in the US, which accounted for 22% of global CO_2 emissions in 2004 (U.S. Department of Energy, 2004). While there are many factors involved in why the US was one of two nations to withdraw from the Kyoto process, the power of the local fossil fuel lobby is likely one of them.

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[7] CO_2 sequestration is considered controversial mainly because of uncertainty about potential leakage from reservoirs and possible environmental side effects.

A counterpoint is that the European Trading System (ETS) only covers carbon dioxide emissions, and yet was implemented fairly rapidly. Oddly, initial trading in the ETS for the first time period yielded very high carbon dioxide prices up to 30 euros, implying that most of the industrial participants expected the constraints to be binding and difficult to meet. On the other hand, academic analyses (Reilly and Paltsev, 2005) predicted very low prices more in line with current prices of a euro per ton CO_2. It is not clear whether the national negotiators had beliefs more in line with the academics or with the industries that held onto their permits until the first inventories demonstrated that the initial carbon allocations were in fact quite generous. However, regardless of the perception of the difficulty of meeting the ETS constraints, an initiative entirely within the boundaries of the European Union will have very different barriers to implementation than a more international policy.

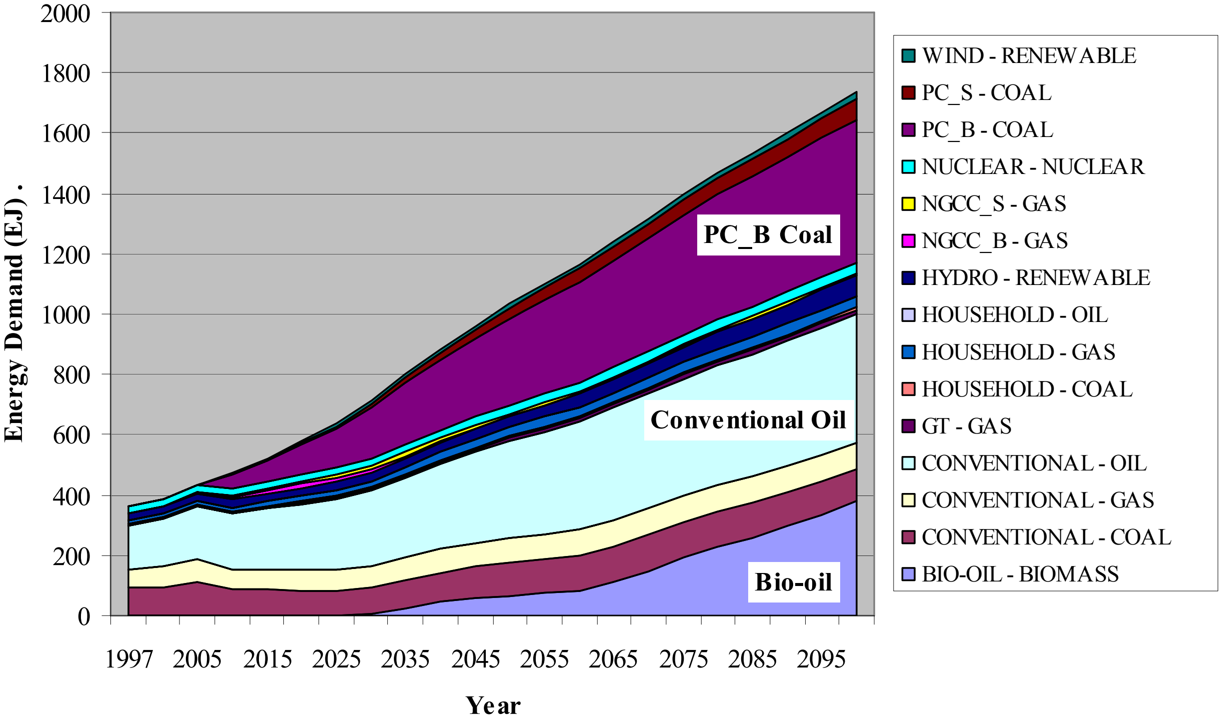

Figure 1-6: EPPA reference projection of Energy Use by Technology and Fuel

CO_2 is also unique among the greenhouse gases in terms of its lifecycle. N_2O degrades mainly through photodissociation, CH_4 and the hydrofluorocarbons react with the hydroxyl radical, CFCs are destroyed in the stratosphere, and perfluorocarbons and sulfur hexafluoride (SF_6) degrade through photolysis in the mesosphere, but CO_2 has a very different pathway. Because carbon in the atmosphere eventually oxidizes to CO_2, it is often more relevant to track overall carbon than CO_2 itself. Elemental carbon is of course never destroyed. Rather, in the short term CO_2 in the atmosphere can be transformed into carbon compounds in the biosphere through biochemical plant photosynthesis pathways, or into carbonates in the ocean by exchange into the surface layer followed by a slow process carrying carbon down into the deep ocean until the ocean and atmosphere reach equilibrium. Therefore, burning fossil fuels effectively moves carbon from geological storage into the ocean/ecosystem/atmosphere stock permanently, in the absence of technologies such as carbon sequestration. There are geological processes that eventually bury carbonates in the deep ocean sediments, bury surface organic matter sufficiently deeply to take it out of the available carbon pool, or capture CO_2 through chemical weathering, but these mechanisms are all slow enough that they can be ignored on human timescales.

One difficulty in predicting future CO_2 concentrations is uncertainty about the behavior of various components of the carbon cycle. We cannot even accurately allocate current fluxes with significant certainty between these components. Sabine et al. (2004) provide a summary of recent estimates of global fluxes in the carbon cycle, showing a range of uncertainty for the different components. The increase of CO_2 in the atmosphere can be measured precisely, and anthropogenic CO_2 sources from fossil fuels are fairly well understood. There is greater uncertainty in partitioning the remainder of the carbon cycle between the ocean sink and the terrestrial sink, and within the net land-atmosphere flux there is further uncertainty in partitioning between emissions from land-use change and uptake. Median estimates of the net sink (ocean uptake plus net terrestrial flux) center around -2.6 PgC yr^{-1} from various studies for the 1980s and 90s, but with significant uncertainty. There is less agreement about the land use change component of the total terrestrial sink, ranging from a median estimate of a carbon source of +0.9 PgC yr^{-1} (DeFries et al., 2002) to +2.2 PgC yr^{-1} (Houghton, 2003), and the IPCC AR4 estimates a source of 1.6 GtC from land use change with a range from 0.5 to 2.7 GtC for the 1990s (Alley et al., 2007). This historical uncertainty leads to even greater uncertainty in future projections. The response of the ocean to saturation of the upper layers, or temperature impacts on circulation, is poorly understood, but may lead to a significant decrease in ocean uptake in the future. The role of land-use change is clearly very important, but the accuracy of current models is limited. Another issue resulting from the complications of the carbon cycle is the difficulty of assigning CO_2 a single "lifetime". The IPCC Technical Summary of Working Group I (Albritton et al., 2001) lists a lifetime of "5 to 200 yr". Indeed, given the length of time that a ton of fossil carbon once burned will remain in the ocean/atmosphere/ecological system, lifetime may not even be the appropriate concept to use (Tans, 1997). Of course, because CO_2 is the gas against which all other greenhouse gases are measured, changes in how the carbon cycle is calculated will then lead to changes in the GWP weightings of every other gas.

Distribution issues are also worth noting. CO_2 emissions also form a higher percentage of emissions from developed economies. In 2000 80% of GWP weighted Annex B emissions were from CO_2, compared to only 57% of non-Annex B emissions (EPPA calculations). By 2100, in the reference EPPA scenario, the share of CO_2 in total global emissions grows. In Annex B nations, the share of CO_2 emissions reaches 88%, but even in the non-Annex B nations it grows to 71%. These values do not include deforestation emissions, which would obviously contribute to the CO_2 share in non-Annex B nations in early periods, but the inclusion of deforestation emissions (or of agriculture and forest sinks) in policies remains a complicated issue. As the Byrd-Hagel resolution (Sen Byrd, 1997) and the recent Methane to Markets Initiative (US Environmental Protection Agency, 2006b) and the Asia-Pacific Partnership on Clean Development and Climate (Office of the Press Secretary, 2005) show, the inclusion of non-Annex B countries – especially China and India – is important politically at the federal level for US policy. Given that these non-Annex B nations have a large share of non-CO_2 emissions with cheap abatement potential, inclusion of these nations in global climate policy could perhaps concentrate on these substances.

1.3.2 The Potential of Methane

CO_2 is the past and present and projected future largest contributor to anthropogenic well-mixed greenhouse gas forcing. However, the 2nd largest contributor is worth examining in its own right. The increased concentration of methane from a preindustrial level of 700 ppb to a current concentration of about 1775 ppb has led to an increase of 0.5 W/m^2, nearly a third of the contribution from CO_2. We project a continued increase in methane concentrations over the century, though not to the same extent that CO_2 concentrations increase. We have a more detailed analysis of methane in the second chapter of this thesis, as well as in Appendix E, but there are some attributes of methane that are worth mentioning here.

The first attribute is that methane has a much shorter lifetime than CO_2. We discussed one of the implications of this when we showed that two "GWP equivalent" scenarios will have different outcomes in terms of radiative forcing over time. However, the lifetime of methane actually depends on the oxidative capacity of the atmosphere, whereas the "lifetime" of CO_2 as discussed above is a reflection of the carbon cycle. This means that the lifetime of methane will change depending on what other substances are being emitted in large quantities, including emissions of methane itself. Indeed, if emissions of methane increase substantially, this will lead to an increase in the lifetime of the gas, and therefore in a positive feedback loop even higher concentrations than would otherwise be expected. Additionally, increased methane emissions also lead to increased ozone concentrations through the interaction with the ozone cycle, and ozone has both health impacts and additional forcing impacts.

While 75% to 90% of carbon is emitted by fossil fuel combustion (Alley et al., 2007), only about 10% of methane comes from the fossil fuel sector, and that mainly in the form of leakage during exploration, production, transport, and utilization (Chen and Prinn, 2006). Most of the remaining anthropogenic methane emissions are produced as a result of anaerobic processes in the agriculture and waste disposal sectors. There are many inexpensive abatement options available in these sectors, some of which carry the additional benefit of capturing the methane for use as an energy source thereby potentially displacing additional greenhouse gas emissions. Due to the inexpensive abatement options and significant contribution to forcing, we felt that methane was worth individual consideration rather than just being included among a host of other gases. However, it is important to note that the nature of methane sources makes them difficult to quantify. As we demonstrate in the next chapter, our results show that methane is not only worthy of separate academic consideration, but that there are compelling reasons to address it separately from carbon dioxide in the policy realm as well.

1.3.3 The Question of Air Pollutants

The third chapter of the thesis addresses air pollution. Some air pollutants such as ozone, black carbon, and sulfate aerosols have direct climate impacts, though it is difficult to quantify the radiative impact of substances that are not well mixed in the atmosphere. Air pollution emissions are also linked to carbon dioxide emissions because they have a common source in fossil fuel combustion. Finally, air pollution emissions also have an impact on methane lifetimes. However, while air pollution has been studied in an academic context, emissions constraints have not been directly addressed in any of the major climate policies. Certainly, no stabilization scenarios that this researcher is aware of have included explicit air pollution targets. However, it is not clear to what extent or in which manner climate policies should coordinate with air quality standards. One rationale for coordination is that there are local incentives for addressing air pollution, and that therefore this local incentives can serve as leverage in order to gain support for complementary greenhouse gas reductions. Or vice versa – international support for GHG reduction may provide funding for air pollution reduction in countries that could otherwise not afford it. However, while it is possible at least to measure direct impacts using sophisticated modeling tools, the interactions between greenhouse gas policies and air pollution policies are difficult to resolve on a global scale. And if coordination benefits do exist, it is still not clear whether policies should directly address both kinds of emissions simultaneously, or whether it is sufficient to implement flexible measures that allow the market to optimize across multiple simultaneous objectives.

1.3.4 Temporal Issues

One of the key differences that we highlight between CO_2, methane, and air pollution is the timescale issue. CO_2 has a lifetime on the order of a century, methane has a lifetime on the order of a decade, and air pollutants have lifetimes on the order of hours, days, or weeks at most. These lifetime differences imply consequences for trading between substances, as we demonstrated above for methane and CO_2 trading. They also may imply differences in policy approach.

Because of the lifetime of CO_2, most stabilization scenarios project actual stabilization occurring in the middle of the 22nd century or beyond. This is far beyond policy timelines for most other issues (with the exception of one or two issues such as nuclear waste storage). How does the long term nature of this commitment impact the short term policy process that is necessary to actually getting anything done? On one hand, most arguments about the actual long term goal (550 ppm versus 750 ppm, for example) do very little to inform today's policy making and the effort spent in trying to reach some form of consensus may actually detract from moving forward. On the other hand, the most ambitious targets, on the order of 450 ppm or less, would almost certainly require significant action within the next decade. So if negotiators decided that keeping the 450 ppm option open was an important goal, this would have immediate short term relevance.

An emphasis on stabilization also ignores certain path issues. For example, overshoot scenarios have been proposed, especially in the case of 450 ppm type constraints. The danger of overshoot scenarios is that there are various climatic processes which exhibit hysteresis. For example, permafrost, once melted, releases CH_4 and CO_2 from stored organic material which has a very long restoration timescale. Another issue where path matters might be thermohaline circulation collapse, which may be not only a function of final equilibrium temperature change but also of the rate of change to reach that temperature (Stouffer and Manabe, 1999). And of course, there is the question that applies to any long term emissions path, but especially to one which delays reductions into the future: will future generations comply with ambitious plans designed in the present? Indeed, long term stock problems create a Zeno's paradox-like problem: if reductions tomorrow are equivalent to reductions today, why start now? But the same logic can be applied tomorrow, and the day after.

One of the possible benefits of linking air pollution policies to climate policies is that the immediate benefits to be gained for air quality improvements will spur near term action. This is not only a time scale issue, but also an issue of geographic scale: local benefits create more incentives than do global benefits. Methane has similar advantages of time scale, but lacks the geographic scale advantages. The possible problem is that an emphasis on these other short term substances will make it even easier to postpone action on CO_2 reduction. But we believe that it is appropriate to emphasize those achievable reductions that can be made today, and continue to work on the technologies that may be useful for reductions tomorrow.

1.3.5 A Cross Gas Comparison

We have discussed some of the properties of carbon dioxide, methane, and air pollutants. All three are possible targets of climate policies, but they have very different characteristics. We prepared Table 1-1 to summarize these differences. Note that for carbon dioxide we specify that portion which derives from fossil sources: the table could be easily be expanded to include "CO_2 sinks and sources from non-traditional means" such as tillage, forest regrowth, or land use change. These LULUCF (land use, land use change, and forestry) carbon measures differ from fossil sources in various key ways, the most important perhaps being uncertainty in emissions. This uncertainty contains not only the question of how much carbon is taken up by for example a forest planting, but the permanence of that uptake and questions of what the land had been used for before the planting.

	Fossil CO_2	CH_4	Air Pollutants
Time Scale	Long	Short	Short
Non-climate	Plant fertilization, ocean acidity	Ozone production, energy production, coal mine fires, ancillary landfill odor	Human health, visibility, hydrological cycle impacts, ozone-ecosystem link
Temperature Reduction	Half of accessible 21st century reductions from reference temperature increase, even more important on long time scales	1/3 of accessible 21st century reductions (depending on definition of "accessible"), less on longer time scales	Policy can lead to 8% direct reduction in 2100 temperature increase
Uncertainty in impacts	Climate sensitivity uncertainty plus sink uncertainty	Climate sensitivity uncertainty plus natural emissions uncertainty plus chemistry uncertainty plus ozone uncertainty	Large uncertainty in aerosol impacts and atmospheric chemistry. Sign even in dispute for some substances.
Uncertainty in emissions	Small	Large	Medium
Uncertainty in projections	Large	Large	Large
Uncertainty in abatement costs	Large	Medium	Large
Availability of low cost reductions	Small (as a percentage of total emissions)	Large	Medium (in developing world)
Local benefits of reductions	Zero	Small	Large
Ancillary benefits	Large (air pollution)	Small	Medium (CO_2 reduction)
North-South equity issues	US refuses to act without inclusion of China, India: but CO_2 and economic growth are linked so LDCs resist constraints	A lot of emissions are in the South, but are cheap to abate	A lot of emissions are in the South, and have large local benefits to reduction, but can be expensive.
Regional Differentiation	Small	Small	Large
Interaction with Existing Policies	Medium	Small	Large
Necessity for technology development	Affordable zero carbon energy sources may require significant R&D investment	Available technology is sufficient for significant abatement	Continued incremental improvements should suffice

Table 1-1: A Cross Gas Comparison: How methane, CO_2, and air pollutants differ in many characteristics that might have policy relevance.

1.3.6 Other Greenhouse Gases

We address fossil CO_2, CH_4, and the air pollutants in depth in this thesis. N_2O, HFCs, and SF_6 are all included in the Kyoto Protocol, but we limit our discussion of them in this thesis to Appendix C. Because these gases have smaller contributions to climate change in the next century than do CO_2 and CH_4, we felt it was acceptable to leave them out of this analysis. We note that source characteristics of N_2O are similar to those of methane, though its lifetime is more similar to that commonly assigned to CO_2, so it is not clear how much of the methane chapter would be applicable to N_2O. The industrial gases, on the other hand, are mostly emitted as leaks, and in physically small quantities, and therefore containment and disposal should be significantly easier. As a follow up study, it would be worth analyzing these substances to determine whether there may be value to addressing them with individual policies as we suggest for CH_4, or if the quantity of GWP weighted emissions are small enough that any drawbacks involved in including them in a CO_2 trading scheme can be ignored.

1.4 Previous Efforts

1.4.1 Stabilization Calculations

The analysis of stabilization scenarios can illustrate issues pertinent to temporal differences between gases, multi-gas scenarios, and trading. In order to explore the ramifications of various definitions of stabilization, we considered several ways that a stabilization goal might be achieved. The following discussion is based on a study by Sarofim et al. (2005). Two primary targets were considered – 550 ppm and 650 ppm – using the MIT IGSM, which includes an economic model capable of estimating the cost of multiple greenhouse gas control (Babiker et al., 2001; Hyman et al., 2003b; Prinn et al., 1999). The CO2ONLY scenarios restrict CO_2 but no other gases. In these scenarios, emissions paths were designed to control CO_2 starting in 2005 with a given global carbon price, and with a price path rising at 5% per year, in order to achieve their target CO_2 stabilization level sometime after 2100 given the median climate parameters described in

Appendix B. Reductions in other GHGs occurred only as side effects of the CO_2 quotas. The GHGTRADE scenarios used the appropriate CO2ONLY scenario as a baseline, and then allowed trading of other GHGs as weighted by their GWPs in order to achieve identical GWP emission profiles. A third case, PROPRED, assumed the same CO_2 quotas as the CO2ONLY scenarios, but imposed proportional reductions from the baseline path of the other GHGs. Finally, a fourth case, GHGCONST, used the same CO_2 emissions pathway but holds all other GHG emissions constant at their 2005 levels.

Each of these scenarios is a plausible interpretation of a stabilization goal but we find very different temperatures changes and economic costs on the century timescale (Table 1-2). In the reference (no policy) case the temperature increase was 2.8 ºC by the end of the century. For 550 (650) ppm stabilization, the CO2ONLY case reduced the temperature by roughly 0.75 (0.5) ºC at a cost of 1.2% (0.4%) of net present consumption (final consumption being a measure of societal welfare in the EPPA model, discounted at 5% per year over the century). The GHGTRADE cases were at least 50% more effective in temperature reduction on the century timescale than the CO2ONLY scenarios, at less than half the cost. The PROPRED case achieved nearly twice the temperature reduction compared to the CO2ONLY case but at a 40% increase in cost.

In general, these costs are likely to be low because optimal reduction through time assumes the most cost effective approach to emissions reduction (Wigley et al., 1996). Our policies also assume participation by all countries from the start, and thus include the most cost-effective reductions in all parts of the world. In contrast, when we simulated the economic cost of an extended Kyoto policy where the Kyoto reductions in 2008-2012 are gradually increased in the industrialized world and then later extended to developing countries to achieve approximate stabilization of CO_2 at 550 ppm,, the net present consumption loss due to this policy was 2.0%, a greater loss than any of the global 550 ppm stabilization cases in this study (Reilly et al., 1999).

	CO2ONLY	GHGTRADE	PROPRED	GHGCONST
650 ppm				
ΔT from BAU(a)	0.47	0.86	0.86	1.02
NPC loss(b)	0.4%	0.2%	0.5%	0.6%
2005 C-eq Price(c)	$23	$1	$0 to $23	$0 to $23
550 ppm				
ΔT from BAU(a)	0.75	1.18	1.46	1.34
NPC loss(b)	1.2%	0.5%	1.7%	1.4%
2005 C-eq Price(c)	$50	$4	$0 to $50	$0 to $50

Table 1-2: Results of different stabilization policies on temperature and costs

a) ΔT : difference in decadal global mean temperature in 2100 between the policy case and the no policy case (with warming of 2.80 °C).

b) NPC loss: percent reduction in net present consumption through 2100 given a 5% discount rate.

c) C Price: The carbon-equivalent price is the price that would clear a permit market in emissions given the emissions constraint imposed on the model in 2005. Note that in the PROPRED and GHGCONST cases there is no trading between gases, so there are different prices for each gas, but the non-CO_2 gases have near zero prices in early periods.

To consider the extent to which year 2100 conditions were consistent with stabilization, we ran the earth system components of the MIT IGSM beyond 2100. We considered stabilization at 550 ppm in the CO2ONLY case. To achieve long-term stabilization of CO_2 required continued emissions reductions at 1% per year after 2100. This simple extrapolation of the emissions path was used because the EPPA model was designed to run only through 2100. For the remaining cases, we decreased CO_2 emissions at the same rate as in the CO2ONLY case and maintained all other gases at their 2100 emissions levels. We note that the CO2ONLY case does *not* stabilize radiative forcing, which is still rising at 0.01 W/m^2 per decade even in 2300 because of the continued increase in other greenhouse gases. Radiative forcing in the GHGTRADE case, which continues to have equivalent GWP weighted emissions to the CO2ONLY case, is rising at the much faster rate of 0.1 W/m^2 per decade in 2300, demonstrating how focusing on short lifetime gases such as methane will eventually result in higher forcing in the long term because of accumulation of CO_2. This is evident in Table 1-3 where the GHGTRADE case has a forcing of 6.3 W/m^2 in 2300 compared to 5.0 W/m^2 in the CO2ONLY case. The GHGCONST case, on the other hand, has nearly stabilized radiative forcing in 2300 despite continued emissions of long-lived gases, and radiative forcing in 2300 is actually decreasing at 0.01 W/m^2 per decade in the PROPRED case.

For the CO2ONLY scenario (Figure 1-7) CO_2 emissions (orange line), which were declining at a rate of 0.1 GtC/yr in 2100, still have not yet reached zero in 2300. Emissions of CH_4 and CO can be significant sources of CO_2 and must be included in the eventual stabilization plan (purple line). In order to stabilize concentrations, CO_2 emissions must continue to decrease, eventually approaching zero (Hoffert et al., 2002), but even out to 2300 there remains some positive ocean uptake (Figure 1-7) mainly due to the ocean's slow mixing processes.

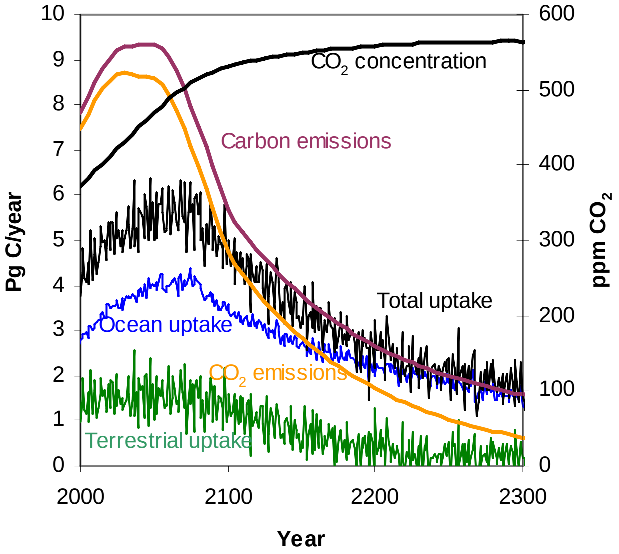

Figure 1-7: Components of carbon-cycle budget Carbon emissions (CO, CO_2, CH_4) and CO_2 concentrations for the CO2ONLY 550 ppm stabilization case. Annual average uptake, emissions, and concentration are shown. (Sarofim et al., 2005)

Uptake by the ocean in the 550 ppm CO2ONLY stabilization scenario peaks at 4.2 GtC in 2070 and drops to 1.6 GtC in 2300 and is still declining thereafter. Terrestrial uptake peaks at 1.7 GtC in 2050 and is nearly zero by 2300. The strength of these sinks at any point in time and their overall response depend strongly on the properties controlling the climate system response (see Appendix B for details about the choice of parameters) and on the features of the terrestrial ecosystems model in the IGSM (Webster et al., 2003). For the CO2ONLY case in 2100, the 95% bounds on CO_2 concentration due to S and Kv uncertainty alone range from 500 to 585 ppm. With declining anthropogenic emissions, atmospheric concentrations of CO_2 begin to stabilize, allowing the terrestrial ecosystem to reach equilibrium with the atmosphere. The ocean mixed layer also approaches equilibrium, and further ocean uptake is then limited by diffusion into the deep ocean. Furthermore, there are negative temperature effects on both terrestrial ecosystem and oceanic uptake rates.

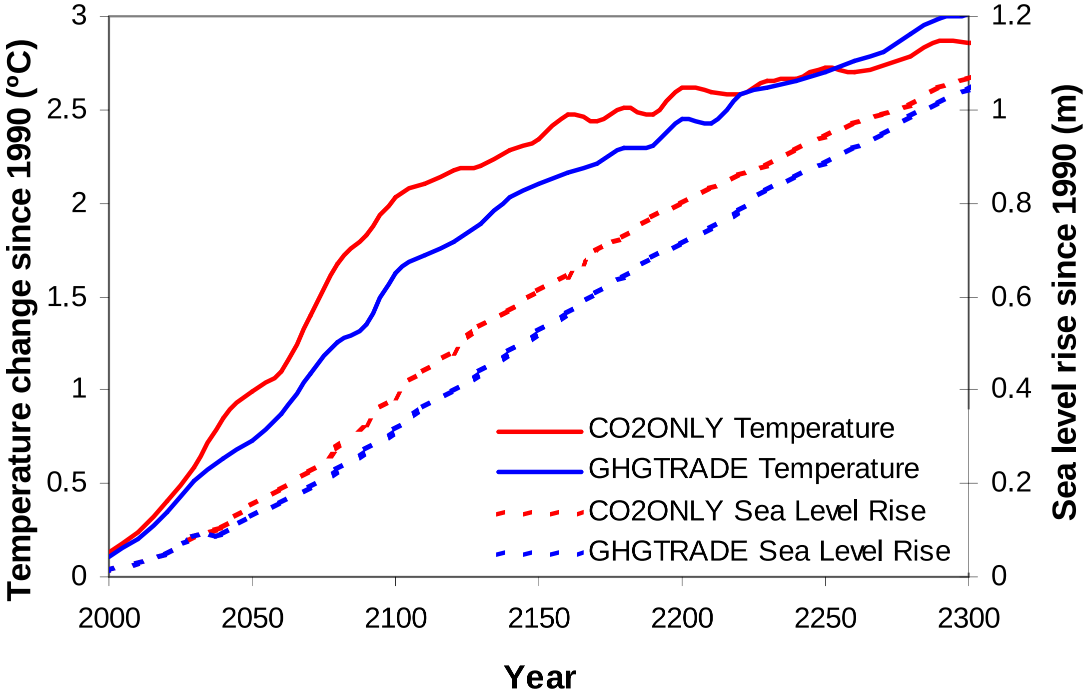

Figure 1-8: Decadal global mean average temperature and sea level rise
Results for the CO2ONLY and GHGTRADE 550 ppm scenarios (Sarofim et al., 2005).

In the trading cases, more of the reductions come from CH_4 than from CO_2 because of the relative opportunities for least cost emissions reductions. Because CO_2 is longer-lived than CH_4, this means that the GHGTRADE cases show greater reductions in temperature from the reference case in the short term than the CO2ONLY cases. But, with more long-lived CO_2 accumulating in the atmosphere, the GHGTRADE cases should eventually become warmer. Analysis of the 550 ppm scenarios (Figure 1-8) shows that the temperature rise in the GHGTRADE exceeds the CO2ONLY case after 2240, when the CO_2 concentration is 780 ppm. The ‘short term’ benefits of CH_4 reduction thus remain for a surprisingly long period. Due to inertial effects, sea level rise in the two cases is comparable only after about another 100 years (2330), when the rise is 1.1m above present in both cases.

The comparison between the GHGTRADE and CO2ONLY cases again raises the question of whether GWPs are an appropriate ’exchange rate’ in trading GHG reductions

(Manne and Richels, 2001a; Reilly et al., 1999; Smith and Wigley, 2000; Sygna et al., 2002). If the rate of temperature change is an important factor in designing a policy, as studies of the possible thermohaline circulation collapse suggest (Schneider, 2004), then non-CO_2 greenhouse gases are being undervalued by GWP measures, whereas if long-term radiative forcing stabilization is the criteria of interest, then gases such as methane are being overvalued. Table 1-3 shows the concentrations of the major gases in 2100 for all cases, and in 2300 for the 550 ppm scenarios. In addition to timescale issues, the implications of non-CO_2 GHGs and non-GHGs for atmospheric chemistry, such as the impact of methane or NOx on ozone levels, might also be important for air quality and for changing the lifetimes of other greenhouse gases. Because the GHGTRADE scenario has both superior temperature and cost characteristics, our study shows that adhering to a definition of stabilization that emphasizes CO_2 is likely to miss win-win opportunities (Reilly et al., 2003b). We note that more than one recent study (Rao and Riahi, 2006; van Vuuren, 2006) have found similar results when comparing a CO2ONLY case to a GWP equivalent optimal GHG mix case, where the multi-gas scenario was both much less expensive and cooler in 2100.

	CO_2 (ppm)	CH_4 (ppm)	N_2O (ppb)	O_3 (ppb)	Δ Rad. Forc.(b) (W/m^2)
No Policy, 2100	822	5.42	483	51	7.4
650 ppm cases, 2100					
CO2ONLY	608	4.09	473	46	5.0
GHGTRADE	673	2.12	410	45	4.4
PROPRED	606	2.23	418	45	4.0
GHGCONST	605	2.12	414	46	3.8
550 ppm cases, 2100					
CO2ONLY	529	3.80	466	45	4.0
GHGTRADE	592	1.96	402	44	3.5
PROPRED	527	1.48	393	41	2.7
GHGCONST	527	2.14	413	45	3.0
550 ppm cases, 2300					
CO2ONLY	562	3.58	676	44	5.0
GHGTRADE	868	1.85	514	43	6.3
PROPRED	540	1.14	444	44	2.8
GHGCONST	550	2.12	510	45	3.6

Table 1-3: GHG Concentrations in 2100 in Four Policy Scenarios

(a) HFCs and SF6 are also included in the model though the numbers are not shown here due to their comparatively smaller contributions to net forcing

(b) Change in radiative forcing since 1990 of all GHGs, not including sulfate aerosols.

These results depend on the specific reference emissions projections which, for CO_2, at a cumulative level of 1700 GtC, falls into the "medium-high" range for the IPCC's SRES scenarios, but considerable uncertainty exists in future emissions of CO_2 and perhaps even more so for the other GHGs (Webster et al., 2002). The projections of non-CO_2 emissions and concentrations in our reference scenario clearly have an impact on the results. By the end of the century, the EPPA model reference scenario projects annual methane emissions of 860 Tg (comparable to the IPCC A2 SRES scenario of 889 Tg), and N_2O emissions of 22 Tg (which is slightly higher than the 20 Tg of the upper range of the SRES scenarios). The resulting methane concentration is, however, significantly higher than the SRES projections. The MIT IGSM includes stratospheric chemistry, natural emissions of methane and N_2O, and a more complex tropospheric chemistry model than the single box model used by the TAR, which likely contributes to the much higher atmospheric concentration results in this study, even though methane emissions are comparable.

The feedbacks and uncertainties involved in the response of natural emissions of CH_4 and N_2O to climate change, like the uncertainty in CO_2 uptake, add to the complexity of designing climate policies. Yet another emission uncertainty has to do with non-GHG climatically important substances that may be controlled by non-climate related policies (Dai et al., 2001b). Our SO_2 emission projections also differ from those of the SRES scenarios. Further exploration of these uncertainties and those of climate system parameters is warranted, but the first step towards a study of stabilization under uncertainty is an examination of what stabilization means for a single set of reference conditions.

Indeed, this section has demonstrated that significant uncertainty arises resulting from definitional issues alone. Whether and in what manner non-CO_2 gases are included within stabilization policies makes a large difference in terms of what temperature change results from a given target. The non-CO_2 gases, and especially methane, are shown to be extremely important for low cost and effective temperature reductions on timescales of up to three centuries. Therefore, we recommend that future studies and proposals involving stabilization include these other gases, and make the manner of their inclusion explicit.

1.4.2 CCSP Scenarios

An example of one approach to explicit inclusion of other gases within a stabilization analysis is present in the second of the 21 synthesis and assessment products of the US Federal Government's *Strategic Plan for the US Climate Change Science Program* (CCSP) (US Climate Change Science Program, 2006). This product was a call for new scenarios of GHG emissions and concentrations. We present our work on this product in this thesis as a further examination of stabilization, demonstrating the importance of the non-CO_2 gases without detracting from the crucial role of CO_2 reduction itself. In addition, the use of two other models within the CCSP product allows some examination of the consequences of different modeling assumptions.

That these new scenarios consisted solely of "stabilization scenarios" indicates some of the power that the idea of stabilization has among climate scientists and policymakers. This influence is especially significant given that the Bush administration has usually avoided the standard climate policies, rejecting Kyoto, proposing emission intensity targets rather than standard caps, and starting programs such as Methane to Markets, the Asia-Pacific Development Initiative, and FutureGen.

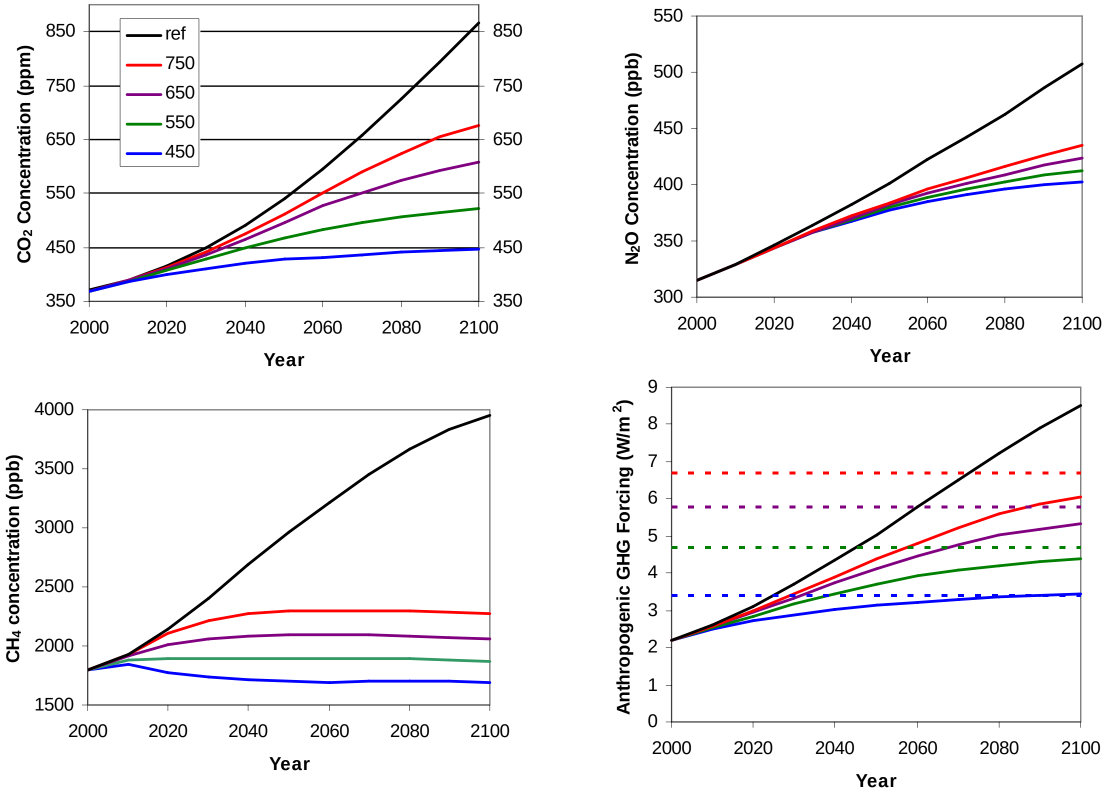

Figure 1-9: CO_2, CH_4, and N_2O concentrations and total forcing. Results from MIT IGSM calculations using CCSP targets.

The multigas targets themselves were chosen in order to yield atmospheric CO_2 stabilization at 450, 550, 650, and 750 ppm (Figure 1-9). This choice of targets was designed in order to allow comparisons to previous work that was often focused on CO_2 stabilization at these levels. A further forcing increment was allowed for non-CO_2 GHGs. This increment of 0, 0.1, 0.2, or 0.3 W/m^2 was determined in a somewhat arbitrary fashion, using Sarofim et al. (2005) as a guideline for what non-CO_2 GHG constraint might yield a price comparable to the price of meeting the CO_2 target. Results from the economic analysis of these scenarios show that for the EPPA simulations in the CCSP study, methane prices for the last half of the simulation period were fairly close to the price they would have under GWP based trading, but N_2O prices were significantly higher due to insufficient N_2O abatement options to achieve stabilization of that gas. Two other computer models developed and run by other research groups at Stanford and the Pacific Northwest National Labs (PNNL) were used in the CCSP study, with differing approaches to the non-CO_2 gases: mini-CAM had the prices rise at a rate that was consistent with their GWP values and the CO_2 price, whereas MERGE used a forward looking model to dynamically determine the price of each gas separately (Figure 1-10). Non-GHG substances with climatic implications such as black carbon, tropospheric ozone, or sulfate aerosols were not considered at all in calculating allowable forcing increases, though secondary impacts of GHG constraints on emissions of these substances or their precursors were included in the MIT study.

The policies necessary for stabilization were implemented such that they started post-2012, with Kyoto Party members pursuing the Kyoto Protocol limits through 2012 and the United States pursuing the Bush goal of improving US GHG intensity by 18 percent from 2002 to 2012. After 2012, further reductions were allocated such that each country/region bore the cost of reductions within the region and marginal costs of reductions were equal across regions. That is, allocations were set such that there was no incentive for emissions trading. This convention was chosen so that regional costs reflected reduction efforts in each region and was not intended to represent a fair, feasible, or likely result of a negotiated agreement (US Climate Change Science Program, 2006).

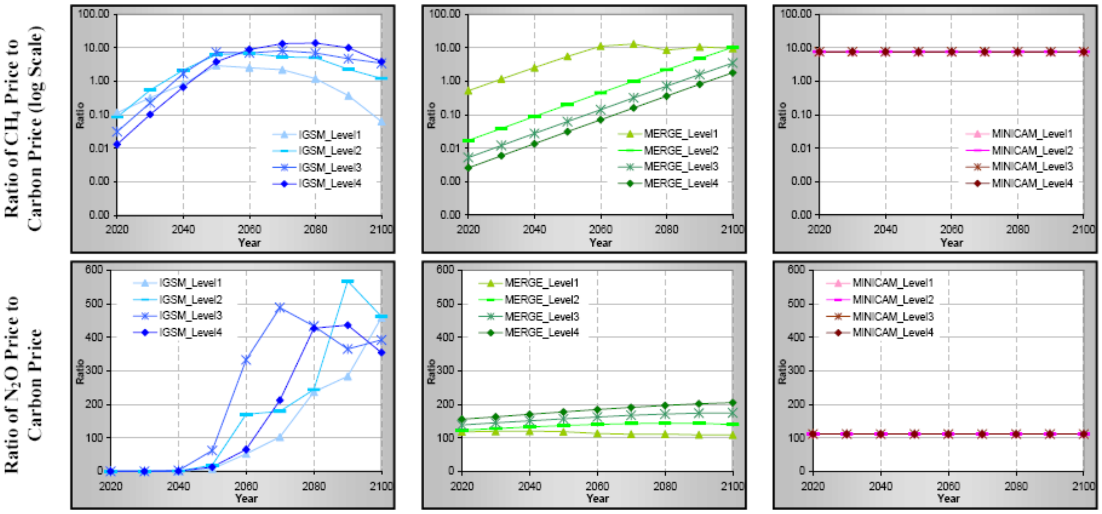

Figure 1-10: Relative Prices of CH_4 and N_2O to Carbon Across Scenarios (CH_4 in log scale). Differences in the relative prices of CH_4 and N_2O to carbon reflect different treatments of this tradeoff, often referred to as *what* flexibility. In the MiniCAM scenarios, the tradeoff is based on the GWP of the non-CO_2 GHGs, which are constants, leading to constant ratios of the non-GHG prices to the carbon price. In the MERGE scenarios, relative prices are optimized with respect to the long-run stabilization target. In the IGSM scenarios, stabilization was forced for each gas independently. Emissions were set so that concentrations of CH_4 would stabilize and allowed the CH_4 price path to be determined by changing opportunities for reducing emissions. Given N_2O emissions from agriculture, the relative price of N_2O is very high, in part because reference emissions were high. Lower reference scenario emissions of N_2O for the MERGE and MiniCAM scenarios allowed them to achieve relatively low emissions at lower N_2O prices. (US Climate Change Science Program, 2006)

For the EPPA simulation, stabilization scenarios were implemented such that the carbon price rose at 4 percent per year, to yield a Hoteling approximation to an optimal market solution over time. This is not necessarily a socially optimal solution given the existence of other distortions in the economy such as: pre-existing taxes on fuels, labor, and capital; unexplained differences in purchasing power parity across countries; unpriced externalities related to energy use such as environmental pollution; or public goods resulting from research and development. In the EPPA simulation there were separate targets for each of the major gases, due to the inconsistency of stabilization with allowing GWP based trading and stabilization as mentioned in Sarofim et al. (2005) and discussed earlier in this chapter. However, 100 year GWPs were used to trade between HFCs, PFCs, and SF_6. This is a reasonable approach because even fairly low carbon prices result in near zero emissions of these substances, and their total GWP weighted sum is fairly small in comparison to the CO_2 constraints.

The CCSP exercise was also designed to terminate in 2100. This left unspecified how to take into account various long-term factors, such as the issue of how to address gases with long lifetimes (namely CO_2 and N_2O) which would not have reached equilibrium in that time period, or the changes in natural emissions and uptake to be expected post-2100.

Outside of the CCSP exercise, we have performed analyses extending the EPPA based simulations within the CCSP scenarios to 2400 (Figure 1-11). Because we do not extend EPPA itself past 2400, we made the assumption that the emissions of all gases except CO_2 would remain constant post-2100. CO_2 itself would decrease at a rate calculated to approximate stabilization. While it may have been a poor assumption to extend throughout this period the 1.42 GtC/year uptake adjustment factor used to balance the land sink (TEM), the ocean sink, and the atmospheric accumulation rate in the 1980s, the existence of this adjustment factor allows us to effectively eliminate CO emissions through accounting measures without changing the chemistry of the atmosphere[8]. Initial attempts to balance the carbon cycle including CO reductions led to a significant decrease

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[8] This bookkeeping adjustment is visible in Figure 7. After 2100, the TEM uptake adjustment factor is presumed to decrease at 1% per year, and the effective total carbon emissions are decreased appropriately to compensate.

in CH_4 concentrations as OH levels increased in response. Physically, given how low-CO_2 scenarios result in significant dependence on biomass energy sources which have no net CO_2 emissions but do produce CO, it is possible that CO will continue to be emitted in significant quantities into the distant future, depending on the efficiencies of the technologies involved in combustion of these substances.

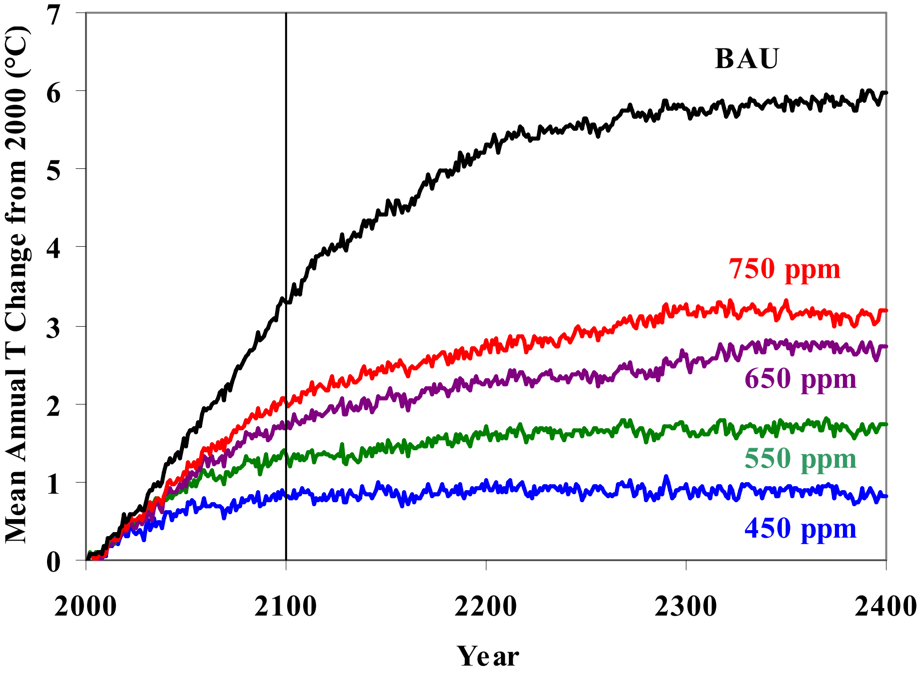


Figure 1-11: Temperature Change to 2400 for MIT IGSM extensions to the scenarios developed for CCSP Product 2.1.

Figure 1-12 demonstrates again the necessity of reducing carbon dioxide emissions drastically in the post-2100 world in order to achieve stabilization. The extension of the CCSP analysis requires a reduction to 2 GtC levels by 2200. Note that the 3 dimensional ocean included in these long term stabilization analyses to 2400 has a much smaller ocean uptake post-2100, and therefore the carbon emissions in that period are even more constrained than in the first century of the policy. This uptake in this 3 dimensional model is much lower than the uptake in the IGSM1 2D model had been, not only because of a slower uptake parameter, but also because the model captures physical processes that tend to shut down circulation at higher temperatures. This analysis reinforces the point that if we are serious about stabilization, we will need to create significant new zero carbon emitting technologies. Even if actual stabilization is not the goal, but merely reduction of

CO_2 growth to levels that may prevent dangerous anthropogenic interference, there will have to be significant advances in the energy production and transport sectors in order to achieve low levels of emissions.

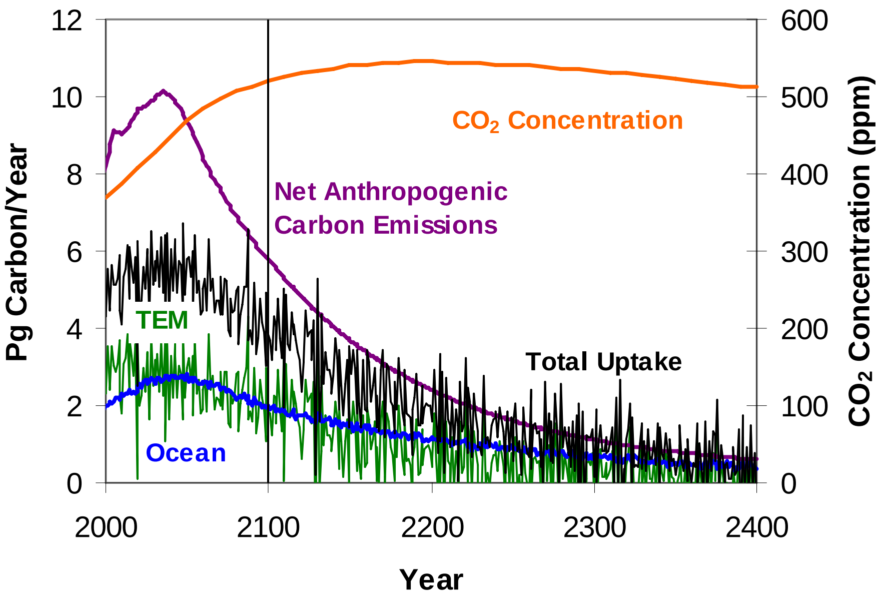


Figure 1-12: Components of the carbon-cycle budget and CO_2 concentrations for the MIT IGSM extension of the Level 2 scenario used in CCSP Product 2.1.

Differences between the EPPA simulations used for the CCSP scenarios and the previous Sarofim et al. (2005) analysis include the use of EPPA4 rather than EPPA3, IGSM2 rather than IGSM1, and a 3D ocean rather than a 2D ocean. Also, the climate parameters used were updated based in part on a recent pdf estimation study (Forest et al, 2006). Therefore, the ocean heat uptake was significantly lower. A Kz of 0.4 cm^2/s was used which is approximately equivalent to a 2D Kv of 3 cm^2/s, compared to a Kv of 9.2 cm^2/s used in Sarofim et al. (2005). Because the 3D ocean includes a biological carbon uptake mechanism, the reduction in carbon uptake was not as drastic as it might have been otherwise. Climate sensitivity (CS) was 2.0 (lower than the pdf estimation study median, though still consistent with 20th century climate), and the aerosol forcing parameter (Faer) was -0.35 W/m^2 (later versions of the model, used in subsequent chapters adjust Faer to -0.85 W/m^2 in order to appropriately balance BC forcing). These changes in parameters lead to a warmer 21st century, but significantly less additional warming post stabilization, as the upper layers of the ocean rapidly enter into equilibrium with the atmosphere and the deep ocean hardly enters into the equation. The slow ocean also leads to significantly less sea level rise (Figure 1-13), and even the reference scenario has little more rise than either of the stabilization scenarios from Sarofim et al. (2005). If this update of ocean uptake parameters proves accurate, the need for short term reductions in GHG concentration growth becomes even more important, but perhaps we may not need to worry as much about system inertia carrying on long after we stabilize concentrations.

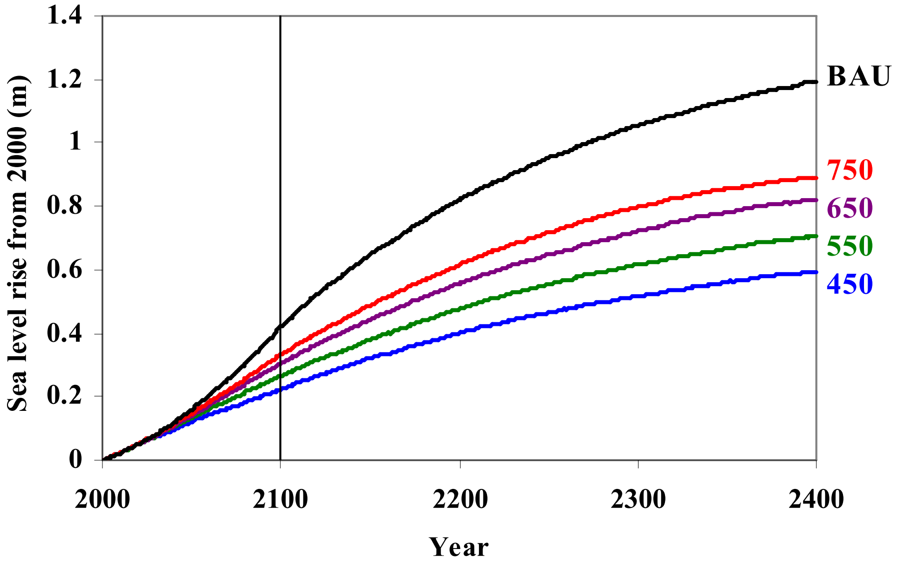
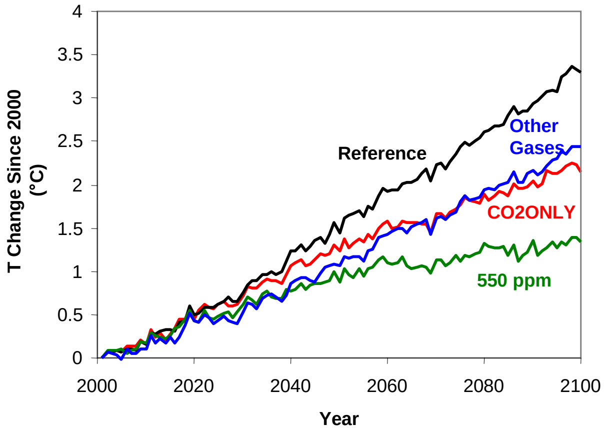


Figure 1-13: Sea level rise to 2400 for MIT IGSM extensions to the scenarios developed for CCSP Product 2.1.

Finally, the importance of the non-CO_2 gases is demonstrated in Figure 1-14. Using as a baseline the 550 ppm scenario from EPPA produced for the CCSP exercise, one simulation controlled CO_2 but none of the other greenhouse gases, the other constrained the non-CO_2 GHGs but not CO_2. This experiment shows that in the 550 ppm stabilization scenario we created for the CCSP exercise, fully half of the temperature reductions during the 21st century are due to reductions in non-CO_2 gases. Of course, due in large part to the inclusion of methane, the temperature reductions of the Other Gases scenario are weighted towards the early part of the century. We can expect that in a manner similar to Figure 1-8, the Other Gases scenario which is barely warmer than the CO_2 only scenario in 2100 will become relatively much warmer as time progresses.



CO2ONLY scenario: CO_2 emissions from 550 ppm scenario, all other gases as reference.

Other Gases scenario: CO_2 emissions from reference, all other gases from 550 ppm scenario.

Figure 1-14: Temperature change from CO_2 and non-CO_2 scenarios
Reference and 550 ppm (or Level 2) scenario from CCSP Product 2.1. The two other scenarios are hybrids: CO2ONLY uses the reference scenario for all gases other than CO_2 which are emitted as in the 550 ppm scenario, and the Other Gases scenario uses the 550 ppm scenario for all gases but the reference CO_2 emissions.

Many other groups have simulated stabilization scenarios, with wildly different assumptions and cost estimates. A special issue of the Energy Journal on endogenous technical change and the economics of atmospheric stabilization shows a range of costs for a 450 ppm CO_2 constraint of 8 percent of Gross World Product in 2100 to a gain of nearly 4 percent (Grubb et al., 2006). Gains can result either from optimistic assumptions about revenue recycling or manner in which the endogenous technical change itself was implemented. The average cost of climate policies for stabilization at 450 or 550 ppm (after excluding the most experimental of the models) was 0.39% and 0.1% respectively (Edenhofer et al., 2006), still lower than any of the CCSP models, and significantly lower costs than calculated by the MIT IGSM.

1.5 Conclusions

Climate change is widely acknowledged to be one of the major international policy challenges of this century. Problems that make climate change especially difficult to deal with include environmental commons issues resulting from the global scale of climate; intergenerational equity issues because of the long time scale of climate change; north-south equity issues because industrialized nations have high per capita emissions and a large historical burden while at the same time there is a perception that developing nations will ultimately need to be involved in any serious attempt at mitigation; action under uncertainty resulting from the complexity of the climate system and the difficulty of projecting anthropogenic emissions into the future; and the potentially very high cost of reducing emissions from activities that are integral to worldwide economies.

Due to the UNFCCC Article 2, the historical focus of international climate policy has been stabilization. While exact consensus on its meaning may not be needed to proceed with mitigation efforts in the near term, we have shown in this chapter that different interpretations of how other greenhouse gases are considered in a stabilization target have a substantial affect on how much warming is avoided and at what cost. As stated by Hasselmann et al. (2003), successful climate policies should take into account both short term policies and long term goals. Judgments about the adequacy of climate policy in light of a long term target, whatever it might be, will need to consider just what is meant by stabilization and how, in terms of the mix of GHG reductions, a target will be achieved. As seen in the heated debates over forest and agricultural sinks in the Kyoto Protocol negotiations, settling on definitions may ultimately be a political matter, but these debates can only benefit from being placed in a framework that elucidates the discussions (Watson and Intergovernmental Panel on Climate Change., 2000). The analysis within this chapter suggests that any policy measure that does not take into account all greenhouse gases will be both more expensive and less effective through the next century and beyond.

Political and academic dialogue in the past decade has centered in large part on carbon dioxide, and we posit that this focus is a natural result of the long term nature of stabilization. Perhaps due to this long term CO_2 focus, progress in this direction becomes tied up with the issue of whether or not there should be global targets as in the Byrd-Hagel resolution (Sen Byrd, 1997) and has historically stalled or been watered down to the point of inconsequential impacts (Paltsev et al., 2004). Our work shows that in fact CO_2 reductions will clearly need to be a central part of any climate solution. But are there legitimate alternative approaches to the stabilization and CO_2 paradigms for short term policy making? The problems with stabilization are that long term and global scale thinking makes it difficult to implement short term and local policies, and that CO_2 is tightly linked to energy production and therefore economic vitality and international competitiveness. Therefore we must search for policy options that could complement, supplement, or improve on standard approaches, as well as to better understand what is involved in a comprehensive policy analysis to guide future such analyses.

This thesis concentrates on options that involve controlling non-CO_2 gases. Potential key characteristics of these substances include the ability to have near term impacts (mostly through substances with short lifetimes), lower costs and significant impacts of mitigation, and the potential for offsetting local benefits. Are there non-CO_2 substances that have these characteristics? The answer to this question is clearly affirmative, as both methane and various air pollutants meet these criteria, but the mere existence of such substances is not sufficient. We need to address whether or not abatement of these substances has the potential for significant temperature change, whether or not realistic policies can address these substances, what the impact of such a policy focus would be on the long term issues, and how such policies would best be enacted given the characteristics of the controlled substance. Already we see some potential confusion when we examine the case of methane and CO_2 where exchange of reductions of one gas for the other by GWP weighting leads to very different future scenarios.

Regardless, it is important that we begin to address climate change mitigation seriously in the near term. We are uncertain about the threshold for reaching disastrous tipping points, therefore it would be wise to take precautionary measures while we attempt to better understand those thresholds. This especially holds true for reductions that can be achieved at low costs, technology advances that may yield dual benefits, policies that may yield double dividends through reduction of other economically distorting policies, or abatement policies that have ancillary or complementary benefits in air pollution or other areas. CO_2 reduction will remain central to any comprehensive set of mitigation policies and it is urgent that policies be enacted to address carbon dioxide, in terms of the near term emission reductions, avoiding CO_2 intensive capital investments, and researching the technologies necessary for radical CO_2 reductions in the future. However, if reductions in other substances, especially methane, can yield significant mitigation benefits at low cost it would make sense to address such gases as best we can.

2 Methane Policy: An Integrated Approach argues against GWP based trading

2.1 Introduction

Methane has begun to play a role in academic debate, galvanized in particular through the efforts of Hansen who proposed a scenario where a constant CO_2 growth over the next 5 decades would be offset in large part through methane reductions (Hansen et al., 2000). Methane is the second largest contributor to anthropogenic forcing caused by well-mixed gases and there exist many low cost abatement opportunities. With the advent of the Methane to Markets Initiative created by the US government (US Environmental Protection Agency, 2006b), methane has also become a part of international policy on its own merits rather than just as part of the larger bundle of GHGs. Our own stabilization work, as summarized in the previous chapter, suggested that including other gases, especially methane, was an important part of making effective policies at reasonable costs.

In this chapter, we reiterate the importance of methane as a low cost component of climate policies, and show the extent to which methane reduction can contribute to temperature reduction in this century. Through analyzing methane policies by economic modeling, climate modeling, and political analysis methodologies we argue that methane policy should be implemented separately from CO_2 policy. GWP based trading between CO_2 and CH_4 was intended to include "what" based flexibility in broader climate policies such as Kyoto, where efficiency is gained by allowing the market to equalize marginal abatement costs of different substances using a common metric. However, it is our contention that there are a series of drawbacks inherent to doing this.

First, we noted in Chapter 1 that CH_4 is likely mischaracterized by its GWP exchange value as supported by our own work and that of other researchers (O'Neill, 2000; O'Neill, 2003; Reilly et al., 1999; Sarofim et al., 2005). Modeling runs in this chapter show that on a 100 year basis, CH_4 constraints can lead to more than three times as much temperature reduction as does a GWP equivalent CO_2 policy. We showed in previous research (Sarofim et al., 2005) that this temperature advantage is likely to last at least 2 centuries. Alternative GWP methodologies have been proposed; Shine et al. (2005) use various alternative computational metrics, but conclude that their new metrics lead to only a small increase in methane valuation compared to CO_2. However, we argue that the difference between methane and CO_2 lifetimes is such that there is no GWP value that would suffice to address all of our concerns. Furthermore, GWPs have problems with the variability of the OH radical and thus methane lifetimes, the arbitrariness of a 100 year integration period, and the complexity of the carbon cycle. The IPCC Second and Third Assessment Report GWP estimates are presented in Appendix D.

Second, we argue that the difference in accuracy of source inventories is perhaps even more important than lifetime differences between CH_4 and CO_2. CO_2 emissions from fossil fuels can be measured very precisely. Ideally, fossil CO_2 policies would allocate permits or taxes at the wellhead or minemouth, but even if the policy is enacted to cover downstream emissions it is fairly simple to keep track of fossil fuel inputs and thereby be able to calculate CO_2 output. Anthropogenic methane emissions, on the other hand, are relatively hard to measure. Estimates of rice paddy emissions over the past decade, for example, vary by up to a factor of five. Recent inversion results from a top down approach creates tighter constraints on such sources that invalidate many bottom-up estimates (Chen and Prinn, 2006). This is because bottom-up inventory methodologies for methane emissions are often fairly crude. Therefore, in order to allow trading on a GWP basis between methane and CO_2, it is necessary to determine how strict to be when certifying methane reductions. It is quite possible that the certification process would not be sufficient to prevent "fictional" reductions, while at the same time discouraging actual methane reductions.

Third, there are structural economic differences which interact with CO_2 and methane abatement in ways that need to be considered. The first is that policies that constrain CO_2 interact with existing taxes in such a way that CO_2 reduction causes greater consumption losses than would be indicated by the CO_2 price. Given that the goal of trading is in theory to allow the market to find a solution that minimizes net societal cost, this interaction between policies results in more CO_2 abatement and less methane abatement than would be optimal as the price does not fully reflect the actual net present consumption loss. The second is that methane and CO_2 policies have differential impacts on developing nations. Developing nations have a smaller proportion of CO_2 emissions, and a larger proportion of methane emissions. Depending on how permits (in a theoretical trading case) are allocated, this can lead to methane constraints leading to a larger percent welfare reduction in non-Annex B nations than in Annex B nations. Therefore, it might be desirable to allocate permits for the two gases differently.

Fourth, and finally, political differences lead us to suggest separating the two gases. CO_2 constraints have a history of political inertia, and by tying methane policy to CO_2 policy we are potentially slowing down adoption of useful abatement methodologies. Indeed, there is a history of apparently successful methane abatement policies in the US and the EU. Reaching a broad geographic coverage may also conflict with multiple gas coverage, as developing nations may be more willing to take on methane abatement commitments than CO_2 commitments. The design and incentive structure of the methane policy would of course be critical in securing such developing nation accession.

There are some caveats in this analysis. The primary issue is whether our reference case has overpredicted methane growth, thereby overpredicting the available temperature reduction from methane. Given that CH_4 concentrations have leveled off in recent years, this is certainly a possibility. This does not change our argument that methane is best dealt with separately because the source estimation issue remains as large as ever. But it would mean that the benefits of methane reductions would be smaller than presented herein.

The point of this analysis is that policy design needs to be based on the characteristics of the substance being controlled, and that the characteristics of methane and CO_2 are sufficiently different that reductions of the two substances should not be considered interchangeable. Methane is also significant enough in and of itself that it is worth crafting a separate policy to address it. However, this research does not support any proposal that methane reduction can be a substitute for action on CO_2: rather, that the two gases are best addressed with separate strategies, and that policy should move forward as quickly as possible on both fronts.

2.2 Modeling Costs and Benefits of Methane Policies

2.2.1 Modeling

Modeling is a useful tool to answer some basic questions about methane abatement in order to understand its place in climate change policy. What is the potential for temperature reduction from methane control? How expensive is it to abate methane compared to a GWP equivalent quantity of carbon dioxide? How does an efficient trading policy allocate reductions across nations within the modeling framework? We recognize the limitations of modeling, some of which can be addressed by sensitivity or uncertainty analyses, others of which require stepping back and analyzing the broader picture. However, within those limitations modeling continues to be a useful tool and starting point for policy discussions.

We begin the study of methane control by modeling abatement within the framework of the MIT IGSM. The MIT EPPA4 model is used to project emissions into the future under different policy scenarios, and to project the economic costs of those policies. The projections of business as usual methane emissions and the elasticity assumptions that go into the model are both important in determining how much reduction can be achieved at what cost. The policy case and reference case EPPA emissions projections can then be used as input into the MIT IGSM version 2.3 (Prinn et al., 1999; Sokolov et al., 2005) which takes into account all the chemistry feedbacks important to determining methane lifetime and secondary ozone interactions (though the standard version of the model still does not take into account ozone impacts on ecosystems). The EPPA4 model has been described in depth in several publications, most recently in Report 125 of the MIT Joint Program (Paltsev et al., 2005b). The model versions used for this study are similar in most part to that described in Report 125 and is described in more depth in Appendix B.

It is worth repeating here key details of the model that pertain to methane and methane abatement. Hyman et al. (2003a) chose to simulate methane emissions as an input at the top of the production nest. If the elasticity of substitution between methane and the rest of the nest is zero, the implication is that methane emissions cannot be reduced without reducing the production of that sector. Hyman et al. used EPA data to estimate elasticities of substitution for individual sectors. Elasticities in the agricultural sector were further specified by region, and updated to match the new regions in EPPA4. Note that methane abatement through this mechanism (as differentiated from sectoral shifts) is mostly independent of other gas abatement: this is not a perfect assumption, but for methane is probably a fairly good approximation. In fact, in both our model and reality, this kind of methane abatement may actually lead to an increase in emissions of other substances, as the abatement will require an increase in other input factors which may have their own related emissions.

Using the EPPA model with the above elasticities we are able to estimate costs of various policy constraints. In general throughout this section we only model cap and trade policies. Within the modeling framework these kind of policies (or an equivalent carbon tax) are generally the most economically efficient means of achieving a given abatement target. Clearly, even if we assume that the model accurately represents the real world, a real world policy is unlikely to actually cover all sectors and all nations, nor to have perfect compliance and measurement techniques. However, for evaluating policies this is a natural choice to use for comparison purposes.

2.2.2 Abatement Opportunities

We first applied our model to examining the impact of methane constraints on the economy. Figure 2-1 shows the major economic rationale behind addressing methane. Worldwide constraints were placed on each gas in 2010, and the trading costs were plotted on the graph. For a price of $10/ton, 600 MMT carbon equivalents of methane can be reduced per year. For the same price, only 200 MMT of carbon dioxide are abated. If we presume that GWP weightings are close to accurate, this set of modeling simulations confirm the result shown in previous studies that significant reductions of methane can be made cost effectively (Hyman et al., 2001), and show that the quantity of inexpensive reductions available in the near term is on the order of one half gigaton to one gigaton of carbon equivalent per year. For comparison purposes, when we model the Kyoto Protocol in this framework, without the US and including hot air from the FSU nations, there were negligible reductions in 2010 and only 140 MMT reductions in 2015. An additional comparison is that had the US not withdrawn from the Kyoto Protocol, its CO_2 reductions from a BAU emissions case of 1800 MMT would have been 550 MMT, and therefore the entire Kyoto agreement would have had about 550 MMT of reductions in 2010, which is on the order of available very inexpensive methane reductions.

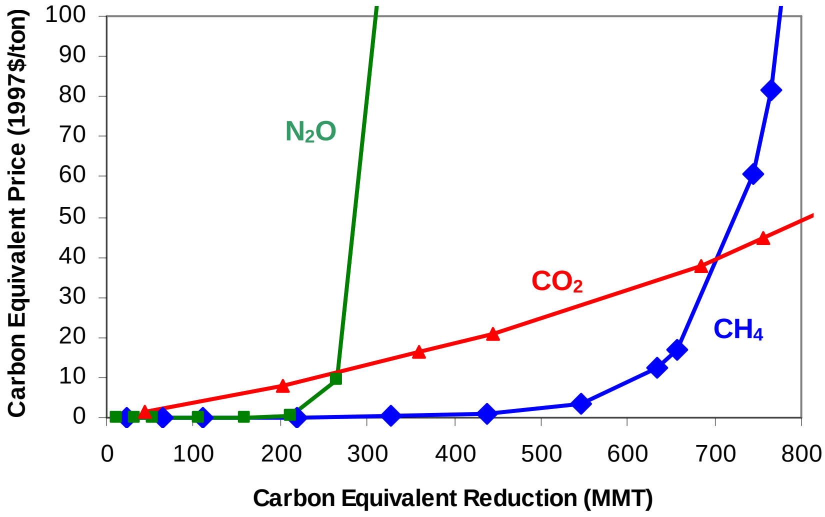


Figure 2-1: Global Marginal Abatement Curves derived from EPPA4 in 2010 for CO_2, N_2O, and CH_4

"No-regret" options are those abatement opportunities that can be achieved at zero or even negative cost. Such an opportunity in the methane case might include capping a landfill where the captured methane has a larger net present market value than the cost of the capping. Some economists claim that these "no-regrets" options do not actually exist, because an efficient market would have already found and used them. Other researchers examine the reasons why a no-regret option might not have been implemented, because of lack of information, political barriers, or other issues. In any case, computable general equilibrium models do not usually include "no-regrets" reduction options. However, marginal abatement curves can be estimated such that what might be "no-regrets" reductions under a bottom-up approach will merely be very low cost options under a CGE approach.

As mentioned previously, the United States has spearheaded the international Methane to Markets (M2M) initiative. This policy is designed specifically to capture those no regrets policies that do not exist in a CGE framework. M2M is discussed in more detail later, but for the modeling simulation the important characteristic of the policy is that it has a target of 8 MMT of CH4 reductions across the member nations. We can still apply the EPPA4 model to examining low cost methane emissions reduction in a group of regions similar to that addressed under the M2M policy, and compare it to various other "methane-only" policies in order to gather an idea of the realism and scope of M2M. Therefore we examined one policy that was an 8 MMT quantity constraint on methane, and additional policies that put constraints yielding carbon prices of $1/ton on both the M2M regions and all regions.

Methane reduction in 2010 (MMT)	M2M	M2M regions All sectors (~$1/tonCE)	All Regions All sectors (~$1/tonCE)
Total Reduction	8	51	87
Non-Ag Reduction	8	36	63
From Agriculture	0	15	24

Table 2-1: Calculated costs using EPPA4 of near term methane reduction scenarios

We see in Table 2-1 that by our estimates a minimal price yields about 4 times as much reduction from the non-agricultural sector in the M2M regions. This indicates that the M2M goal is not only achievable, but perhaps not sufficiently ambitious. Those nations included in the M2M partnership do, however, include the majority of easily abated emissions, and while there is some loss of low cost abatement opportunity by not including the agricultural sector, it represents less than a third of such opportunities according to our model.

2.2.3 Modeling Climate Impacts

One of our contentions in this chapter is that GWPs are not in fact an accurate measure of the impact of greenhouse gas reductions. Recalling Figure 1.2 from Chapter 1, we would ideally be able to measure some net present marginal cost to humanity from each ton of gas emitted, and then trade off between gases based on such an accounting. However, the uncertainties and complexities involved in such accounting make it practically impossible. Therefore, we need to choose an intermediate variable to measure in order to determine policy impacts. Global mean average temperature is the normal metric used to measure climate impacts – it is not a perfect metric, but it is likely to capture most of the desired information. There is significant uncertainty due to climate sensitivity and ocean uptake (Webster et al., 2003) in determining temperature from a given emissions scenario, but various model simulations indicate that the percentage reduction of temperature increase across the century is fairly robust across the most likely range of climate parameters, and we will therefore use it throughout this thesis.

Temperature Reduction in 2020	M2M	M2M regions All Sectors \$1/tonCE	All Regions All Sectors \$1/tonCE	CO_2 \$1/tonCE
Percent reduction in rise from reference	11%	13%	26%	14%

Table 2-2: Temperature reductions resulting from near term climate policies

We first examine the temperature impact of the Methane to Markets scenarios we modeled in the previous section. These three scenarios were used as inputs into the earth systems component of IGSM1, and the results are shown in Table 2-2. Given the noise in the model, examining temperature reductions in 2020 must be taken with caution, but we can see that a global CO_2 policy at \$1/ton carbon equivalent gives temperature reductions on the order of a methane policy concentrated on the M2M regions. The indication here is that methane control has substantial implications for reducing near term warming.

However, when comparing temperature impacts of methane reductions to carbon dioxide reductions, we have much more confidence in century long experiments. We examine multiple policies, with two different versions of EPPA and the MIT IGSM. In Figure 2-2 we show the results of three runs performed with IGSM1: a \$15/ton (carbon equivalent) methane reduction policy, a CO_2 policy of similar price, and a policy wherein Annex B nations meet their Kyoto Protocol commitments and maintain them until the end of the century (and the non-Annex B nations are unconstrained). We see here that a fairly inexpensive methane policy has significant returns in terms of temperature reductions on a century timescale, but that the equivalent CO_2 policy has a minimal impact. Part of this may be due to methane being undervalued by the GWP metric. This could easily occur due to secondary impacts on ozone and changes in CH_4 lifetime. We also used a GWP of 21 to be consistent with the Kyoto Protocol and other current policies, whereas as is discussed in the appendix, the IPCC TAR (Ramaswamy et al., 2001) has updated methane's GWP to be 23. This GWP increase is less than 10%, and therefore should account for only a small fraction of the difference between the CH_4 and CO_2 scenarios. The other reason that the temperature impact of the methane policy is so much larger than the temperature impact of the carbon dioxide policy is due to the large lifetime differences between the two gases. In the short term, methane reductions are expected to lead to larger temperature reductions.

In the long term we would expect to see that CO_2 reductions would eventually have a larger climate mitigation impact than the GWP equivalent methane reductions, but this timescale is to be likely to be on the order of three hundred years (Sarofim et al., 2005). Three hundred years is a much longer time horizon than most policy planners are seriously considering. For reference we have included a "Kyoto forever" policy in which the current Kyoto nations (i.e., not including the US) maintain their targets until the end of the century, but developing nations continue on a business as usual path. We see that a fairly inexpensive but global policy targeting only methane yields more climatic benefits on the century time scale than a much more expensive all gas policy limited to the Annex B nations, or a global CO_2 policy of comparable cost to the methane policy.

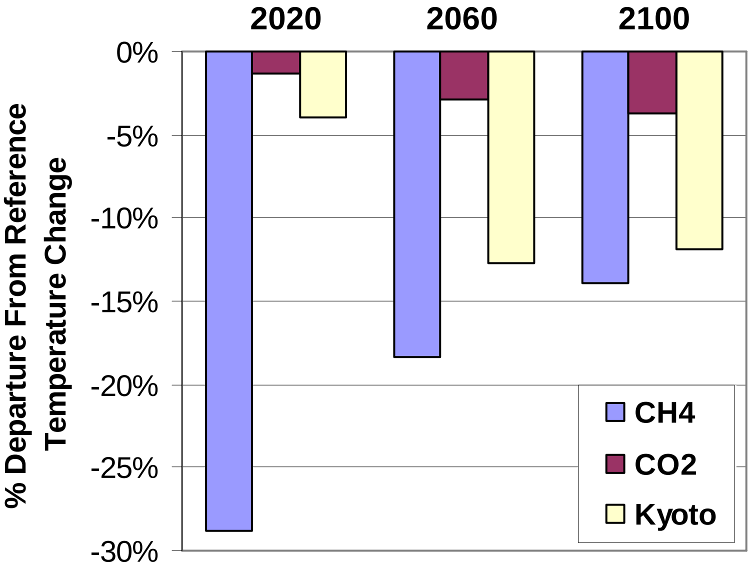


Figure 2-2: Impact on global mean temperature increase over the 21st Century in three selected policies using IGSM1
CO_2, CH_4: $15/ton carbon equivalent. Kyoto: Hold emissions in Annex B constant at Kyoto target levels

We have repeated a similar analysis with IGSM2, but this time rather than analyzing a cost-equivalent CO_2 policy, we analyzed a GWP equivalent CO_2 policy. The results were fairly similar (Table 2-3). We chose two scenarios to examine, using EPPA4 for the emissions projections. The first scenario was a "25% methane reduction from reference" scenario, which yields methane prices that start at $3.5/ton C equivalent ($20/ton CH_4

equivalent) to \$11/ton C equivalent by the end of the century. The second scenario kept methane emissions constant at 2010 levels. This policy has zero price in 2010 (of course) but yields prices of \$1700/ton C equivalent by the end of the century. Then we ran runs that were equivalent in terms of GWP weighted emissions, but constrained only CO_2. In the 25% reduction case, while the CH_4 reduction run led to a 7% temperature change reduction (with a peak decrease of 24% in 2035), the GWP-equivalent CO_2 run only led to a 1% decrease in temperature change. We do expect CO_2 reductions to be accompanied by SO_2 reductions, and the SO_2 reductions will lead to a warming effect that will counter some of the cooling. For the most part, CH_4 constraints should not be directly associated with SO_2 reductions.[9] However, tight CH_4 constraints can lead to an overall reduction of economic growth, thereby indirectly reducing sulfate emissions. Indeed, in the constant emissions case SO_2 reductions are actually larger in the CH_4 case than the CO_2 case by the end of the century, and yet we still see a 15% temperature change reduction in the CH_4 case compared to a 4% reduction in the equivalent CO_2 case. Therefore we can reject the hypothesis that the differential in temperature between the GWP equivalent scenarios is due to reductions in SO_2. The price of the carbon reductions in the 25% reduction case are much higher than the equivalent methane run (starting at \$25/ton C equivalent), but are nowhere near the extremely high prices reached at the end of the constant methane emissions run.

	25% CH_4 Reduction		CH_4 Constant Scenario	
	CH_4	CO_2	CH_4	CO_2
Total GHG Reduction	3.4%	3.3%	6.4%	6.4%
SO_2 Reduction (2100)	0%	2.7%	3.7%	3.3%
BC Reduction (2100)	0%	0.2%	2.2%	3.6%
O_3 Concentration (2100) (ppb)	38.4	40.0	36.8	40.1
Temperature Change Reduction (2100)	7.4%	1.0%	14.9%	4.0%

Table 2-3: Comparing GWP equivalent CH_4 and CO_2 policies in terms of impact on CO_2 equivalent emissions reductions (sum over century), sulfate aerosol and black carbon emissions in 2100, ozone concentrations, and reduction in global mean temperature change over the 21st century.

Methane reduction does not only yield direct radiative forcing benefits, but it also interacts with atmospheric chemistry which can yield secondary effects on ozone levels

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[9] In the EPPA model we assume that the use of natural gas leads to no sulfur emissions: however, sour natural gas fields do contain some quantity of H_2S. However, amine extraction methods are fairly effective for cleaning natural gas.

with further beneficial health and cooling impacts. Methane, like other VOCs, reacts with hydroxyl radicals to produce an organic peroxy radical. That organic radical, in the presence of NOx, can lead to the creation of ozone molecules. In addition, the reduction of hydroxyl radical concentrations due to methane concentration increases leads to longer lifetimes for a variety of other pollutants. Because methane's lifetime is sufficiently long for the gas to be fairly well mixed globally, its impacts on ozone and OH levels occur on a global scale, unlike the local impacts of air pollutants which will be addressed in the next chapter.

Ozone also has a negative impact on ecosystems, and therefore on carbon uptake, as was shown in Felzer et al. (2005) and discussed in more depth in the next chapter. However, this ecosystem uptake effect is not included in the standard version of the IGSM. In a scenario using EPPA4 reference emissions and IGSM2.3 , global background ozone concentrations rise from 34 ppb in 2000 to 39.9 ppb by the end of the century. In the constant methane emission case, ozone concentrations plateau at levels 8% smaller (36.9 ppb) (or only 50% as much increase!). This is more than half as effective as capping the other major ozone precursors (NOx, VOCs, and CO) at 2005 levels (3CAP from Chapter 3). The 3CAP policy yields a background ozone concentration of 35.0 ppb. Of course, the 3CAP policy would presumably be much more effective at reducing local urban ozone levels in addition to impacting global background ozone levels.

West et al. have estimated impacts of ozone mitigation through methane reduction on global health (West et al., 2006). They showed a 1 ppb reduction in daily maximum 8-h surface ozone from a 20% methane emissions reduction (compared to a 40% emissions reduction by the end of the century in our constant methane emissions case leading to a 3 ppb decrease). Their estimates were that this reduction would eliminate 30,000 premature mortalities per year, which extrapolated would indicate 90,000 avoided deaths per year by the end of the century in our constant methane scenario. Of course, we note that CO_2 reductions also have similar air pollutant benefits through complementary reductions of other combustion derived emissions, as will be explored more thoroughly in the Chapter 3.

We can calculate methane lifetime over the timescale of a simulation, where the lifetime is defined as the atmospheric burden divided by the sum of sinks in a specified time period. The burden is equal to 2.76 Gt times the methane concentration in ppm. We expect that higher methane emissions will lead to longer lifetimes as the methane sink (the OH radical) is consumed, and indeed by the end of the century the lifetime of methane increases by 22% from its 2005 lifetime in the reference simulation. In the constant methane emission scenario, the methane lifetime is about the same in 2100 as in 2005. For comparison, keeping NOx emissions constant (which also reduces OH) but leaving all other emissions at reference levels leads to a 32% increase of methane lifetime over the 2005 lifetime. This increase in methane lifetime is significantly higher than the 6% projected to occur in the IS92a scenario by Lelieveld et al. (1998) (the Lelieveld paper also references a historical increase of 25 to 30% for methane lifetime over the past 150 years).

Therefore, this work demonstrates that a constant GWP for methane over the century significantly undervalues methane in terms of century timescale temperature reductions. Likely physical culprits[10] for this undervaluation include underestimating lifetime feedback effects, impacts on ozone concentrations. While it is possible that GWPs could be continually manipulated over the century to compensate for these effects, given that the IPCC is still using GWPs from the 2nd assessment report in 2007, after the 4th assessment report GWP estimates have been released, indicates that there is significant inertia in the political system that will resist updating these numbers.

2.2.4 Limitations of Market Trading

Trade as a means for mutually beneficial enrichment is enshrined in all economics textbooks (Pindyck and Rubinfeld, 2001). There are a set of standard caveats: false information can lead to non-optimal trades; in the case of environmental cap and trade systems trading can potentially lead to unjust geographic redistribution of pollutant emissions; the market needs to be competitive, where no individual agent has monopolistic power. But greenhouse gas emissions seem like an ideal target, as they become globally well-mixed on a timescale much shorter than their lifetime, and therefore reduction of a ton of CO_2 emissions in China is equivalent to a similar reduction in the US (Goulder and

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[10] It should also be noted that because reductions occur throughout the century in question, 100 year GWPs would a priori be expected to undervalue short lifetime gases in a century long policy because some of these short lived gas reductions are occurring at the very end of the period.

Pizer, 2006). Indeed, as a long term stock problem, a reduction of CO_2 today is equivalent to a similar reduction in a year, and therefore greenhouse gases seem like an ideal case for intertemporal trading as well as geographical trading. And for the same reasons that geographical and intertemporal trading create benefits, it seems likely that trading between gases for "what" flexibility would also be beneficial. Therefore, theoretical considerations would suggest creating a policy that was as broad as possible in both geographical coverage and multiple gas coverage, allowing emissions trading to find the cheapest possible reductions to meet a given total GHG constraint. However, such trading turns out to have both political and economic disadvantages.

Recent work has shown that inter-regional market trading of CO_2 can interact with existing taxes in such a way as to reduce welfare for trading nations compared to the non-trading case (Babiker et al., 2004; Paltsev et al., 2005a). We see similar results when we compare the marginal abatement curves developed in Figure 2-1 with the actual global net present consumption loss suffered in those scenarios. Figure 2-3 shows that the marginal consumption loss in $/ton is significantly higher than the actual carbon price in $/ton, starting at $25/ton for a minimal constraint. In a system without distortions the starting price should be $0/ton. Methane constraints, on the other hand, lead to marginal consumption losses that have a close correspondence with marginal prices. Presumably this is a result of the fact that methane production has much less interaction with the key taxes. Therefore, we can expect a significant difference in cost between a policy based on equalizing GWP based gas prices and equalizing marginal consumption losses with differentiated gas policies, without even regarding the differential impact on climate change. In fact, a GWP-based policy would be both more expensive and less effective in terms of temperature change reduction than would a hypothetical policy that equalized marginal consumption losses. Note that we are examining 2010 marginal abatement curves here: the curves are expected to be different in different time periods as sectoral production and available technologies shift.

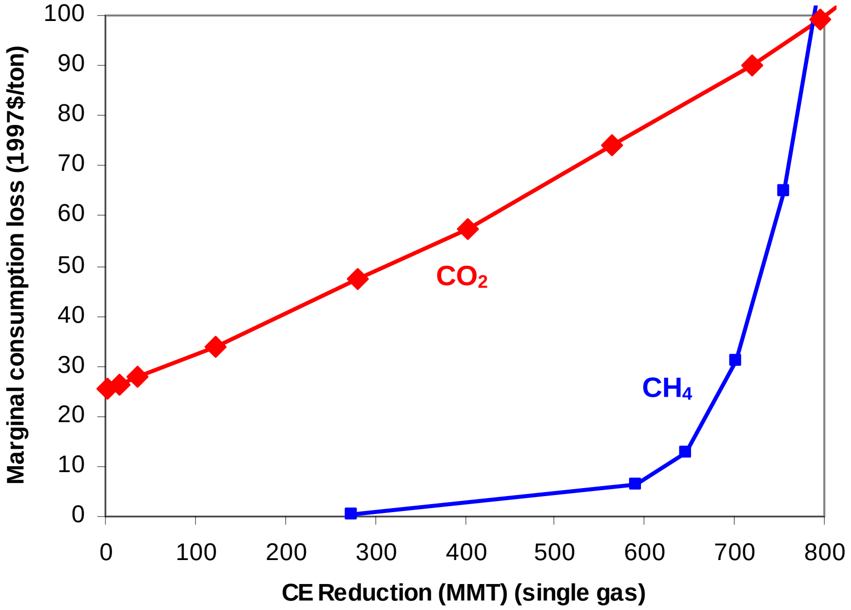


Figure 2-3: Global marginal consumption loss in 2010 derived from EPPA4 for CO_2 and CH_4 constraints.

The above marginal consumption loss analysis examined global consumption loss, which is a reasonable metric to use when comparing the cost of different policies. However, for reasons of equity it might also be important to examine how the loss is distributed between Annex B and non-Annex B nations. We use the case of the 25% CH_4 reduction policy and its GWP equivalent CO_2 policy from section 2.2.3 to look at the near term cost distribution implications. Naturally, this distribution of loss will depend heavily on how the policy constraint is structured. The standard approach we use to generate our policy is to take every EPPA region and enact a cap on emissions of the constrained gas equal to 75% of the business as usual (BAU) baseline for that gas in that region, and then allow trading between all regions to reach a common marginal price. However, such a policy is not consistent with the "common but differentiated responsibilities" delineated by the UNFCCC. One approach to differentiated responsibilities is to delay constraints on non-Annex B nations until an indeterminate future time. Such a policy by nature would have limited "where flexibility", excluding many low cost abatement opportunities, and additionally would likely be politically unpopular with nations such as the United States. Another approach would be to place emissions constraints on all regions, but design the constraints such that the reductions are large in Annex B nations and small in non-Annex B nations. For the purpose of our calculations, we take the extreme example where non-

Annex B nations are given a constraint equal to their BAU emissions. The Annex B nations are then required to reduce emissions more sharply such that the total global emissions are still only 75% of the reference value. Trading enables the Annex B nations to purchase reductions from non-Annex B nations to reach a solution that should be similar to the solution in the original equal percentage allocation case in terms of the distribution of regional emissions and the global consumption total (Coase, 1960), but with very different distributional welfare implications.

We therefore analyzed the consumption loss in 2010 in four cases using the EPPA model. We started with the 25% CH_4 policy and the GWP equivalent CO_2 policy in the equal percent allocation form that we had previously modeled, and then take each policy and use the reasoning in the paragraph above to allocate all the reductions to Annex B nations while constraining non-Annex B emissions at their BAU levels in order to generate a second pair of policies. Because, as discussed in Chapter 1, CO_2 emissions comprise a greater percentage of Annex B GWP weighted emissions than they do of non-Annex B GWP weighted emissions, we expect for equal percent allocation that Annex B to have a larger share of total consumption loss in the CO_2 constraint case than in the CH_4 constraint case. Table 2-4 demonstrates that our expectations are met, as the ratio of the consumption loss between Annex B and non-Annex B in the CO_2 case is 0.97, whereas for CH_4 it is 0.33. This may indicate that a global CH_4 policy is less fair to non-Annex B nations, though it is still almost two orders of magnitude less expensive than the CO_2 policy. However, if we look at the differentiated responsibilities case with the reductions allocated entirely to Annex B, we see a different picture. Here, the CH_4 policy actually leads to an increase in welfare for non-Annex B nations as they sell permits for cheap reductions. In the CO_2 case the non-Annex B nations, while better off than in the even allocation case, still have a net consumption loss as global economic damage overwhelms the benefit from selling a small number of permits. There are also small differences in total welfare loss between the even allocation and the distributed responsibilities cases, indicating complicated interactions in the economy that cause it to deviate from a pure Coase allocation problem.

	Even Allocation (% basis) Consumption Loss (2010) (billions)	Annex B-only Reductions Consumption Loss (2010) (billions)	Total Reference Consumption (trillions)

	CH_4 policy	CO_2 policy	CH_4 policy	CO_2 policy	
Annex B	0.063	11.3	1.44	19.9	21.2
Non-Annex B	0.189	11.7	-1.09	6.46	6.7

Table 2-4: Consumption loss in Annex B vs. non-Annex B nations for the 25% reduction CH_4 constraint policy and the GWP equivalent CO_2 policy

The distribution results in these cases may be further exaggerated if we include the difference between purchasing power parity (PPP) and market exchange rates (MER). EPPA uses MERs for calculating consumption. PPPs take into account the fact that a dollar in a developing nation will purchase more goods than a dollar in an industrialized nation. Therefore, a reduction in consumption of a given number of dollars for a non-Annex B nation will have a greater welfare impact than the same consumption change in an Annex B nation. An odd result of this calculation is that if the average PPP/MER ratio in non-Annex B nations is greater than 1.3, then the global methane policy in the case where reductions are only allocated to Annex B nations can actually lead to a global net welfare increase.

This scenario in which Annex B nations take on the burden of reductions but purchase reductions from non-Annex B nations is similar to the goal of the Clean Development Mechanism (CDM) in the Kyoto Protocol. While the CDM does not have the capability to set non-Annex B national targets at their reference emissions levels, because such emissions levels would be difficult to predict, it approximates this by attempting to certify “additional” credits for reductions from specific projects. In an ideal world, where it would be possible to take advantage of all projects that could generate CDM credits for less than the market price of the gas, where no “fictional” credits were generated due to unscrupulous companies or inventory issues, and no leakage occurred due to increased emissions from companies not involved in CDM projects, then the CDM would enable the Kyoto Protocol to exactly match a cap and trade policy like our Annex B only Reductions case. CDM will also be discussed in greater length in the air pollution chapter.

Ancillary benefits of air pollution emissions reduction from carbon abatement further complicate this story. Specifically, reductions of CO_2 emissions in non-Annex B nations are likely to carry much greater simultaneous reductions in air pollution, and therefore lead to larger increases in welfare from health improvements, than will the same CO_2 reductions in an Annex B nation. In addition to increasing the ratio between Annex B and non-Annex

B consumption losses (presumably an improvement from an equity viewpoint), ancillary benefits also reduce the total welfare loss in the CO_2 cases compared to the CH_4 cases.

However, the ratio of consumption loss of a CO_2 policy compared to a CH_4 policy will still be much larger than issues such as air pollution ancillary benefits and less just distribution between Annex B and non-Annex B. Therefore, our conclusion that emissions trading between CH_4 and CO_2 is inefficient due to interactions effect still holds. Furthermore, though it is unrealistic to expect implementation of a policy wherein Annex B nations subsidize methane reductions in non-Annex B nations to the extent shown in the Annex B-only case in Table 2-4, it should be possible to design a system that takes advantage of the non-Annex B reductions opportunities without being an economic hardship for those nations.

2.2.5 Uncertainty in Modeling

Any projection of the impact of policies will depend on assumptions about reference emissions and economic response to policies. We summarize in this section some of the potential issues involved with our modeling, and discuss the implications of prior uncertainty work and comparisons to other modeling groups. While no model is perfect, however, we do believe that our major conclusions are not likely to be very sensitive to these issues.

The first issue involves projections of methane emissions in the reference scenario. The first stage of emissions projections involves benchmarking the model in 1997 using the best estimates available for emissions. Section 2.3 is devoted to the difficulty of creating accurate source inventories, and if the inventories are not accurate, the model will by necessity be benchmarked to the wrong numbers. Indeed, there is even uncertainty in the value for the total anthropogenic CH_4 source term. The result of allocating wrong 1997 emissions to a sector is that as that sector changes in different proportions to the remainder of the economy, total emissions will diverge from an accurate number – even if the global total term was correct in 1997. These methane projections also depend on assumptions about how a given sector's emissions will evolve in relation to the sector's activity. The combination of these uncertainties determines how realistic the business as usual scenario will be. This projection is important because if methane is not actually on a growth path, then there is less value to addressing methane as a separate issue.

There are time-varying emissions coefficients within the EPPA model to reflect changing relationships between sectoral outputs and methane emissions. As discussed in Hyman et al. (2001), industrial sources become more efficient and have higher value product per unit mass, which means that less raw material is used per unit output, and therefore fewer emissions. Additionally, methane emissions related to landfills are linked with final demand (eg, consumption) within EPPA. However, we expect these CH_4 emissions to rise at a rate approximately proportional to population and not proportional to the much larger consumption increase over the century. Therefore, in order to get a reference CH_4 trend in the final demand sector that follows population growth, we apply a CH_4 emission coefficient that is approximately equal to the value of population divided by consumption in the reference case. This approximation is fairly rough, as the details are complicated; for example, while an increase in income leads to a reduction in wastewater emissions for Annex B nations, for very impoverished nations (where waste is not normally collected) an increase in income actually leads to an increase in emissions per capita as landfill use increases.

An indication of a potential problem in our projections is that observed methane concentrations from the period 1997 to 2003 have shown a leveling off effect. Measurements indicate that long term hydroxyl radical trends have been small (Prinn et al., 2005b) implying a fairly constant oxidative capacity of the atmosphere (though with some interannual variability). Therefore this halt in methane concentration growth would be an indication that methane sources have leveled off or decreased in the 1990s. The reference simulation of EPPA4 projects an increase in methane emissions of 10% from 1997 to 2005. Due to this increase in emissions, the IGSM system yields a fairly constant concentration growth during the past decade, unlike observations, resulting in a methane concentration in 2004 of 1823 ppb compared to 1783 ppb (World Meteorological Association, 2006) or 1775 ppb (NOAA/GMD). However the most recent evidence shows that the post 1999 portion of this leveling off phenomenon may have been a temporary artifact of wetland drying masking a renewed anthropogenic emissions increase (Bousquet et al., 2006).

We can also compare the EPPA4 model to the other models used in the CCSP exercise (Figure 2-4) (US Climate Change Science Program, 2006). The Stanford-EPRI MERGE and PNNL MiniCAM base-year emissions are similar. The MIT IGSM reference scenario has higher initial anthropogenic methane emissions than the other models, reflecting an independent assessment of historical emissions and uncertainty in the scientific literature regarding even historic emissions. Note that the IGSM has a correspondingly lower natural methane source (from wetlands, termites, etc.) to balance the observed concentration change, rate of oxidation, and natural and anthropogenic sources. Both the MIT IGSM and Stanford-EPRI MERGE models exhibit steadily growing methane emissions throughout the 21st century as a consequence of the growth of methane-producing activities such as ruminant livestock herds, natural gas use, and land-fills. Unlike CO_2, where the combustion of fossil fuels leads inevitably to emissions (absent capture and storage), slight changes in activities can substantially reduce emissions of the non-CO_2 gases (Reilly et al., 2003a). The PNNL MiniCAM reference scenario assumes that, despite the expansion of human activities traditionally associated with methane production, emissions control technologies will be deployed in the reference scenario in response to local environmental controls. This leads the PNNL MiniCAM reference scenario to exhibit a peak and subsequent decline in CH_4 emissions in the reference case.

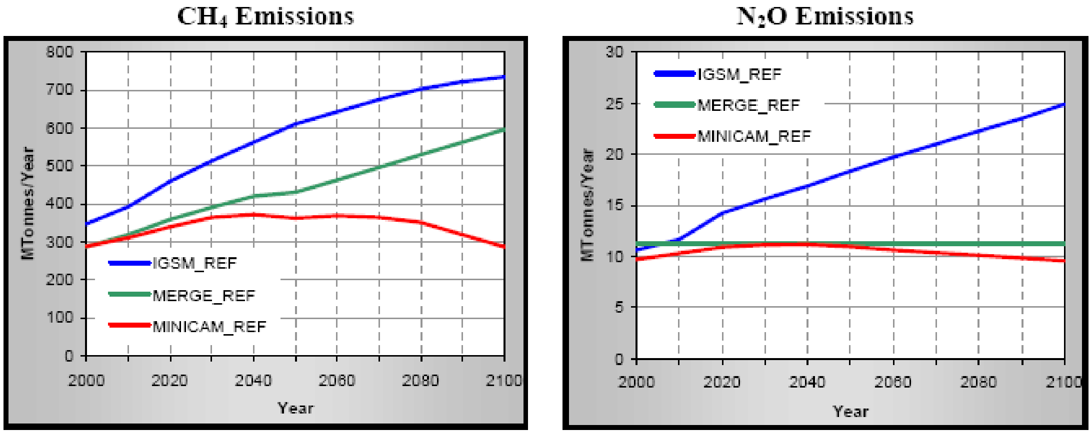


Figure 2-4: Global CH_4 and N_2O Emissions Across Reference Scenarios (US Climate Change Science Program, 2006)

Some existing projections suggest that the relative contribution of CH_4 to radiative forcing may decrease somewhat in the future. Webster et al. (2003) estimated that CH_4 might contribute another 0.6 (-0.17 to 1.71) W/m^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) W/m^2. At the median values the additional CH_4 contribution drops to about 15% of that from CO_2, from the historical share of 1/3. CO_2 and CH_4 are produced in part by related processes such as fossil fuel production, and the two gases are produced in part by separate processes such as agriculture, biomass burning, land fills and other waste disposal. Also 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. This does not rule out cases where the CH_4 contribution remains high or even increases relative to CO_2.

The EPPA4 reference being used in this thesis has the CH_4 contribution to radiative forcing increase over the century from 0.5 W/m^2 to 1.0 W/m^2, but decrease as a fraction of total well-mixed GHG forcing from 21% to 12%. However, as we showed in the previous section, reductions in methane emissions can still lead to greater than a 12% reduction in temperature increase over the century despite the decrease in methane's relative contribution.

The other major sensitivity involves the elasticities of methane within a given sector. This does not affect the reference scenario, but is extremely important for calculating the response of the model to policy constraints. Hyman et al. (2001) generated elasticities based on EPA data which include known abatement opportunities, but the costs and magnitudes of these known abatement technologies are not known precisely. There may be other reduction options which were not included in the study, and it is to be expected that abatement technology will change over time.

2.3 The Source Estimation Problem

Methane emissions are hard to measure because they do not come from point sources, there are significant natural emissions that can confound inverse calculations, there are large geographic and temporal emission variations, and much of the emissions come from regions that do not have sophisticated inventory capabilities. This difficulty in source estimation leads to problems in modeling, as EPPA has been calibrated against data from

EDGAR (bottom up analysis) with adjustments due to top down analysis by Yu-Han Chen et al. (2006), and adjusted again such that the IGSM yields concentrations consistent with observations. In addition to a modeling issue, however, this also has significant policy implications: how do you judge if constraints are being met if it is difficult to measure the emissions?

A detailed analysis of methane source estimations in the literature is included in Appendix E, with the anthropogenic estimates from three inventory estimates presented in Table 2-5. The issue of relevance is that most methane emissions come from area sources, not point sources, and this makes them difficult to quantify. Quantification of fossil fuel CO_2 emissions are accomplished easily by measuring the fossil fuel inputs. In addition, there are significant natural sources of methane (30 to 40% of the total), and the sink term (mainly reaction with the hydroxyl radical) is difficult to calculate. Only recently has the total annual emission of methane become well constrained to 589 Tg (Chen and Prinn, 2006) based on the most recent OH radical estimations (Prinn et al., 2005b). Certain sectors such as rice paddy emissions are especially contentious, with significantly different estimates from bottom-up and top-down estimations, as seen in Table 2-5. For modeling purposes, total emissions have to be calibrated to the specific treatments of natural source and OH sinks in the earth systems model to ensure that near term methane concentrations behave in a believable manner similar to observations. However, it is not obvious that only CH_4 emissions should be adjusted. The hydroxyl radical concentration, and therefore the methane lifetime, depends on emissions of CO, NOx, and VOCs as well as CH_4. There exist a number of ways to adjust multi-gas emissions such that CH_4 concentrations become consistent with observations, especially given the poor constraints on inventories of most non-GHG emissions. And of course, it is always possible that the earth systems model itself has source and sink process flaws.

Anthropogenic CH_4 emissions in 2000	Inverse Modeling Results	Bottom-up Inventory Results	
	(Chen and Prinn, 2006)	EPA Inventory (US EPA, 2006)	EDGAR 32FT2000 (Olivier et al., 2005)
Rice	112	30	39
Biomass Burning	48	22	22
Animals & Waste	185	156	147

Energy	48	75	94
Other	37	3	19
Total	430	287	321

Table 2-5: Anthropogenic methane inventories using different methodologies

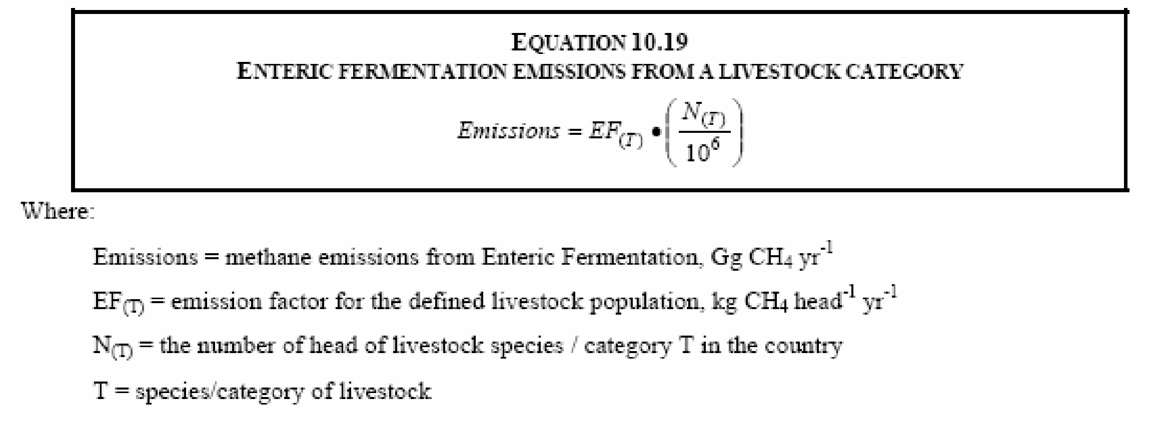
Given the uncertainty in all factors of the methane lifecycle, it is interesting to ask how we appropriately choose to model them all together. Taking separate "best estimates" of anthropogenic emissions (whether from bottom-up studies or inverse modeling), natural emissions, hydroxyl levels (and all the emissions that feed into determining hydroxyl radical concentrations), may yield a poor fit to the observed concentrations for the past decade. As unwieldy as an adjustment factor is for balancing the carbon cycle (as discussed in Chapter One), an adjustment factor for methane is worse because we do not even know whether our uncertainty is in the sink, natural emissions, or anthropogenic emissions.

Ongoing work by Sokolov, Asadoorian, and myself to simulate historical climate using the coupled climate-chemistry model with estimated historical emissions may shed further light on the relationships between these uncertain variables and may even elucidate what should be fixed. For example, if it looks like there is a fixed emission term missing over the past century, then perhaps the issue is that we have not included geological emissions (Kvenvolden and Rogers, 2005). We could then add that quantity to the EPPA emissions postprocessor. However the very large variability due to wetland and biomass burning emissions (Chen and Prinn, 2006) may prove to confound such attribution. The IGSM natural emissions module (NEM) projects a small (20 Tg) and approximately linear increase in natural emissions over the century, but given the modern variability in natural methane emissions the confidence in historical NEM projections would be low, making it difficult to attribute discrepancies in our historical simulations to natural versus anthropogenic origins. We are also unlikely to have great confidence in our simulated historical hydroxyl radical concentrations.

We will also note that the difficulty of measuring emissions from area sources will inherently impact the creation of policies to address it. If the estimates of global methane emissions from rice paddies can range from 30 Tg or less to 112 Tg or more depending on whether bottom-up (Chen and Prinn, 2006; Olivier, 2005; US EPA, 2006) or top down

(Chen and Prinn, 2006) techniques are being used, how does one credit a country that changes its rice cultivation techniques to reduce methane emissions? New Zealand proposed but failed to institute a so-called “flatulence tax” on its livestock, but the tax was based per animal – varying by species, but not by diet or other factors that impact actual emissions. Methods do exist that can reduce emissions from ruminants without reducing their number, but a tax per animal will not encourage such changes in the way that a tax on actual emissions would accomplish. In any case, the removal of subsidies for sheep likely has had much more impact than the tax would have had, in much the same way that breaking the coal unions in Great Britain may have had a greater impact on their GHG emissions than all the actual greenhouse measures they have implemented combined. One study attributes 45% reduction in sheep numbers from 1982 peak to subsidy reforms in the mid 1980s (New Zealand Ministry of Agriculture and Forestry, 2003).

The point here is that a per-head tax is not necessarily the most efficient way to reduce methane emissions (in fact, the New Zealand flatulence tax was actually designed more to raise funds to research methane reduction methods than to discourage raising livestock). Yet current IPCC inventories use the number of animals to determine national emissions (Monteny et al., 2006), with the precise equation shown in Figure 2-5. Therefore we might expect that inventory methodology can directly impact what is considered to be a desirable solution. Changing the methodology at this point may be difficult, as those nations which may have higher rice or livestock emissions than predicted by bottom-up methodology would be resistant to change. But what are the alternatives? Tax or cap and trade policies are standard economic instruments, but how can they be easily applied to livestock methane emissions, other than on a per-head basis? Surely farmers will not be required to use sulfur hexafluoride tracer techniques to measure methane emissions. Similar problems arise with all the other non-point-source emissions. Such problems are endemic to methane and N_2O emission inventories, but it may be just as difficult to measure CO_2 sources and sinks resulting from land use change. For example, returning again to the case of rice paddies, given the variation in emission estimates how can it be possible to accurately calculate credits for emissions reductions to a particular nation? IPCC guidelines instruct nations to first estimate emissions from a continuously flooded field as a baseline, and then apply adjustment factors for water management style (five possible types), fertilizers (the EPA assumes that 40% of fields have doubled emissions due to fertilization), and soil type, finally summing across harvested areas of each type of rice paddy (IPCC, 2006) (Figure 2-6). Even if a superior method for quantifying such area emissions existed, it will be politically difficult to change previously agreed upon methodologies for inventories.



EQUATION 10.19
ENTERIC FERMENTATION EMISSIONS FROM A LIVESTOCK CATEGORY

$$Emissions = EF_{(T)} \bullet \left(\frac{N_{(T)}}{10^6} \right)$$

Where:

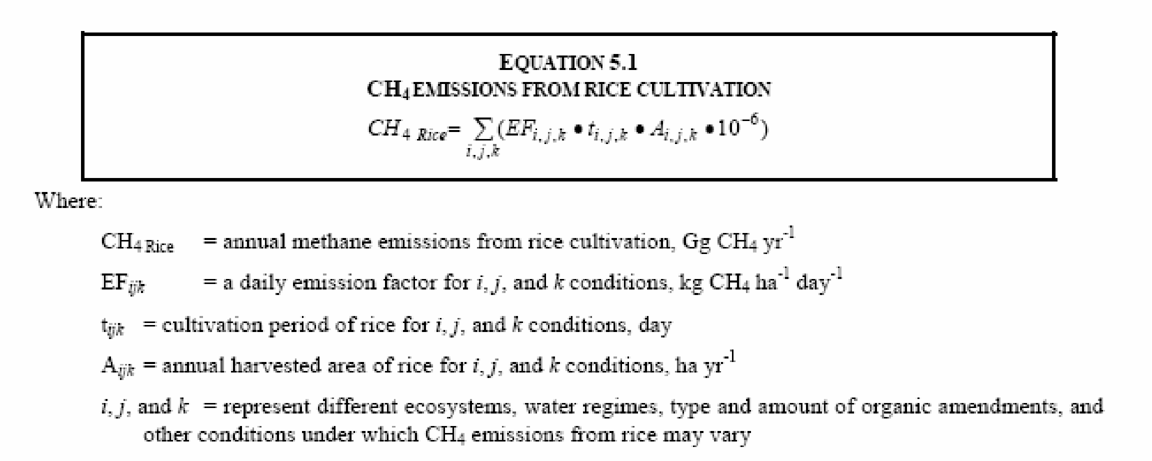
Emissions = methane emissions from Enteric Fermentation, Gg CH_4 yr^{-1}

$EF_{(T)}$ = emission factor for the defined livestock population, kg CH_4 $head^{-1}$ yr^{-1}

$N_{(T)}$ = the number of head of livestock species / category T in the country

T = species/category of livestock

Figure 2-5: IPCC inventory methodology for livestock methane emissions (IPCC, 2006)



EQUATION 5.1
CH_4 EMISSIONS FROM RICE CULTIVATION

$$CH_{4\ Rice} = \sum_{i,j,k} (EF_{i,j,k} \bullet t_{i,j,k} \bullet A_{i,j,k} \bullet 10^{-6})$$

Where:

$CH_{4\ Rice}$ = annual methane emissions from rice cultivation, Gg CH_4 yr^{-1}

EF_{ijk} = a daily emission factor for *i*, *j*, and *k* conditions, kg CH_4 ha^{-1} day^{-1}

t_{ijk} = cultivation period of rice for *i*, *j*, and *k* conditions, day

A_{ijk} = annual harvested area of rice for *i*, *j*, and *k* conditions, ha yr^{-1}

i, *j*, and *k* = represent different ecosystems, water regimes, type and amount of organic amendments, and other conditions under which CH_4 emissions from rice may vary

Figure 2-6: IPCC inventory methodology for rice cultivation methane emissions (IPCC, 2006)

In the area of methane inventory methodology, there are significant potential political pressures. The worry is that politics will interfere with scientific development. “Theoretical uncertainty about the causal impact of particular human activities on the environment – may fuel political controversy. In turn, political conflict may contaminate processes of knowledge production and dissemination” (Underdal, 2002). Those nations who have been reporting low emissions using EPA’s current methodology might object strenuously to any attempts to change the methodology to more closely match Chen’s inverse estimates (Chen and Prinn, 2006). In fact, there have been discussions between

EPA officials and this researcher on how to reconcile our two very divergent estimates. We have been encouraged to examine potential solutions to the discrepancy such as including possible emissions from dams (Giles, 2006) or from living plants (Keppler et al., 2006) that would not lead to necessity of adjusting the EPA rice paddy methane emission estimates. Of course, a large natural plant source would mostly lift responsibility from the involved nations, whereas a dam source might merely shift the burden within the nation from farmers to dam operators.

There might be some way to set national scale caps where emissions are either measured by inverse modeling or by some agreed upon national inventory methodology that takes into account the practices used in that nation. Then each nation can determine its own method for reducing emissions, such as a cap and trade mechanism or a flatulence tax or research subsidies or command and control systems or economic reforms to reduce subsidies. While a more accurate means of creating incentives to reduce methane is intellectually appealing, it may be the case that we will remain with the current simple method which has the advantage that it is easily applied and already ensconced in current practice. However, if we are using admittedly limited inventory methodologies, we should not continue to allow trading of poorly quantified methane and N_2O reductions for fossil fuel CO_2 reductions that are well measured. As was stated by Reiner, “Bringing all possible countries and source categories and gases and sinks on board simultaneously where data is weak and methodologies are still in the process of being developed seem to be a surefire recipe for fraud, corruption, and bias by allowing for trading across categories” (Reiner, 2002)

2.4 Implications of uncertainty

We have seen that there is uncertainty in many aspects of methane reduction, from future projections to estimating current emissions to determining the costs of policy constraints to determining interactions with atmospheric chemistry. However, uncertainty is not a valid reason to avoid making policy: rather, the existence of uncertainty should inform policy creation. One of the major conclusions of this chapter, in fact, derives in large part from the difference in uncertainty in anthropogenic methane source inventories and fossil fuel CO_2 source inventories. As we have stated, this uncertainty difference is a significant reason for us to suggest that methane and CO_2 should be separated and not traded by GWP weighting.

There are other uncertainties that should be taken into account while creating methane policies. First, we address the uncertainty in climate predictions. Webster et al. (2003) calculate a 95% probability range of possible temperature rise in the next century from 1.0 to 4.9 ºC. It is likely that an ongoing repeat of this study will yield higher temperature results due to modifications of the input probability distribution functions (pdfs) (Forest et al., 2006). We are especially interested in policies that can reduce the probability of dangerous consequences – e.g., reducing the size of the high temperature tail of the warming pdfs. Work on determining optimal R&D policy under uncertainty (Baker et al., 2006) or optimal abatement given uncertainty with learning (Webster, 2002) show that it is not always obvious how to best structure policy given the breadth of possible mitigation strategies and the likelihood of different information becoming available in the future. However, we argue that, because of its low cost, significant methane abatement in the near term is a low risk immediate action in this arena. Indeed, low cost climate policies of all kinds should be implemented. We expect fewer such inexpensive reductions to exist for carbon dioxide because the high cost of fuel will have created incentives to implement such reductions. Chapter 3 explores the idea that pollution abatement might be another approach where, while the policies themselves might not be low cost, their additional benefits in terms of air quality improvement may also move them into this low risk category. There is a further question about whether having separate policies for methane and carbon dioxide will make it easier or harder to adapt to new information about various climatic change outcomes. We argue that if the new information changes our perception of the carbon cycle or methane lifetime, it will be easier to adjust separate policies to take this new information into account than to reach agreement about changing the GWPs of a global integrated policy such as the Kyoto Protocol. This is especially true if future versions of Kyoto allow banking (does a carbon equivalent banked credit carry a memory of whether it was originally abated methane or CO_2?). For additional information about climate sensitivity, critical thresholds, or other non-gas specific information, there is not an obvious conclusion. If such information requires a tightening of constraints, will it be harder to tighten one global integrated policy, or to achieve equivalent reductions from two separated policies? Answering this question requires more specific information about the adaptability designed into the policy to begin with.

The next area of uncertainty is that of uncertainty in projections and costs. Effectively, the original rationale for including "what" flexibility is that decision makers do not have full information about abatement costs of CO_2 and CH_4 and other gases. Therefore, if a common metric such as GWP can be developed, then the market can optimally allocate reductions between the difference gases to ensure a common marginal cost of reduction. Therefore, if CH_4 abatement turns out to be more expensive than expected, CH_4 reductions can easily be traded for CO_2 reductions, and vice versa. However, we are recommending that this kind of trading should not be allowed for the reasons argued throughout this chapter. The problem is that if there is significant uncertainty involved in calculating the abatement curves in Figure 2-1, it becomes very difficult for a decision maker to choose abatement levels of the two gases in order to approximately equalize marginal costs of reduction. Of course, there are alternatives to cap and trade policies that perhaps should be explored. Anything from tax policies to cap and trade policies with safety valves, or even policies based on standards and measures may be useful inclusions in a methane-only abatement policy. Standard and measures approaches would also avoid some of the issues resulting from inventory estimation problems.

Note that reduction of uncertainty does not automatically make policy design easier. For example, there is a lack of knowledge about the regional impacts of climate change and the economic impacts of constraints that leads to a "veil of uncertainty". If it becomes possible to project regional impacts precisely, those nations with the least to lose would have an incentive to free ride on the rest of the world. As in insurance pools, it may be the very uncertainty of risk which leads to a pooling of resources.

2.5 Policy Analysis

2.5.1 Historical policies and Methane to Markets

It is worthwhile to examine historical and current methane reduction efforts. In the decade of the 1990s (using bottom up estimation methods) the OECD and EU nations decreased their methane emissions by 6%, non-EU Eastern Europe by 9%, and the former Soviet Union by 38% (US EPA, 2006). The reductions in the FSU and Eastern Europe can be attributed to the post-break-up economic collapse event. But the OECD reductions may be in part the result of intentional policymaking and economic development, which would be a hopeful sign for future abatement of methane. The OECD trend was attributed to landfill and coal mine methane reductions in the US, landfill methane reductions in the EU resulting from waste directives, and decreased use of coal in England and Germany (US EPA, 2006). Based in part on this experience, the US government launched the Methane to Markets (M2M) program in an inaugural meeting held in November of 2004 (US Environmental Protection Agency, 2006b).

The stated goal of M2M is to reduce methane emissions by 50 MMt Carbon Equivalent per year by 2015 from the participating nations (though occasional press releases have, presumably accidentally, confused this with 50 MMt of actual methane reductions, which would be a larger number by a factor of six). The policy is designed to be a voluntary, non-binding agreement that works through encouraging “public-private partnerships”. There were 14 signatory nations included in the original partnership (Argentina, Australia, Brazil, China, Colombia, India, Italy, Japan, Mexico, Nigeria, Russia, Ukraine, United Kingdom, United States), accounting for approximately 60% of worldwide methane emissions in 2000, and several more nations have joined the partnership since then. It is noteworthy that China, India, and the US are all members of this treaty, when none of these three major greenhouse gas emitters have taken on binding targets under the Kyoto Protocol.

The methane reductions are supposed to come from four sectors: oil, natural gas, coal, and landfills. We can see from Figure 2-7 that these sectors make up slightly less than half of total worldwide anthropogenic emissions. The theory behind the treaty is that in each of these sectors there exist opportunities to capture methane that can be sold or used as fuel in order to offset the costs of capture. If energy prices are high enough, and the capture equipment is inexpensive, these capture technologies could even be implemented for net profits. The theory is that since these near-zero or negative cost technologies exist but are not being used, there must be non-market barriers (such as unclear ownership rights or imperfect information) that could be easily removed by the member nations.

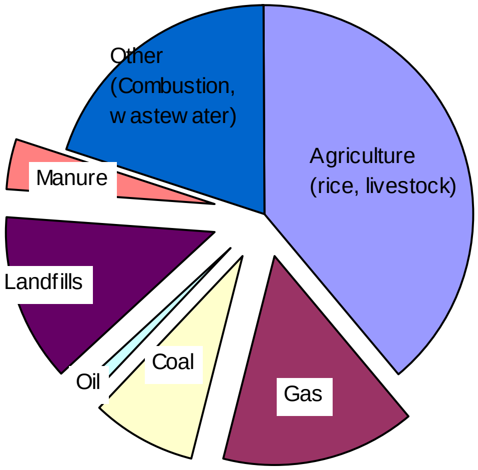


Figure 2-7: Global anthropogenic methane budget by sector in 2000. 'Capturable' methane represented by exploded slices. (US EPA, 2002)

The US has allocated $53 million over a five year period in order to pay for administrative costs, which will be spread across the EPA, DOE, and AID agencies. Some of it may be used for feasibility analysis, technology demonstration, and outreach. However, this money is not designed to provide direct incentives. The hope is that either these projects will pay for themselves, or that they will be able to access CDM or World Bank Carbon Fund moneys, or that local governments will provide preferential pricing or other mechanisms in order to encourage project development.

The US EPA had already started an emphasis on reductions of methane for global warming rationales in 1988 (Beck, 1993) because it could produce impacts in a short timescale. Early on, the research program identified landfills, coal mines, and natural gas systems as being good targets for cost-effective methane reductions, in part because of the recoverable properties of the methane. In 1992, when estimates of total emissions were between 400 and 600 Tg of methane, Hogan et al. (1991) estimated that a 40 to 60 Tg reduction would halt the rise of methane concentrations. Lelieveld et al. (1998) estimated that only a 20 Tg reduction would be necessary, and Dlugokencky et al. (2003) concluded that concentrations might have already plateaued beginning in 1999. The most recent study showed that plateau to possibly be a temporary situation (Bousquet et al., 2006).

The EPA programs implemented in order to reduce methane emissions were AgStar, the Landfill Methane Outreach Program (LMOP), and CMOP (coal mine methane). Large landfills have been regulated since 1996 under the New Performance Standards for Municipal Landfills. For the most part they control methane by using flaring, though electricity-generation also occurs. In either case, combustion creates further pollutants such as NOx, CO, SO_2, and PM10. Unflared gas is 50% methane, 45% CO_2, 5% N_2, and trace amounts of other gases including NMVOCs (Jaramillo and Matthews, 2005). The EPA has used both incentives and controls in reducing methane emissions. For example, landfills are covered under both Section 29 of the Windfall Profits Tax Act and the New Source Performance Standards. Of 2300 active landfills in the US, 382 have landfill gas-to-energy projects, there are 25 projects under construction, and 630 further candidates have been identified. EPA data shows that the 10% decrease of US methane emissions (17 Tg C equivalents) from 1990 to 2004 resulted mainly from landfill and coal mining improvements. However, manure and wastewater emissions continue to grow (U.S. EPA, 2006). It is interesting that these improvements seem to come in large part from standards and tax incentives, while M2M expects similar improvements to come abroad from voluntary partnerships with no provided funding.

Attempts to extend the geographic range of the Kyoto Protocol has mostly been through instruments such as the CDM. However, 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. The Designated National Authority (DNA) for the Kyoto process in Mexico City described the difficulty of certifying “additionality”, given the difficulty in objectively demonstrating that a project would not have occurred in the absence of CDM funds. In many cases, the kind of methane projects that CDM and M2M are trying to target are exactly those projects which are “no-regret” options that have faced institutional or informational barriers, and where the opportunity for extra funds from international climate funds will serve as the tipping point. Also, given the uncertainty about future credits, there is a natural hesitance to investing in a project which will not be sustainable without continuing carbon funds. One potential “silver lining” of the bureaucratic hurdles involved in CDM is that the difficulty of finding appropriate projects may keep the trading price high, enabling implementation of otherwise marginal projects.

In response to these difficulties for CDM, the Mexican DNA suggested that a national cap might be more effective than attempting to ascertain credits for specific projects. His theory was that a cap with a fairly tight constraint but no penalty for exceeding the constraint might provide the appropriate incentives to reduce emissions without the problems of certifying CDM reductions project by project, and avoid the problems of "additionality". This would still, however, require trust in the nationwide inventory system. The same official was dubious about M2M as well, calling it a treaty "en pañales" (diapers), and wondering what it brought to the table given that Mexico already had a methane initiative of its own. He posited that the only near term likely benefit that he saw was aid for analysis, but granted that M2M might evolve into a more useful treaty as time passed. One interesting observation was that he believed that the majority of the projects he saw were initiated at the industry level, and not the government level. He saw the function of his office as that of a facilitator.

Why might it be possible to get global agreement on the methane 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 much more 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 which would produce a small increase in the price of fuels would only yield marginal reductions in fuel use and carbon dioxide 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 of the non-CO_2 GHGs do have some price: CH_4 is an energy source and venting it means the opportunity value of the energy is lost, and the industrial gases (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, one ton of gas will be dozens (in the case of methane) or thousands (in the case of the industrial gases) of tons carbon-equivalent. Therefore, the opportunity cost of venting a gas in the absence of a price on GHGs is pennies per ton carbon equivalent. Looked at in another way, a $15 per ton carbon-equivalent incentive would be several multiples of the opportunity cost of not venting these substances (Reilly et al., 2003a). Specifically, the current natural gas price is about \$7/Mcf (Henry Hub price at the time of this writing), which is about \$30/ton of methane, which amounts to \$1.25/ton CO_2-equivalent, or \$4.60/ton C-equivalent. Compare this to a European Trading System price that has reached as high as \$36/ton CO_2 (\$130/ton C). The ETS price may not reflect the price that will be seen when trading volumes become large (Reilly and Paltsev, 2005), but clearly the value of capturing methane for energy is much less than that of preventing its release to the atmosphere for global warming purposes.

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, 1999). 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.

Not all non-CO_2 emission reductions are completely without pain, however. Cutting agricultural sources of N_2O and CH_4, tied as they are to food production, are potentially as big an economic burden 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. There are some indications that diet and other factors can lead to reductions in emissions, but these reductions are often small or hard to quantify. Diet alone has been shown to reduce methane emissions by 16% (Griggs, 2002), and diets that result in lower CH_4 emissions could be promoted, and might even increase the efficiency of animal growth. There have even been tests of vaccines against methanogens living in the stomachs of ruminants.

Manure is another potential CH_4 source. Manure disposal, however, need not follow 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.

2.5.2 Unintended Consequences

How you structure the incentives for methane reductions will have an impact on the final results. If you give incentives for extracting methane from cow manure, then you may give some incentive to shift from open field grazing (where the dung decomposes aerobically with little methane generation, and serves to fertilize the soil) to a more industrial method where you can make giant manure pits and capture the methane to get subsidies or credits. Not only would such a hypothetical switch not generate any real methane reductions (though the power production could displace some fossil fuel combustion) and siphon money away from other methane projects, but confined animal raising is often considered to be less environmentally friendly. There are other possible negative consequences of methane reduction incentives: for example, Jared Diamond cites decreased water quality resulting from coal bed methane extraction in Wyoming (Diamond, 2005) (this water quality problem was also described by Robbins (2006)):

"Another form arises from an industrial method to extract methane for natural gas from coal beds by drilling into the coal and pumping in water to carry the methane up to the surface. Unfortunately, water dissolves not only methane but also salt. Since 1988, the adjacent state of Wyoming, which is almost as poor as Montana, has been seeking to boost its economy by embarking on a big program of methane extraction by this method, yielding salty water that drains from Wyoming into southeastern Montana's Powder River Basin"

This coal bed methane is currently distinguished from 'coal mine methane', the difference being that 'coal mine methane' is from an active mine and therefore can be considered to be a reduction of methane that would otherwise have been vented into the atmosphere, whereas 'coal bed methane' is extracted from deep seams and therefore any leaks actually add to atmospheric methane levels. If methane capture becomes valuable, there might be pressure to classify seams as active mines in order to generate additional credits. Of course, under most climate regimes, methane from any source will still have a carbon efficiency advantage over electricity generation from coal or oil, regardless of additional capture credits. However, this may actually lead to more coal mining, as the cost of mining becomes offset by the sale of methane credits.

The possible perverse incentives identified above are mostly small edge cases. The benefits of methane reduction almost certainly outweigh the risks of these potential perverse outcomes, but it is always important to consider a broad a range of probable impacts when evaluating new large scale programs. This applies to large scale methane policies in much the same way it does to large scale solar, CO_2 sequestration, wind projects, or any other mitigation proposal. Or indeed, to the large scale ongoing atmospheric perturbation that these mitigation methods are designed to solve.

2.5.3 Policy Design

Given the amount of uncertainty involved in methane inventories, how should a policy be designed to control it? To take the problem of sheep, for example: current methane inventories are based on the number of animals. Should we design a policy that encourages better inventory methods? Will nations who have signed up under the old policy be willing to change to a new one if it ends up raising their emissions? Is there a way to reward nations for improved inventory methodology? Should there be a move towards inverse methodologies because they may be a more accurate measure of large scale emissions? Or should sources be addressed individually? The inventory methodology enshrined in climate treaties must be chosen carefully because the monetary incentive will be to reduce the calculated inventory, a number which may not always be well correlated with actual emissions. Dales wrote about attempting to “draw a clear distinction between making a policy and implementing it, yet I realize that the interrelations between a policy and at least the main strategy of its implementation are so close that a good decision about policy goals may easily be rendered ineffective by an inferior strategy of implementation” (Dales, 1968)

The Mexican DNA suggested that a national cap would be much more useful for Mexico than the project based CDM approach. While this statement was about overall GHG emissions, it may also apply to methane only policies. Otherwise it is too easy to shift emissions from one place to another, or to take credits for reducing from a "baseline" that does not really exist. Of course, a national target does not eliminate the need to address sources individually, as within a nation permits need to be allocated. The case of European Trading System demonstrates the complexity involved in negotiating initial permit allocations. Nor does a national target solve the problem of uncertainty in inventories. Taxes or auctioning might work to address the initial allocation problem, but are considered to be politically less desirable. But, should national targets be determined in some manner, then each individual nation could design its own measures, whether taxes, standards and measures, or other approaches.

Then remaining questions become how to allocate national targets, whether to allow trading between nations, designing penalties for exceeding the targets, and choosing appropriate inventory methods for determining whether the target has been met or not. If bottom up inventory methods will be used to determine methane emissions, then the recommendation of this work is that trading between nations should be avoided. There is the potential to use inverse methodologies for determining regional emissions, and in that case trading between regions might be acceptable even if emissions at the level of rice paddy or cattle herd are not well quantified. Such a system based on inverse methods would have to be designed carefully to avoid incentives to eliminate natural methane sources with ecological value such as wetlands and bogs. This design would be especially difficult in cases where natural and anthropogenic emissions have similar temporal and geographic patterns. Nor do the regions used in inverse methodologies necessarily correspond well to national boundaries, which will interfere with creating trading structures.

Therefore in the short term, it appears that global trading regimes for methane may not be wise. On a national level, however, experimentation with different policy structures for methane reduction could be encouraged. Inverse methodologies can be used to determine methane policy success at a regional level. Work should continue to improve bottom-up inventory methods which will enable more efficient policies that require project level resolution, and a broader network of methane sensors should be installed in order to increase the geographical resolution of the inverse methods enabling better evaluation of national level policies.

2.6 Conclusions

In this chapter we have presented converging lines of reasoning that favor eliminating trading between methane and CO_2 in climate policies, and instead addressing the two gases separately. These reasons include differences in their atmospheric reactivity and difficulty in determining an accurate GWP, the sticky issue of trading well quantified fossil fuel CO_2 abatement for poorly quantified methane abatement due to difficulties in measuring methane emissions accurately, political issues of including CO_2 which is difficult to abate and historically tied to powerful political interests with a gas like methane where policies like M2M indicate that there are fewer political barriers to implementing control policies, and economic reasons due to the disconnect between GHG trading price and actual societal costs. This separation of gases would also allow CO_2 policies to continue on a cap and trade path, to which CO_2 may be well suited (especially if the cap and trade is applied to the mine mouth or well head rather than the point of combustion), while methane can be controlled using standards and measures which may be well suited to many of the methane abatement methodologies. This conclusion is directly opposite to that of researchers who argue the benefit of “what flexibility”, but would require more attention from policy makers to achieve an appropriate balance between reductions of the gases.

Given that this research initially began with an analysis of stabilization and its limitations, it is ironic that the conclusion arrived at in this chapter is to not allow trading between CH_4 and CO_2. In chapter one, we noted the inconsistency between stabilization and GWP trading: therefore, separating these gases will enable the implementation of actual stabilization pathways for each gas individually, if so desired. However, this increased feasibility of stabilization was certainly not one of our primary goals.

It may be important to ask what the drawbacks are to forbidding trading between CO_2 and CH_4. Persson et al. (2003) analyzed the economic inefficiencies in using GWPs for methane control given a stabilization target and determined that these inefficiencies were small compared to likely "political controversies and large transaction costs". What are the unspecified costs of having two separate policies for CO_2 and CH_4? We find three categories of possible losses. The first is political. There is significant commitment to Kyoto among Annex B nations, and they may not be willing to change at this late date. Of course, with the second commitment period under debate, there may be significant changes regardless. Additionally, there would be worry that nations would pick and choose whether to belong to both the CO_2 and CH_4 policies, or only one. While this is a disadvantage in the case of nations that would have otherwise constrained both gases, this is an advantage in the case of nations that would not have constrained either gas in the counterfactual. The second category of loss is economic inefficiency: without "what" flexibility, the ratio of the price of methane to the price of CO_2 will likely not stay at a constant "optimal" level. However, part of the point of our analysis is that this optimal ratio is hard to determine, and changes over time, and policymakers can adjust the constraints in rough ways to attempt to minimize this loss. The third category of loss is administrative overhead. This overhead can occur both in the literal sense of the necessity of maintaining two different treaties and trading systems, but also in the sense that it is simpler to build policy around one number representing CO_2 equivalent emissions rather than needing to determine different targets for different gases.

However, we believe that these possible drawbacks to separate policies are outweighed by the political, economic, methodological, and scientific benefits that accrue from separate consideration of the two gases. Some of the costs, such as the administrative overhead of having two separate policies rather than one, are in some sense "fixed" regardless of the quantity of methane reduction available, whereas the advantages of this separate policy approach scale to a certain extent with the importance of methane. Is methane sufficiently important to be worth independent consideration? The argument that it is can be supported by the fact that methane constraints alone can yield almost as much temperature reduction in the 21st century as a 550 ppm CO_2-only stabilization policy, and at a much lower cost. In the longer term, of course, CO_2 becomes relatively more important. The Methane to Markets program is the only current international attempt at such a methane reduction program. The signatory nations do comprise a significant majority of methane emissions, and therefore as a group could achieve most of the reductions modeled in this study. However, the stated targets of the M2M policy are very modest compared to our projections for available inexpensive near-term reductions. Additionally, it is not clear whether the non-binding and voluntary nature of the public-private partnerships in M2M will be effective in achieving even their modest goals. US and EU methane reductions in the past decade can serve as historical examples of apparently effective methane emissions abatement, but those emissions reductions relied in part on standards, subsidies, and other policy changes. If public-private partnerships in OECD nations did not achieve reductions without policy instruments in place, then it might be overly optimistic to hope that merely lowering information barriers will be sufficient to lead to significant methane abatement in developing nations. And if standards or subsidies are indeed necessary, then it is not clear exactly how M2M will encourage such abatement behaviors on the part of its member nations.

A number of potential tipping points were discussed in the first chapter, including the consequences of rate of change on biological systems that adapt slowly (whether human or natural), and on physical systems such as the thermohaline circulation. Because methane has short term impacts, and because we have seen that more than 20% of near term warming can be avoided through methane abatement alone, we believe it is worthwhile to make a significant effort to abate methane now as perhaps the only way to avoid near term crucial thresholds. Unfortunately, if these near term thresholds exist, it may be that we would be able to do no more than delay them.

In conclusion, our analysis suggests that because of its characteristics of lifetime, poor source inventories, inexpensive abatement opportunities, and significant climate impact, there should be a significant effort made to push for international policies to reduce methane emissions without allowing trading between methane and CO_2. We also believe that project based approaches such as CDM are not an ideal manner in which to include non-Annex B nations. Methane abatement in such nations might be better addressed by incentives to implement local standards and measures, or perhaps nationwide caps.

3 Air pollution Constraints: Interactions with Climate Change and Policy

3.1 Introduction

In the previous chapter we used modeling and other analysis tools to study how methane and CO_2 should be included in climate policies, and determined that GWP based trading is likely to lead to suboptimal outcomes. Methane was chosen as a target for study because of its significant contribution to radiative forcing past and present, because of the existence of many inexpensive reduction options, and because there is tension between basket policies such as Kyoto with GWP trading and single gas policies such as the European Trading System or the US Methane to Markets policy.

In contrast to methane, air pollution policy starts in a position where minimal coordination occurs with climate policy, despite a number of academic studies on "ancillary benefits" and "complementarity" (these studies are described in Appendix F). Air pollution is a worthy target of study in relation to climate policy for parallel but differing reasons from methane. In the broadest general outline, air pollution reduction does have a similar temperature mitigation potential as methane, if one includes both direct effects (mainly from black carbon) and ancillary reductions of other gases (because combustion is a source of a large portion of both air pollution and carbon dioxide). And where for methane there are many low cost emissions reduction opportunities, in part due to the high value of natural gas and the ease of flaring, for air pollutants there are desirable mitigation opportunities because of the health benefits that arise from local pollution reductions. Air pollutants, with methane, share the advantage of not being inherent byproducts of the processes that create them: unlike in the case of CO_2, one can use end-of-pipe solutions or more efficient combustion processes to reduce emissions of most pollutants. Because of the temperature reduction potential, and the fact that the abatement costs are offset by ancillary benefits, air pollution mitigation in the context of climate policy is clearly worthy of analysis.

However, atmospheric pollutants differ from methane in many ways. Therefore, we have applied our multi-pronged analysis methodology of climate modeling, economic modeling, and policy analysis to the question of whether and how to incorporate pollution policies into climate policy planning. Several issues need to be resolved in order to make a recommendation on this policy coordination. The first is to determine the direct impact of air pollutants on climate. This requires our atmospheric climate-chemistry integrated modeling system in order to properly model the transformation of emissions into concentrations and then to calculate radiative impacts. A coupled ecosystem model also allows for examination of ozone impacts on carbon uptake. The second step of analyzing coordination between air pollution policy and climate policy is to recognize that emission constraints on air pollutants impact greenhouse gas emissions and vice versa. In order to examine this issue, it is necessary to have an emissions predictions program that has both the capacity to model sectoral shifts in response to constraints as well as to capture the changes within a sector such as the use of end-of-pipe pollution mitigation options. There are three kinds of interactions to be studied between greenhouse gas emission policies and pollution mitigation policies. The first is the impact of pollutant constraints on GHG emissions, the second is the impact of GHG constraints on pollution emissions, and the third is to understand how GHG and climate policies will interact when implemented simultaneously. The third step is to examine air pollution and climate in the context of current policies and political realities, recognizing that there are significant heterogeneities that are not captured by a global level CGE model.

In this chapter we therefore use the MIT IGSM to analyze the direct impacts of air pollutants on climate and show that of the pollutants studied only black carbon constraints have any significant impact on reduction of the temperature increase over the 21st century, and even that reduction is in large part negated by the warming that occurs due to concomitant reductions in SO_2. Controls that lead to ozone reductions also cause increases in methane concentrations, such that the temperature effects are effectively zero; though, if ozone impacts on ecosystems are included, the increase in carbon uptake does lead to there being a small net reduction in temperature change. We then use the EPPA model to study the interactions between greenhouse gas policy and pollution policy. The first step was to update the treatment of air pollution emissions in the EPPA model. In order to examine the impact of air pollution policy constraints, it is necessary to have an estimate of the cost of mitigation. We developed a set of marginal abatement curves for each pollutant, differentiating between Annex B and non-Annex B nations, and used these curves to derive elasticities of subsitution. These elasticities are then used within the production functions within the model. With the upgraded model we are able to demonstrate the impacts that air pollution policy can have on GHG emissions and vice versa. We are also able to analyze the benefits of coordination between the two kinds of policy. Finally, we briefly examine how these interactions differ depending on the characteristics of regional areas using Los Angeles, Mexico City, and China as case studies. We also address how current climate policies such as CDM are currently interacting with air pollution reductions. This analysis allows us to make recommendations on how policymaking should proceed in order to take advantage of the coordination benefits between air pollution and GHG emission constraints.

3.2 The Direct Impact of Air Pollution on Climate

Our first step in addressing air pollution and climate interactions is to examine the direct effect of atmospheric pollutants on climate, but without including any complications from economic interactions. It would be difficult to estimate these direct impacts without modeling. Unlike well-mixed gases, where it is at least sometimes possible to use simple lifetime estimates to calculate concentrations from emissions, and from there directly calculate radiative forcing, the direct and indirect impacts of air pollutants are much more complex. In this work we concentrate on carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), black carbon (BC) aerosols, and sulfur oxides (SO_x, the collective term used for the emissions of some sulfate aerosols, some SO_3, but mostly SO_2 gas which subsequently undergoes atmospheric transformation to form white sulfate aerosols). In order to accurately simulate the atmospheric lifecycles of common air pollutants such as CO, NO_x and VOCs, the climatically important methane (CH_4), and sulfate aerosols, it is important to capture the fast photochemistry of the hydroxyl free radical (OH) (Ehhalt, 1999; Prinn, 2003).

The relationships of these compounds are complex. The nonlinearity of these connections are exemplified by the fact that concentrations of ozone in urban areas for a given level of VOC emissions tend to increase with increasing NO_x emissions until a critical VOC-dependent NO_x emission level is reached. Above that critical level, ozone concentrations actually decrease with increasing NO_x emissions emphasizing the need for air pollution policies to consider CO, VOC and NO_x emission reductions jointly rather than independently. In contrast to urban chemistry, concentrations of ozone in the climatically critical global middle and upper troposphere are determined significantly by long-range transport from urban areas below and the stratosphere above, and the photochemical ozone production is limited by the low ambient NO_x levels.

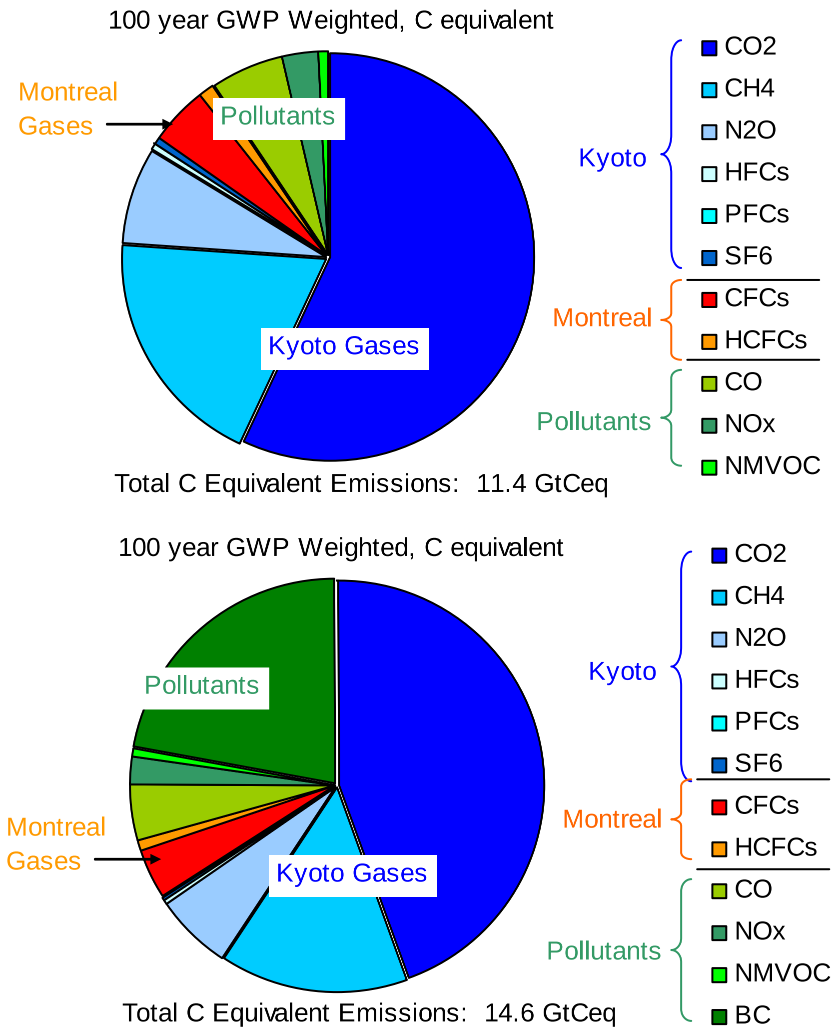
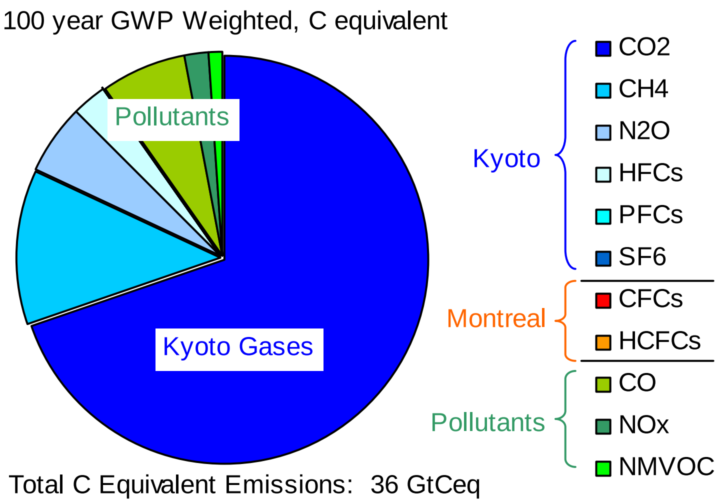


Figure 3-1: EPPA4 emissions in 2000, weighted by 100 year GWPs, including best estimates for pollutant GWPs. Black carbon is included in the second figure.

There have been attempts to give pollutants GWP weights in a similar fashion to greenhouse gases. Using some standard GWP estimates for the ozone precursors CO, NOx, and VOCs we produced a chart of 100 year GWP weighted emissions for the year

2000 and 2100 (Figure 3-1 and Figure 3-2). The GWPs of the three substances included are highly uncertain, both because of scientific uncertainties and because the climate impacts of the substances can depend on time of day, location of emissions, and various climatic conditions in the area. For example, we have assigned a GWP to NOx of 5, but high altitude NOx emissions from aircraft could potentially have a GWP of 400 or more. The uncertainties in impacts of black carbon and the aerosols are even larger than those of the ozone precursors, and therefore have been included in as secondary options in both Figure 3-1 and Figure 3-2. Bond and Sun (2005) suggest that black carbon's GWP should be on the order of 680, but for various reasons, including uncertainty in impact but also the fact that the warming due to black carbon has a very different vertical profile from well-mixed gases or ozone, it is difficult to assign a GWP to black carbon. And our calculations suggest that even the ozone precursor GWP estimates may be flawed, with NOx reductions having no (or even a warming) temperature effect in the absence of concurrent CO and VOC reductions, and with CO and VOC reductions leading to little or no cooling. Other researchers (Fiore et al., 2003) have hypothesized that anthropogenic VOC reductions other than methane should have little impact because methane is the dominant VOC on the global scale.



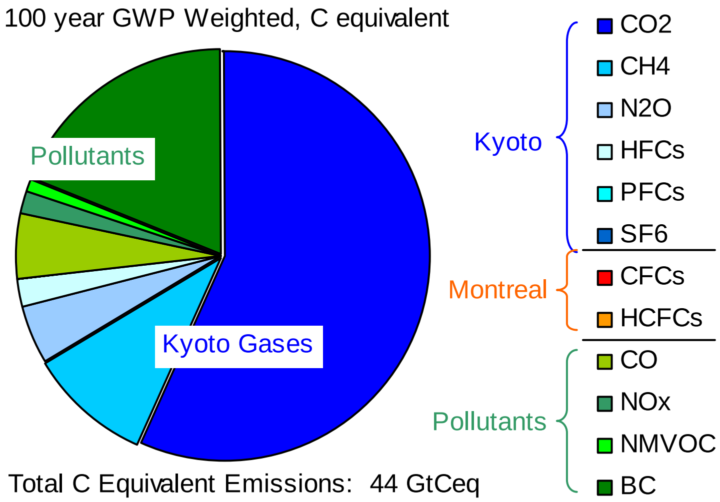


Figure 3-2: EPPA4 emissions in the year 2100, weighted by 100 year GWPs, including best estimates for air pollutant GWPs.

The MIT IGSM can be used to investigate such climate-chemistry interactions. The coupled atmospheric chemistry and climate submodels have sufficient detail to capture most of the important reactions in the troposphere. An urban submodel serves to age emissions before releasing them to the remainder of the model in order to more accurately simulate conditions (Mayer et al., 2000). Additionally, a version of the MBL ecosystem model exists that allows us to examine ozone effects on ecosystems (Felzer et al., 2005), though it is not yet directly coupled into the main IGSM. The computational demands of the IGSM are modest enough (36 hours on a single processor) that it is possible to easily perform many experiments with different emissions scenarios. We performed a first pass at analyzing these interactions previously (Prinn et al., 2005a), but repeat the experiments here with updated model components. The direct comparison of the Prinn et al. (2005) results using the EPPA3 and IGSM1 framework to the new results within the EPPA4 and IGSM2 framework is a start towards examining structural uncertainty within these results rather than just parametric uncertainty. More importantly, repeating the experiments ensures consistency with the subsequent sections which use EPPA4 and IGSM2 to explore the economic side of the interactions between air pollution and climate policy, allowing the direct effect of pollutant controls to be separated from the ancillary reductions of other greenhouse gases.

3.2.1 Scenarios of Air Pollution Reduction

To examine the direct impacts of air pollution control on climate, we establish reference and control scenarios. Our reference scenario (denoted "ref") includes no explicit policy to reduce greenhouse gas emissions and no specific new policies to reduce air pollution (Reilly et al., 1999; Webster et al., 2002). It is therefore somewhat dirtier than an expected "no-climate policy" future which would be expected to include air pollution constraints for health reasons alone. For the control scenarios, emissions were artificially constrained by the EPPA post processor to remain constant from 2005 to 2100 for individual pollutants, or combinations of these pollutants from all anthropogenic activities. Specifically, in six scenarios, we consider caps at the reference 2005 levels of emissions of the following air pollutants:

(1) NO_x only (denoted "NO_x cap"),

(2) CO plus VOCs only (denoted "CO/VOC cap"),

(3) SO_x only (denoted "SO_x cap"),

(4) BC only (denoted "BC cap"),

(5) Cases (1) and (2) combined (denoted "3 cap"),

(6) Cases (1), (2), (3) and (4) combined (denoted "all cap"),

(7) An "allurb" scenario from Section 3.3 that includes all economic impacts is also included in some figures in this section for comparison purposes

Cases (1) and (2) are designed to show the individual effects of controls on NO_x and reactive carbon gases (CO, VOC), although such individual actions are unlikely. Case (3) addresses further controls on emissions of sulfur oxides from combustion of fossil fuels and from industrial processes. Case (4) similarly addresses selective reduction of black carbon from these processes, though again, this is not only politically unlikely but also physically unlikely. Cases (5) and (6) address combinations more likely to be representative of a real comprehensive air pollution control approach. Some complexities arise due to the fact that we define urban areas for the purposes of the model as any grid cell in which NOx emissions are greater than 5 $kg/km^2/day$. Therefore the caps on NOx emissions in cases (1), (5), and (6) lead to a smaller number of total urban areas, and therefore less emissions of all substances passed through the urban module. Note also that all anthropogenic VOC contributions occur within urban areas: it is assumed that the global VOC budget is dominated by natural sources.

In Figure 3-3 we show the ratios of the emissions of NO_x, CO, VOC, BC, and SO_x in the year 2100 to the reference case in 2100 when their emissions are capped at 2005 levels. Because these chemicals are short-lived (hours to several days for NO_x, VOCs, and SO_x, few months for CO), the effects of their emissions are largely restricted to the hemispheres in which they are emitted (and for the shortest-lived pollutants restricted to their source regions). Figure 3-3 therefore shows hemispheric as well as global emission ratios. For calibration, the reference emissions in 2100 of CO_2, CH_4, SO_x, NO_x, CO, BC and VOC's as input into the IGSM are 23.7 gigaton C/year, 731 megaton CH_4/year, 283 megaton SO_x/year, 349 megaton NO_x/year, 4.6 gigaton CO/year, 45 megaton BC/year, and 677 megaton VOC/year respectively (1 megaton = 10^{12} gm). The reference global emissions of NO_x, CO, BC, and SO_x in 2100 are about 1.9, 2.7, 2.3, and 1.5 times their 2005 levels. Note that while our reference emissions are similar to the central IPCC IS92a scenarios (Nakicenovic and Swart, 2000), they differ specifically in having substantially increasing SO_x, NO_x, CO and VOC emissions through 2100 since they assume no specific air pollution policies beyond those already existing (Webster et al., 2002).

The major difference in terms of emissions between this study and our earlier paper (Prinn et al. 2005) besides the inclusion of black carbon is that NOx emissions only double in the reference, rather than increasing nearly fivefold.

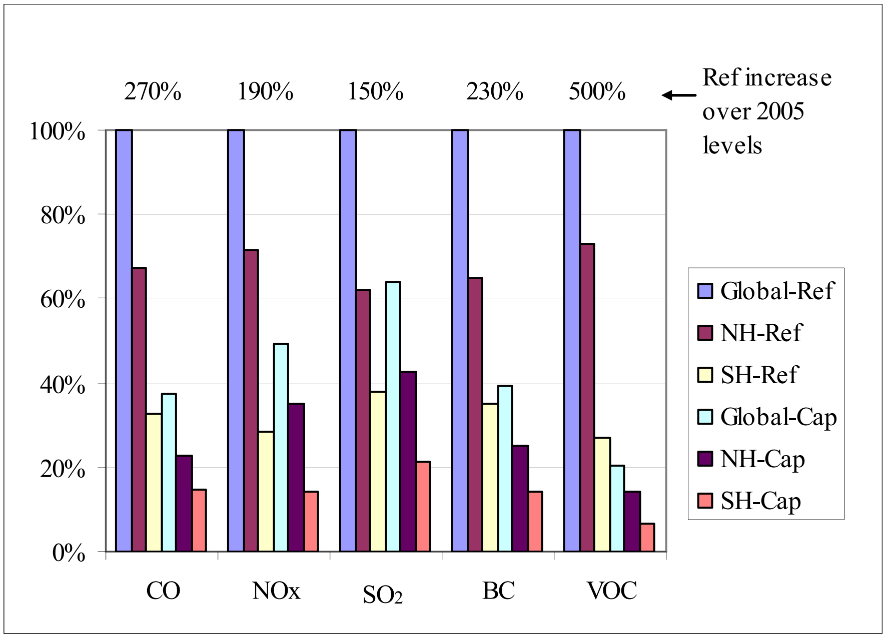
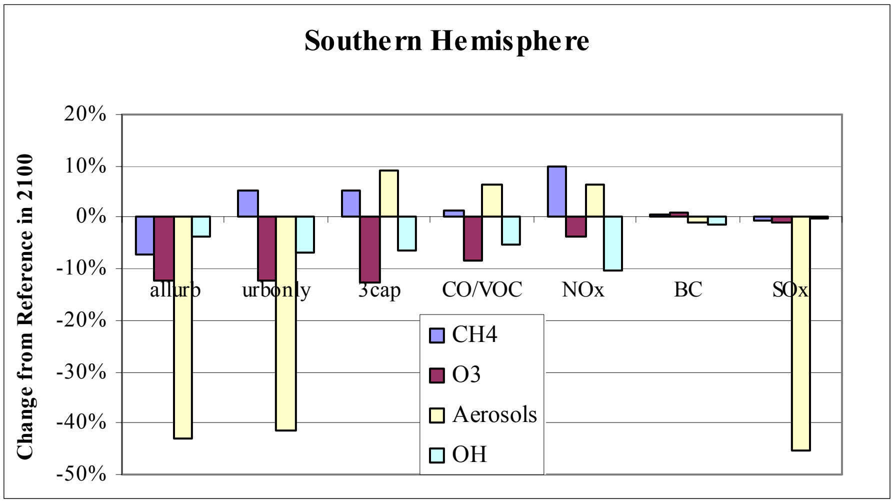


Figure 3-3: Global, northern hemisphere (NH), and southern hemisphere (SH) pollutant emissions. Emissions are shown in the year 2100 as a percentage of global reference levels, with the global increase in the reference case over 2005 levels noted. The Cap policy maintains all emissions at 2005 levels.

3.2.2 Effects of pollution controls on concentrations of key atmospheric species

In Figure 3-4, the global and hemispheric average lower tropospheric concentrations of CH_4, O_3, sulfate aerosols, and OH in each of the above seven pollution constraint cases are shown as percentage changes from the relevant global or hemispheric reference. While most of the impacts on concentrations are similar to the Prinn et al. (2005) results, there are some differences. First, we have included the effects of a black carbon simulation, and the effects of the "allurb" simulation which includes the effect of structural economic shifts on GHG emissions as well as the actual urban emission reductions (the impacts on CO_2 and N_2O of these shifts will be examined in a subsequent section). We see that black carbon reductions have little impact on any of the four substances in this chart. This is not surprising, as the only possible interaction mechanism by which black carbon reductions could impact the concentration of other species is through effects of temperature changes on the reaction rates of the other species. The major difference of the allcap case from the allurb case is an increase in methane concentration rather than a decrease. The allcap and allurb cases have similar emissions of air pollutants, because in one case the emissions path was designated artificially in the postprocessor, in the other the same emissions path was used as a constraint within the EPPA model. However, the emissions of the major GHGs are significantly lower in the allurb case because of the interaction effects between emissions constraints on air pollution and GHG emissions (as discussed in Section 3.3). The next difference is that the CO/VOC reductions, which had led to a small increase in ozone and a slight decrease in methane in Prinn et al. (2005a) now exhibit the reverse effect. This appears to be mainly a southern hemisphere phenomenon, possibly linked to a decrease in OH rather than the expected increase. Additionally, we now see decreases in OH simultaneously with increases in SOx in the NOx reduction scenario. This result is at odds with both expectations (Unger et al PNAS 2006) and our previous results, as we expect lower OH levels to result in less SO_2 oxidation to sulfates , but because of the relationship between NOx emissions and assignment of urban areas there are complicating factors making explanations of this behavior difficult.

The relationship of NOx and O_3, OH, and CH_4 remains normal. Capping of NO_x leads to decreases in O_3 and OH and an increase in CH_4 (caused by the lower OH which is a CH_4 sink). In the 3cap case, we see similar results to the previous study, where combining NO_x, CO and VOC caps leads to a substantial O_3 decrease (driven largely by the NO_x decrease) and a slight increase in CH_4 (the enhancement due to the NO_x caps being partially offset by the opposing CO/VOC caps). Finally, capping all emissions causes substantial lowering of sulfate aerosols and O_3 and a small increase in CH_4, as before. In sum, we see ozone reductions of 7.4% due to NOx restrictions, 3.8% due to CO/VOC restrictions, and 12.8% from capping all three pollutants. This can be compared to the 8% reduction that was seen in the methane control case in the previous chapter.



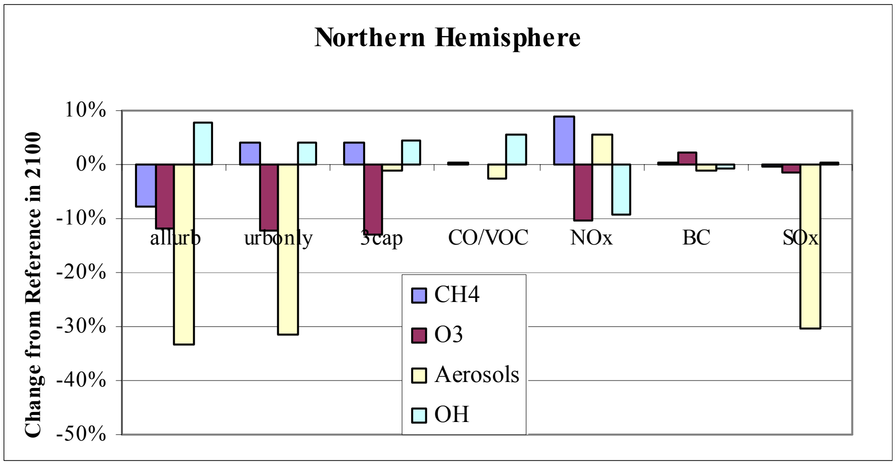
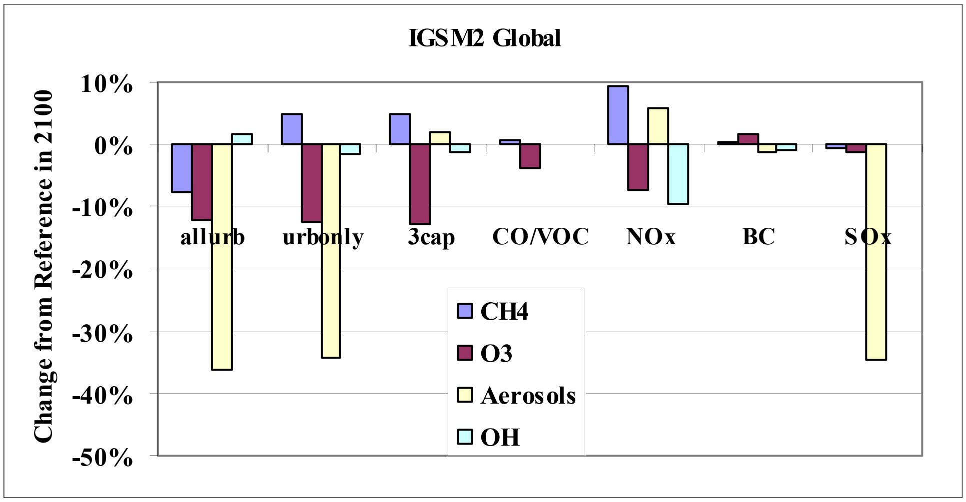


Figure 3-4: Hemispheric concentrations of climatically and chemically important species. Concentrations shown in 6 cases where emissions are capped singly or in groups in an EPPA postprocessing step (3cap = CO/VOC and NOx, urbonly constrains all urban species) and one case in which all the urban emissions are capped within the EPPA4 model (allurb). The changes shown are in reference to the relevant hemispheric average.



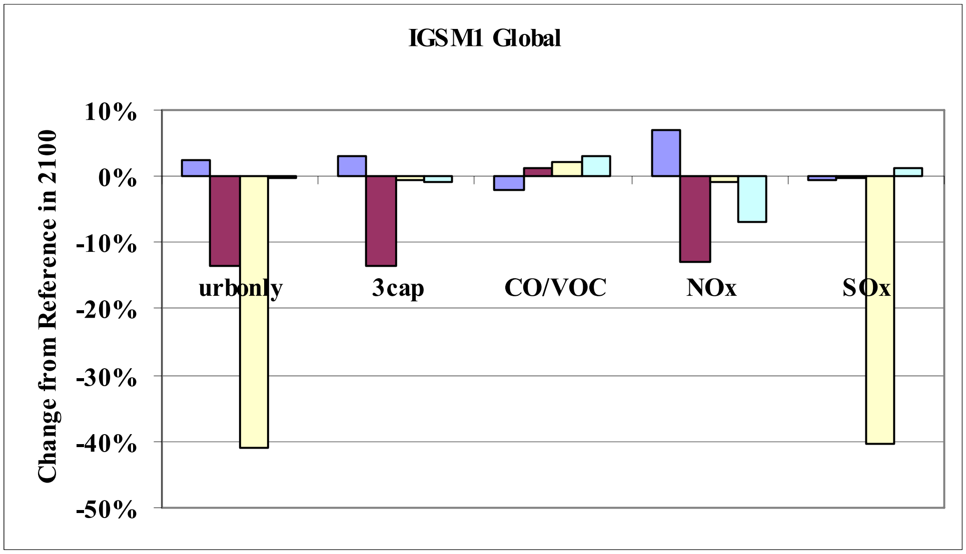


Figure 3-5: Global concentrations of climatically and chemically important species. Concentrations shown in 6 cases where emissions are capped singly or in groups in an EPPA postprocessing step (3cap = CO/VOC and NOx, urbonly constrains all urban species) and one case in which all the urban emissions are capped within the EPPA4 model (allurb). The changes shown are in reference to the global average. The lower figure from (Prinn et al., 2005a) is included for comparison, and does not include the BC or allurb cases.

The two hemispheres respond somewhat differently to these caps due to the short air pollutant lifetimes and dominance of northern over southern hemispheric emissions. The northern hemisphere contributes the most to the global averages and therefore the globe responds to the caps similarly to the northern hemisphere. The southern hemisphere shows very similar decreases in sulfate aerosol from its reference when compared to the northern hemisphere when either SO_x or all emissions are capped.

When compared to the southern hemisphere, the northern hemispheric ozone levels decrease by much larger percentages below their reference concentrations when NO_x is capped. Capping NO_x emissions leads to significant decreases in non-urban OH and thus increases in methane in both hemispheres. Because methane has a long lifetime of about 9 years (Prinn et al., 2001), relative to the interhemispheric mixing time (about 1 to 2 years), its global concentrations are influenced by OH changes in either hemisphere alone, or in both. Hence CH_4 also increases in both hemispheres when NO_x or all emissions are capped even though the OH decreases only occur in the southern hemisphere in these two cases. In the case of CO/VOCs the story is slightly more complicated: we see OH and O_3 decreases in the southern hemisphere, but an OH increase in the northern hemisphere. Again, the aerosol concentrations move in the opposite direction from the OH concentrations, which is not the expected correlation. Further experiments show that all the concentration changes are mainly due to the CO reductions, with the VOCs playing a lesser role. Further examination of this chemistry is ongoing.

Effects of air pollution on the land ecosystem sink for carbon can be significant through reductions in ozone-induced plant damage (Felzer et al., 2005; Prinn et al., 2005a). Net primary production (NPP), the difference between plant photosynthesis and plant respiration, as well as net ecosystem production (NEP) (NEP is the difference between NPP and soil respiration plus decay, and represents the net land sink), both increase when ozone decreases. In the Prinn et al (2005) study, when all pollutants were capped ozone decreased by about 13% globally. The result on ecosystem production was to increase NEP by 30 to 49% (0.6 to 0.9 gigatons of carbon) depending on fertilization assumptions. The increase in uptake over the century resulting from capping pollution in the reference case ranged from 36 to 75 gigatons of carbon, or about 6 to 13 years of fossil carbon emissions at current annual rates. In the absence of any other climate policy, the central value of this uptake range is sufficient to decrease temperature increases over the century by almost 5%.

Of course, as a supplement to a GHG policy, pollution reduction will not be as effective at increasing uptake, both because the GHG policy will lead to some amount of ancillary pollution reductions resulting in less ozone to begin with in the counterfactual, and because the starting level of uptake will be lower due to there being less of a CO_2 fertilization effect. However, when applying pollution caps to a 550 ppm stabilization case, the cumulative 2000-2100 increase of carbon uptake was still 13 to 40 gigatons of carbon, which is about one-half of the above increased cumulative uptake when the pollution cap occurs assuming there is no climate policy. This uptake would decrease the cost of such a 550 ppm policy significantly (of order 10 to 20%) because it would eliminate the need to undertake the most costly of the carbon emission reduction options. This reduced pollution would come at a cost: the interaction effects are explored more fully later in this chapter.

The ecosystem calculations do not include the additional positive effects on NPP and NEP of decreased acid deposition and decreased exposure to SO_2 and NO_2 gas, that would result from the pollution caps considered. They also do not include the negative effects on NPP and NEP of decreasing nutrient nitrate and possibly sulfate deposition that also arise from these caps.

3.2.3 Effects of air pollution controls on temperature change and sea level rise

The impact of these pollutant caps on global and hemispheric mean surface temperature and sea level changes from 2005 to 2100 are shown in Figure 3-6**.** The results are stated as percentages relative to the global-average reference case changes of 4.0°C and 0.51 meters respectively. The largest changes in temperature and sea level occur when black carbon alone is capped. Because most BC emissions are in the northern hemisphere, the temperature decreases are greatest there. Reduction of cooling sulfate aerosols leads to a change half as large in magnitude but opposite in sign from the black carbon impacts. For the NO_x caps, global methane increases lead to a small temperature increase in the southern hemisphere. However, as shown in Figure 3-4, O_3 reductions in response to the decrease in NOx emissions occur mainly in the northern hemisphere where the majority of the emissions reductions occur, and therefore there is a temperature decrease in that hemisphere. For CO and VOC reductions, there are small increases in temperature especially in the southern hemisphere, despite what looks like decreases in forcing.

Combining NOx and CO/VOC reductions may lead to non-linear effects. For example sea level rise, which serves as an indicator of integrated warming over time, is negative in the 3cap case even though it is positive in the cases where the pollutants are capped individually. However, the magnitudes of these changes are too small to be able to state anything definitively. Finally, capping all the pollutants leads to a net cooling, as might have been expected due to the effects of BC reductions being twice as large as those of SO_2 reductions, with the other substances being minor impacts in comparison. Note that these climate calculations in Figure 3-6 omit the cooling effects of the CO_2 reductions caused by the lessening of the inhibition of the land sink by ozone. This omission is valid if we presume that anthropogenic CO_2 emissions, otherwise restricted by a climate policy, are allowed to increase to compensate for these reductions. If not, our previous work (Prinn et al., 2005a) suggests that the increased CO_2 sink would lead to another couple of percent of cooling, for a sum total of 7 or 8% reduction below reference, or about half as much as keeping methane emissions constant through the century.

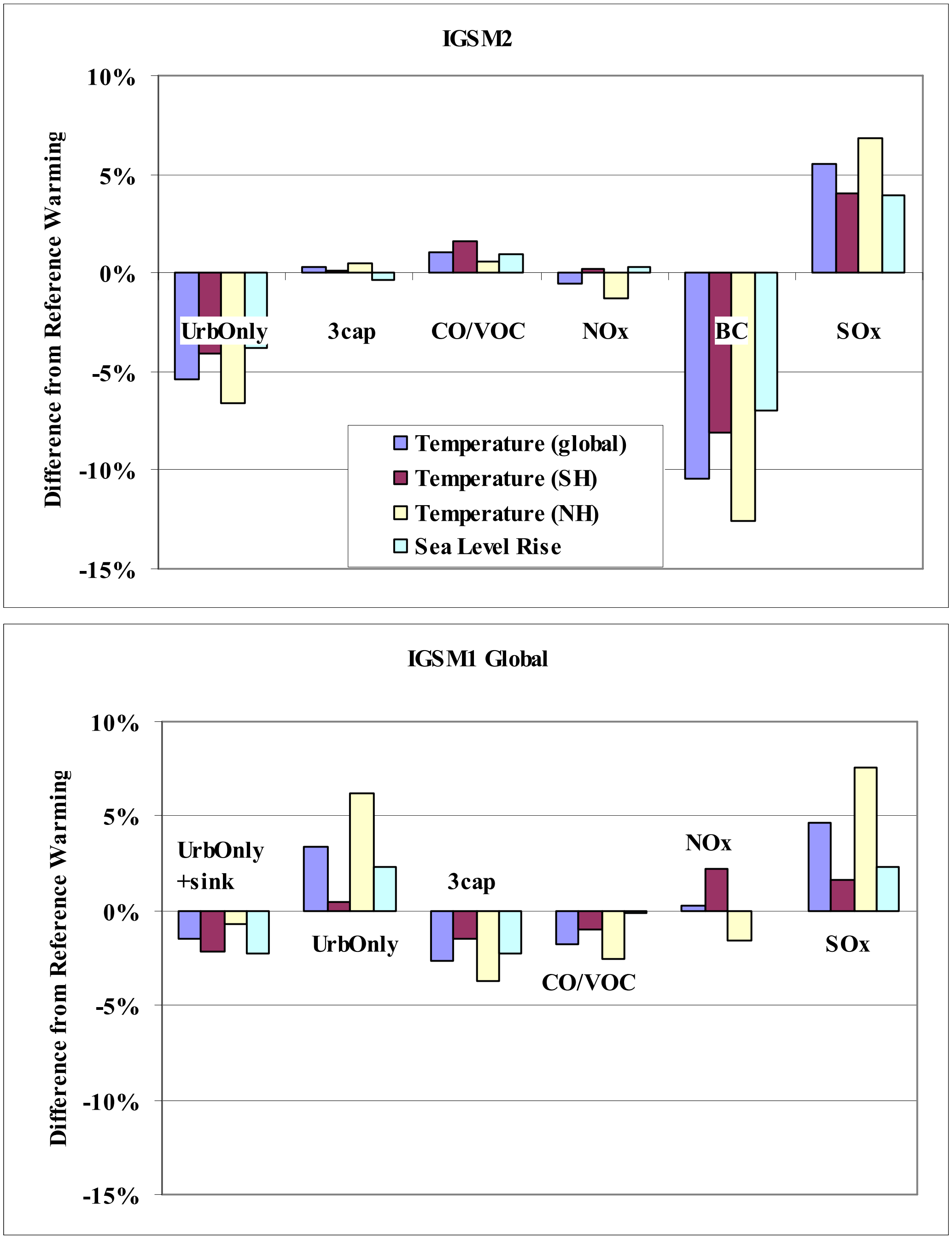


Figure 3-6: Effects of air pollution caps on global, southern hemispheric and northern hemispheric temperature increases and global sea level rise
Tempereature change and sea level rise shown as a percent difference from the reference increase between 2000 and 2100. 3cap includes CO/VOC and NOx, UrbOnly includes constraints on all pollutants but no interaction effects with the major GHGs. IGSM1 figure comes from (Prinn et al., 2005a) and does not include BC impacts. The IGSM1 figure does include one run (UrbOnly+sink) that includes ozone impacts on terrestrial ecosystem carbon sinks.

3.3 Air pollution constraints in the context of an economic model

3.3.1 Motivation for Inclusion of Economics

One of the limitations of both Prinn et al. 2005 and the preceding section of this chapter was the lack of an economic analysis of the pollution policies, which were implemented artificially in a post-processing step to the EPPA model. Figure 3-6 demonstrates the temperature impact of various policies, but gives no guidance as to the relative costs of the policies to each other or to greenhouse gas policies. In order to give policy guidance such cost estimations are necessary. Additionally, we expect that a constraint on a given urban gas will have impacts on the emissions of other gases.

There is a considerable literature on "ancillary benefits" and "complementarity" between air pollution policies and carbon dioxide policies. The rationale for this extensive literature is that fossil fuel combustion emits both CO_2 and air pollutants. Therefore, we can expect that a constraint on CO_2 emissions would likely lead to an ancillary benefit of a improvement in air quality, and a constraint on air pollution emissions will lead to an ancillary benefit of a reduction of CO_2 emissions. In the case where both CO_2 and air pollution are being constrained simultaneously, the two constraints can be seen to serve as "complementary goods", where a reduction of CO_2 emissions leads to a reduction of the cost of reducing air pollution emissions and vice versa. Most of the literature in this area has used ancillary benefits of CO_2 reductions to justify climate policies, but there has also been some work on complementarities, ancillary benefits of air pollution, and designing optimal policies to combine air quality and climate policies. This research has been done with a variety of approaches: bottom-up analyses, regional CGE models, health models, and others, as presented in more detail in Appendix F. However, to the best of our knowledge, this problem has rarely been addressed on a global spatial scale, a century long timescale, including climate impact analysis, or within a modeling structure where the economic feedbacks well represented in a CGE model have been coupled with substitution elasticities grounded in empirical studies allowing for end-of-pipe abatement effects.

Certainly no work has attempted to combine all these challenges into a single integrated study, which we do here.

3.3.2 Model Development

3.3.2.1 EPPA implementation

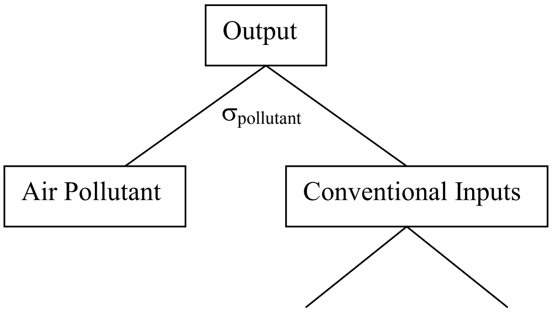


Figure 3-7: Generalized production structure for including air pollutants in the EPPA4 model

The first step of integrating pollution abatements into an economic model is determining the appropriate functional form. The EPPA model, as detailed in Appendix A, has production sectors based on nested constant elasticity of substitution (CES) functions. In order to integrate air pollution abatement into such a structure, we decided to model air pollution emissions as an input into the sector rather than as an output (Figure 3-7). In effect, one can consider disposal of air pollutants as the input. An elasticity of substitution between this pollutant disposal input and the remainder of the inputs implies that pollution abatement can be achieved within a sector by increasing the supply of other inputs such as labor and capital. In this structure, if the substitution elasticity of the pollutant with the other sectoral inputs is zero (eg, a Leontief relationship) then the only way to reduce emissions is to reduce the output of the sector. A positive elasticity indicates some ability to abate pollutant emissions without reducing output, at some cost of other inputs. The larger the elasticity, the fewer other resources are necessary to yield the same quantity of abatement. This implementation parallels the manner in which non-CO_2 GHGs are treated in the model, as originally described in Hyman et al. (2003a).

Ideally, each pollutant in each sector in each region would be given a separate elasticity. However, the estimation problem is large: 6 major pollutants (CO, VOCs, BC, OC, SO_2, and NOx) multiplied by sixteen sectors plus eleven electric generation technologies with relevant emissions possibly including different fuels for each sector would mean over a hundred different elasticities to estimate, and then attempting to make estimates for each of sixteen regions would make the problem completely unmanageable.

3.3.2.2 Parameter Estimation

In order to derive elasticities of substitution, it is necessary to base them on available data. We had access to the RAINS-Europe database with tables of pollution abatement technologies in Europe, their costs, and abatement characteristics for all of our desired air pollutant emissions except for carbon monoxide. Additionally, the RAINS-Asia databases had equivalent data for SO_2 in China, but not for any of the other pollutants. Following the methodology of De Masin (2003) and Hyman (2001) it is possible to construct marginal abatement cost curves from this data (Figure 3-8), and then create a fit that will enable determination of an abatement elasticity. Given a price P and an abatement A(P) and a relationship $P = P_0 \left(\frac{1}{1 - A(P)} \right)^{\frac{1}{\partial}}$, it is possible to do a linear regression on (log(P), log(1-A)) to derive the elasticity sigma. Most of the fits had R square values of 0.85 to 0.95, but some (especially for the fits to the RAINS-Asia database) were as low as 0.7.

It was assumed that all Annex B nations would have the same elasticities as Europe, and that all non-Annex B nations would have elasticities equal to those of China. Sectors where data were not available were assumed to have an elasticity of 0.05. There was limited sectoral coverage for the VOC data, but where it existed the elasticity was only 0.04. For non-SO_2 substances in non-Annex B nations, it was assumed that the elasticity would be 1.5 that of the appropriate Annex B sector. Backstop technologies were given an elasticity of 20% larger than that of the conventional technology they most resembled (eg, advanced coal such as pulverized coal or integrated coal gasification are assigned elasticities 20% larger than that of standard coal power). The elasticities are presented in Table 3-1.

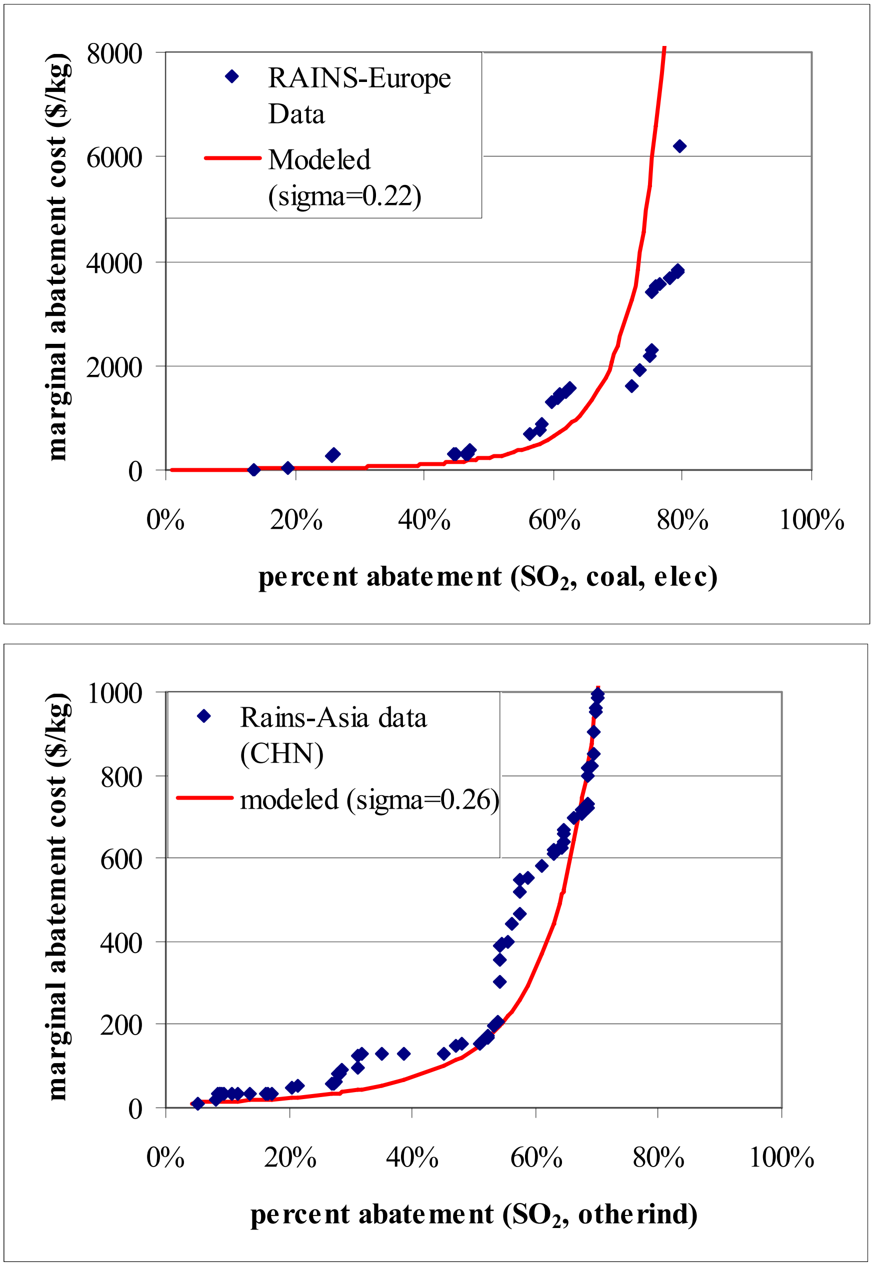


Figure 3-8: Sample marginal abatement curves derived from RAINS data

	SO_2	NOx	BC	Asia-SO_2
COAL	0.25	0.12	0.13	0.33
ROIL	0.28	0.11	0.37	0.17
GAS	0.05	0.07	0.05	0.08
FD	0.08	0.03	0.09	0.10
TRANS	0.17	0.05	0.05	0.06
ELEC	0.25	0.11	0.11	0.32
EINT	0.12	0.08	0.21	0.24
OTHR	0.08	0.1	0.04	0.33

Table 3-1: Elasticities of substitution by substance and sector[11]

There are various model limitations that should be noted. First, elasticities are based on current technology options. This has two pertinent implications: one is that elasticities might be expected to grow in the future (though we also have some technology improvement in our baseline). The other implication is that when we extrapolate from Annex B pollution control elasticities to their equivalent non-Annex B elasticities using the European SO_2/Chinese SO_2 elasticity ratio we assume that this ratio will hold across other gases, which is not necessarily true. Additionally, some of the abatement curves had less than ideal fits, and, as mentioned above, there was a necessity to extrapolate into sectors and pollutants not covered in the databases. Therefore we felt that an analysis of the sensitivity of the model to these elasticities would be useful, and that is covered in a later section in this chapter. Our cost estimates may therefore be considered to be rather preliminary. In the future, it would be an improvement to have a more consistent means of dealing with pollution projections that would allow for nations at different points on the Kuznet curve as a default policy, and then further constraints could be added to examine tighter air pollution policies imposed as part of a climate regime. Also, the current version of the model does not distinguish between different transportation fuels. This lack of resolution means that policies that control air pollution will not, for example, lead to a substitution of gasoline for diesel in Europe which would actually increase greenhouse gas emissions. Similarly, we do not include the tradeoff between CO reduction and NOx reduction, where higher temperature combustion reduces the first (and often has higher efficiency in general) but increases emissions of the latter pollutant. Note that most CO reductions are presumed to occur through more complete combustion: therefore, most of

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[11] CO abatement was not included in the RAINS database: elasticity of substitution was assumed to be 0.05 in this study, except in transport and power sectors, where it was assumed to be 0.2.

the CO reductions are indeed balanced by an increase in CO_2 emissions in the IGSM. Other end-of-pipe technologies might be presumed to reduce multiple pollutants simultaneously, most obviously in the case of scrubbers that would reduce both warming and cooling aerosols at the same time. Many of these technologies (such as flue gas desulfurization), however, lead to slightly reduced efficiency and therefore greater CO_2 emissions. The switch to bio-fuels which reduces GHGs but may increase air pollution is included in the model, however, as that is a sectoral shift and not an end-of-pipe technology represented through an elasticity of substitution.

3.3.3 Pollution Control impact on GHG emissions

The first case to study is the impact that increased pollution control might have on greenhouse gas emissions and therefore on climate. Similarly to the direct impacts case, we have examined the results of various policies, the difference being that in this case we have constrained pollutant emissions within the framework of the EPPA model, and can examine the impacts on the economy and other emissions. Additionally, we examine three different sets of substitution elasticities as a sensitivity study for the case where we control all pollutants. We used three possible sets of elasticities: a reference elasticity based on the RAINS datasets, an elasticity of zero (requiring that all air pollutant reductions result from sectoral shifts), and a "high elasticity" of five times the reference in all sectors. In each case, all pollutants were capped at 2005 levels for the whole century, in similar fashion to the previous section. Additionally, individual runs using the reference elasticities were performed for caps on each individual pollutant. The ratios of reference run emissions in 2100 to 2005 were 3.2, 2.0, 3.5, 2.3, and 1.6 for CO, NOx, VOCs, BC, and SO_2 respectively (the ratios for the emissions in EPPA are slightly different than for emissions entering the IGSM due to certain natural sources that are added into the process in a post-processor step). While unrealistic in terms of actual policy, emissions within a region of a given pollutant was capped from 2005 to 2100 at the level at which it had been emitted in 2005. Trade was allowed between regions in order to yield as low a global cost policy as possible.

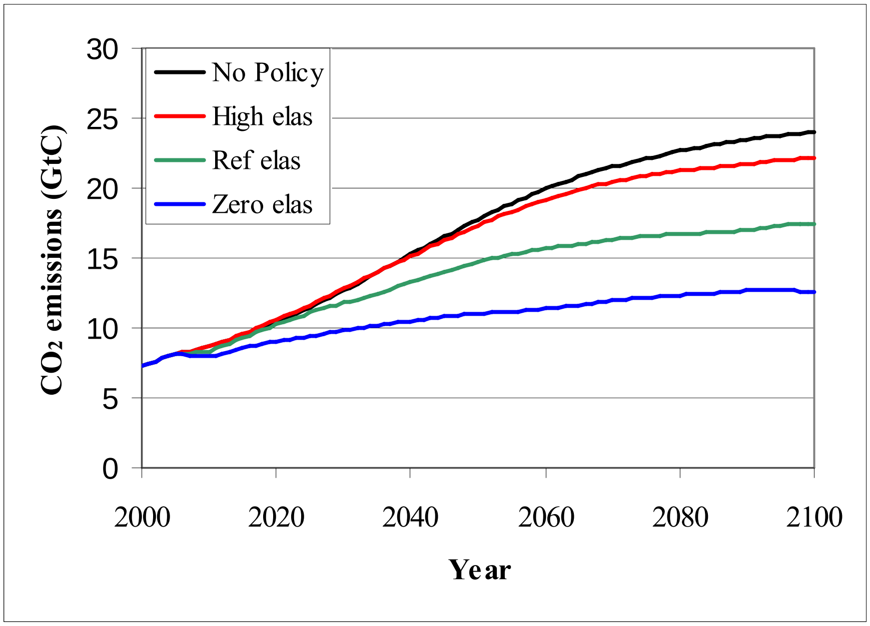

Figure 3-9: CO_2 emissions under constant air pollution emission constraints given different elasticities

The direct impact on CO_2 emissions over the century of the three elasticities is shown in Figure 3-9. In the reference case for the first two decades the constraints are sufficiently loose that nearly all the pollution reductions are accomplished without any ancillary reductions in CO_2 emissions. In the zero elasticity case the lack of "end-of-pipe" options leads to immediate CO_2 reductions. σ_{elas} from Figure 3-7 is zero when there are no abatement opportunities available within a sector – eg, in Figure 3-8 the marginal abatement cost would be infinite at 0% reductions. Therefore, in order to get abatement from a given sector, that sector must reduce production rather than reallocating its use of input resources. In the high elasticity case on the other hand, it is many decades before CO_2 reductions become noticeable, as there is no barrier to reducing emissions in a given sector by increasing the use of other resources such as capital and labor. The reductions in CO_2 concentrations in 2100 (Figure 3-10) show the integrated effect of emissions reductions over time. The no policy scenario has a concentration of nearly 890 ppm, while it is reduced to 751 ppm in the emission control scenario with reference elasticities. Of the individual pollutant constraints it is the NOx reductions that have the largest ancillary CO_2 reduction. The relationship between pollution reduction and CO_2 reduction results from a combination of the quantity of pollutant being reduced, the elasticities assigned, and which sectors are the source of the emissions.

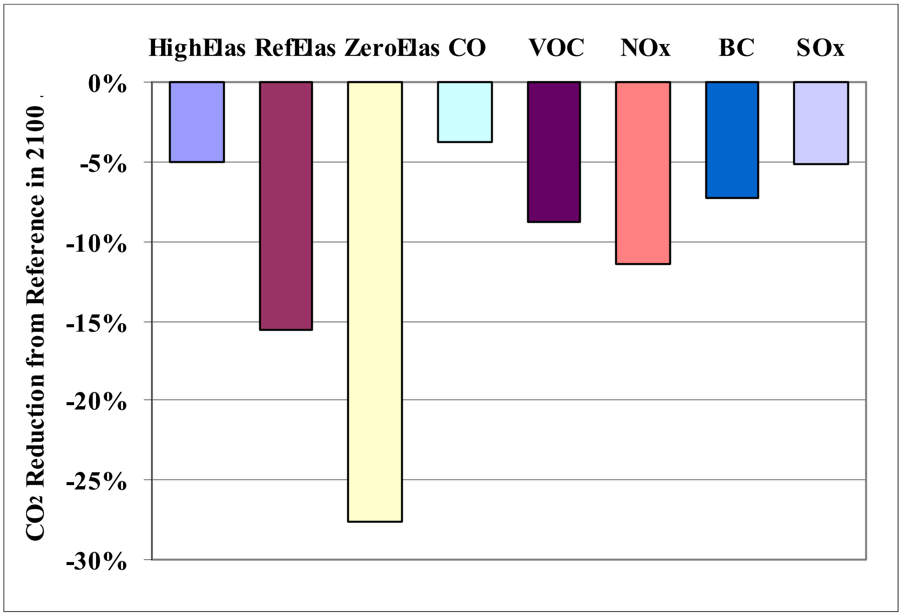

Figure 3-10: CO_2 concentrations resulting from air pollution constraint scenarios: 5 individual pollutant constraints, and three sensitivities for constraining all pollutants
CO_2 concentration in reference is 889 ppm

Given that the majority of CO_2 emissions come from energy production, in Figure 3-11 we can examine the breakdown by energy source to further examine how different pollution policies will impact the economy. We see in the reference elasticity control case that there is a significant reduction in coal use, along with some reduction of bio-oil and normal oil, but an increase in gas use. A shift from coal to gas is a textbook example of ancillary benefits of air pollution reduction: gas is a much cleaner fuel and also happens to be much less carbon intensive. The bio-oil reduction is less clear-cut, as bio-oil is in fact carbon neutral in our model. There is a clear difference in the impact of an air pollution policy from the impact of a carbon policy, which would also cause a similar shift away from coal towards gas, but would encourage rather than discourage bio-oil use. The large reduction in overall energy production results from the tight constraints – there are factor of three reductions in some pollutant emissions by the end of the century. It is possible that the elasticities of substitution should increase over time, as more pollutant abatement technologies become available.

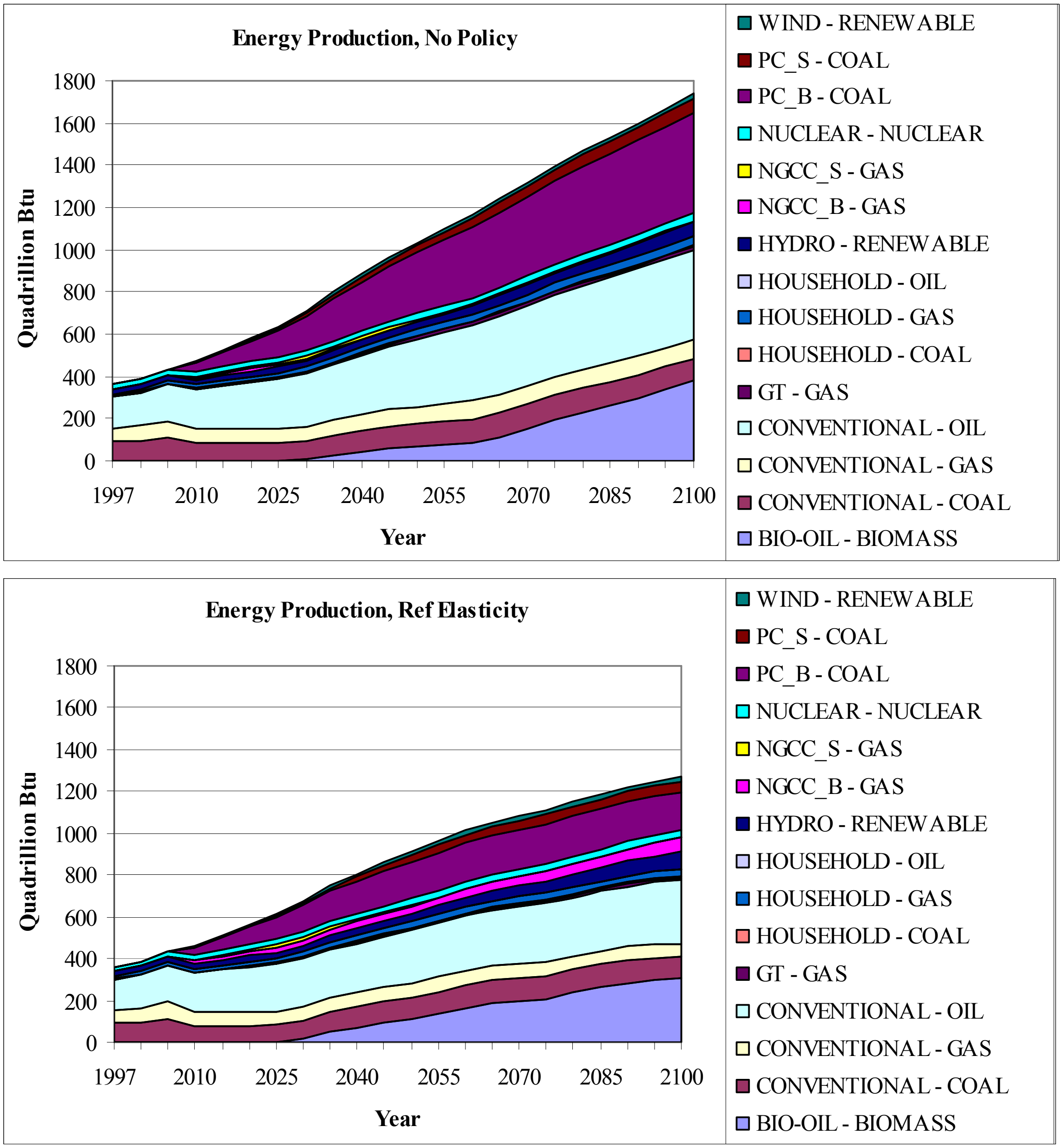

Figure 3-11: Energy production by technology in the reference scenario and an air pollution constraint scenario controlling all pollutants with the reference value for pollutant elasticities.

The individual constraints (all using reference elasticity values) have varying effects, depending on which substance is being controlled. Table 3-2 shows the impact of the various different pollution constraint policies on energy demand by source. For example, gas combustion has no SO_2 or black carbon emissions in our model, so controlling those substances leads to large increases in natural gas use. On the other hand, NOx, VOC, and CO are all products of natural gas combustion and processing, and therefore constraints on these emissions lead to reductions in natural gas use. Our coal technologies, as implemented in EPPA4, are assumed to have efficient combustion processes and therefore low CO emissions, so CO constraints do not lead to reductions in coal use though the CO constraints do lead to reductions in bio-oil. Because there is little reduction in coal and a decrease in zero carbon technologies such as bio-oil, CO constraints lead to very little reduction in actual CO_2 concentration. There is some amount of further detail in the model that is not shown in this chart involving switching between conventional coal and advanced pulverized coal technologies, or between conventional gas and NGCC. Note that in the zero elasticity and black carbon cases, a small quantity of power from coal is actually coming from IGCAP. In general, the BC constraint is too limiting on pulverized coal, and conventional coal and IGCAP both have insufficient BC emissions. This is unrealistic, but we do not have IGCC without capture currently implemented as a separate sector in the EPPA model.

	Bio-oil	Coal	Gas	Oil	Renewable	Nuclear	Total
Ref	379	657	149	425	91	36	1737
HighElas	341	514	163	397	96	36	1548
RefElas	309	341	178	305	100	37	1270
ZeroEals	203	257	137	267	102	37	1002
BC	366	481	204	422	96	36	1606
CO	276	613	146	389	90	36	1550
NOx	296	415	135	400	107	38	1620
SO_2	356	436	213	421	96	36	1557
VOC	330	596	129	316	88	36	1495

Table 3-2: Energy Demand in Quadrillion Btu by Energy Source for different control scenarios

Gases other than CO_2 are also impacted by air pollution control policies. Methane and N_2O emissions decrease by 11% and 8% respectively by 2100 in the reference elasticity case, compared to 30% for CO_2. This is because CO_2 emissions are much more tightly linked to activities that also have high pollutant emissions (coal use, transport), whereas the largest N_2O sources are in the agriculture sector and a large portion of methane emissions are also linked to agriculture as well as fairly clean natural gas use.

The temperature decreases resulting from the combination of GHG reductions and pollutant reductions are shown in Figure 3-12. Naturally, they are largest in the zero elasticity case, where CO_2 emissions are drastically reduced. For single pollutants, black carbon reductions have the largest impact, with a total reduction of 17% from reference. As we saw from the artificial constraint in the earlier modeling approach, there is a 10% reduction from black carbon alone, so the remaining 7% can likely be attributed mainly to reductions in carbon dioxide. Interestingly, the 6% temperature increase from capping SO_2 is nearly exactly balanced by compensating reductions of other gases: this is the flip side of the story where CO_2 emissions increases in the 50s and 60s from combustion were mostly masked by simultaneous SO_2 emissions before pollution policies were enacted.

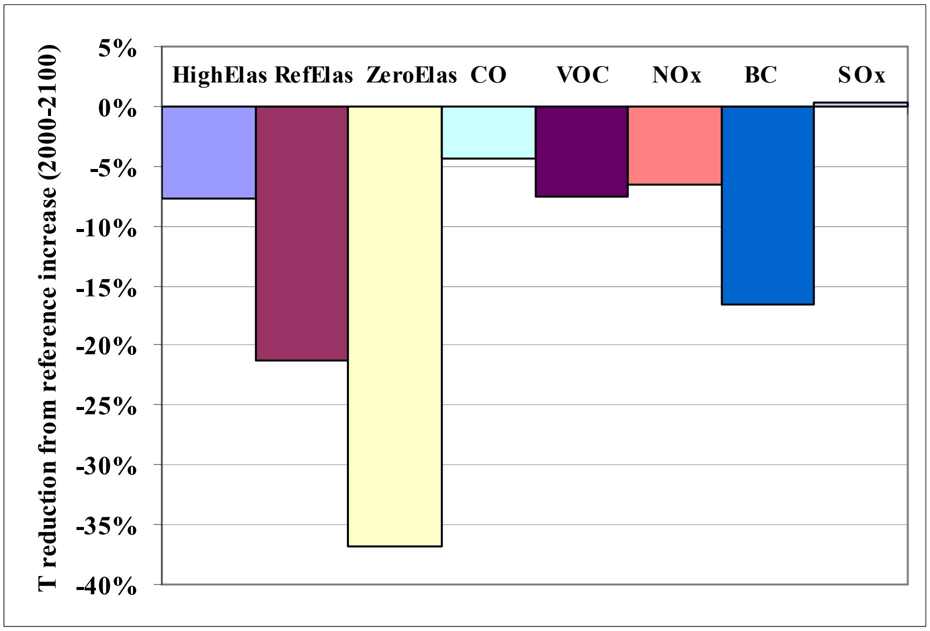

Figure 3-12: Percent temperature reduction resulting from air pollution constraints as a percent of reference temperature increase, including all GHG interactions

These constraints naturally have an impact on welfare (ignoring any climate or health benefits), as they force the economy to reallocate resources. Table 3-3 and Table 3-4 show the impact of pollutant constraints on net present consumption. Table 3-3 shows the different impacts of the three possible elasticities on both global net present consumption (NPC) and on NPC in Annex B versus non-Annex B nations. Table 3-4 shows the impacts of single pollutant control on NPC in the reference elasticity scenario. There are various caveats to keep in mind when examining the welfare results. First recall that in a CGE model “no-regret” options do not exist. Second, we do not include health valuations in this model. Also, the distribution of the constraints across regions is fairly unrealistic, as is the temporal allocation of reductions, wherein the costs do not follow a Hoteling path. Finally, though the high elasticity case has a fairly large elasticity, not all sectors have been given abatement potential; therefore there are limits in the model for adoption of efficient end-of-pipe abatement solutions.

However, the general magnitudes of the costs are still informative. A 1.2% global net present consumption loss is on the order of the cost of a 550 ppm CO_2-only stabilization policy (Sarofim et al., 2005). The temperature reduction of such a policy is about 21% below reference (not including additional ozone reduction effects on carbon uptake), which is not much less than the 27% below reference of the 550 ppm policy, and has much larger ancillary health benefits. We also see that the majority of the cost comes from VOC and CO constraints. The black carbon constraint, which leads to a 17% temperature decrease, has a cost of only 0.19% of net present consumption in our modeling system, which reinforces the Hansen and Jacobson conclusions (Hansen et al., 2000; Jacobson, 2002) that vigorous particulate matter policies would be extremely beneficial for climate. Of course, because we have implemented the emissions structure of the model to make pollution abatement independent between substances, this does not take into account the fact that black carbon abatement would likely be linked to simultaneous reflective aerosol abatement which might reduce this effect.

	Elasticities of Urban Control		
	Zero	Ref	High
Global NPC Loss	3.34%	1.17%	0.24%
Annex B NPC Loss	1.22%	0.36%	0.07%
Non-Annex B NPC Loss	9.26%	3.44%	0.72%
Global 2100 C Loss	11.6%	5.8%	1.8%

Table 3-3: Sensitivity of Welfare Cost to elasticity

	Allurb	BC	CO	NOx	SO_2	VOC
Global NPC Loss	1.17%	0.12%	0.55%	0.23%	0.10%	0.96%
Non-Annex B NPC Loss	3.44%	0.19%	2.17%	0.87%	0.42%	2.72%

Table 3-4: Sensitivity of Welfare Cost to Pollutant Controlled

3.3.4 Climate control impact on air pollution

Our second case to analyze is the impact of climate control scenarios on air pollution emissions. In the literature there are many cases where climate control policies are justified based on expected ancillary health benefits. These health benefits may, in some cases, be illusory. In cases where the air pollution policy is based on air quality standards or cap and trade measures, as in many industrialized nations, reductions in air pollution emissions due to climate mitigation efforts may result in countervailing emissions increases elsewhere in the economy. For example, imagine a hypothetical nation with an SO_2 cap and trade policy with a trading price of \$50/tonSO_2. This nation enters a climate regime, and the CO_2 constraints result in a coal fired power plant shutting down. This would nominally lead to a reduction of some tons of SO_2 emissions: however, the idle plant is now able to sell its unused emission permits to the rest of the economy. SO_2 emissions will therefore stay at the level of the counterfactual, but the permit price will decrease due to increased supply. If the permit price drops to zero, then, and only then, will climate policy lead to actual SO_2 reductions in this hypothetical example. Of course, it is possible that the effective reduction in cost of air pollution control due to complementarities between CO_2 reduction and air pollution reduction will enable localities to impose tighter air quality constraints. Also, in non-OECD countries there is some hope that climate projects from the OECD nations, through CDM or the GEF, might fund air quality projects that would otherwise have gone undeveloped.

CO	VOC	NOx	SO_2	BC
84%	80%	57%	42%	56%

Table 3-5: Reduction of Urban Gas emissions in CCSP 550 ppm policy (percent reduction of total emissions from 2005 to 2100)

In any case, in Table 3-5 we present the impact on air pollution emissions that results from implementing the 550 ppm CCSP scenario in EPPA4, as the policy was described in Chapter One (US Climate Change Science Program, 2006). This both addresses questions of ancillary benefits, and will aid in understanding the interactions between climate policy and air pollution policy in the following section. We can see that the integrated emissions over the policy period decrease significantly, especially in the cases of SO_2, BC, and NOx. In fact, in the SO_2 case emissions in 2100 are nearly equal to their 2005 levels, meaning that the CO_2 control scenario nearly meets the emission constraints set in the previous section.

3.3.5 Complementarity: The policy interaction between air pollution control and CO_2 mitigation

We have seen literature claiming that the air pollution reduction due to climate policy will lead to large health benefits, larger than the cost of the climate policy (Cifuentes et al., 2001b; Davis et al., 1997). But what climate policy has been enacted in a region without air pollution controls? The only way this might happen is for an international climate regime to invest in developing countries with little or no air pollution policy, but already countries like China and Mexico are instituting their own pollution policies, and even if they were not addressing their own pollution issues, our analysis of CDM shows that so far few registered projects have significant air pollution benefits (CDM Registry, 2006). The previous section does show the potential for significant reductions in pollutants, but this is a case in which air pollution constraints, which are nearly certain to exist, have not been included in the reference scenario.

We have also done an analysis showing that air pollution policy can have ancillary CO_2 reductions in the general case, though there are obviously local cases (Los Angeles) where it appears that the increased costs of transport and energy use due to pollution controls have certainly not halted GHG growth. Indeed, emissions per capita of greenhouse gases may actually be inversely correlated with local air quality standards because of the correlation between air quality standards and the wealth of a society. Perhaps a better measure to demonstrate the relationship between air quality standards and GHG emissions might be emissions intensity (CO_2 equivalents per unit of GDP) rather than emissions per capita, though there are likely various other confounding factors as well.

In this section, we examine the third possibility, namely that there are synergies between pollution prevention and CO_2 reductions. This synergy could take one of two forms: enabling tighter targets for the same cost, or reducing the cost of the initial targets. Therefore we did the modeling study of a combined CO_2 policy and pollution policy to show how the economic adjustments to the combined policy differ from the policies individually, in order to measure this synergistic reduction in cost.

For our sample policies we took the CCSP 550 ppm scenario from Chapter One and the previous section, and the air pollution policy that we examined for the ancillary GHG benefits (Chapter 1.4.2 and Chapter 3.3.3). The CCSP 550 scenario constrains CO_2 to be on a path to 550 ppm, but also constrains CH_4 and N_2O separately with no trading allowed, and the air pollution policy maintains all pollutants at their 2005 levels for the period of the simulation. The version of the model used with these policies was slightly modified from previous versions for computational reasons: the largest change was the removal of the carbon capture backstops (an unfortunate necessity). Our initial expectation is that the reduction in net present consumption in the CCSP policy scenario plus the reduction in NPC in the air pollution policy scenario should be greater than the reduction in NPC of the two constraints applied simultaneously.

And indeed, the net present consumption loss (using a 5% discount rate) from the CCSP policy is 2.58%, the NPC loss from the urban constraint is 2.90%, and the NPC loss from applying both policies is 3.34%. Now, a simplistic view would say that the efficiency gain from implementing the two policies simultaneously is 2.14% of net present consumption (2.58 + 2.9 – 3.34), or effectively a 65% surcharge for inefficient policymaking. However, this does not account for the fact that there is already some pollution abatement in the scenario with the CCSP policy, and similarly, some GHG abatement in the urban policy case. This would serve make the efficiency gains look much larger than they actually are. In order to compensate for this double counting, we would want to know the cost of achieving the pollution abatement resulting from the CCSP scenario in the absence of any actual GHG policy. Conversely, we also want to calculate the cost of achieving the GHG abatement in the pollution scenario in the absence of a pollution policy. This comparison can be stated in the form of a mathematical equation:

> Cost of inefficient policymaking = Cost(550ppm policy + no air pollution reduction) + Cost(no GHG reduction+ air pollution policy) – Cost(550ppm policy+ air pollution policy).

However, we can not determine the cost of a 550 ppm CO_2 policy with no air pollution reduction directly, because of the ancillary pollution reduction that results from the GHG constraint. We can estimate the policy cost, however, as the following equation:

> Cost(550ppm policy + no air pollution reduction) = Cost(550ppm policy + ancillary air pollution reduction) – Cost(no GHG reduction + ancillary air pollution reduction).

We can calculate the cost of a 550 ppm policy and its ancillary air pollution reductions directly merely by imposing the CCSP constraint and calculating the NPC. We cannot, however, calculate the cost of the ancillary air pollution reduction without additional GHG reductions, for the same reason that we could not calculate the cost of a normal air pollution policy without ancillary GHG reductions. However, we can calculate the costs as follows:

> Cost (no GHG reduction + ancillary air pollution reduction) = Cost((ancillary GHG reduction from the ancillary air pollution reduction) + ancillary air pollution reduction) – Cost((ancillary GHG reduction from ancillary air pollution reduction) + no air pollution reduction)

using the same methodology as above. Fortunately, these additional GHG reductions will be much smaller than the GHG reductions from original CCSP 550 ppm constraint, so enough iterations of this methodology should approach the right answer. We have demonstrated this methodology in Appendix H in a simple system, wherein we elucidate the rationale for this approach as well as demonstrate its accuracy.

In order to estimate these costs, we generate two new scenarios. For Scenario 1, “urban from CCSP” or “ufc”, we use the urban emissions from the CCSP runs as the constraint for a new run. Scenario 2, “ghg from urban” or “gfu” uses the GHG emissions from the pollution runs as a constraint. The “ufc” scenario still results in a 0.87% loss of net present consumption, or a third of the cost of the CCSP scenario overall. Similarly, the “gfu” scenario results in a 1.2% loss of NPC, or 40% of the cost of the pollution constraint. If we apply these adjustments to our earlier calculations, then the cost of the CCSP constraint minus the urban benefit is 1.71%, and the cost of the urban constraint minus the

GHG benefit is 1.7%. The total is 3.41%, or only 0.07% more than the two constraints applied simultaneously.

However, this does not yet resolve the problem. We are now underestimating the efficiency gains, for the same reason that we were previously overestimating them. The "gfu" and "ufc" scenarios both have their own ancillary impacts. We can run another iteration, a "ufgfu" and "gfufc" calculation, yielding 0.34% and 0.4% reductions of NPC respectively, and leading to a 4.15% total loss (CCSP – ufc + gfufc + URB – gfu + ufgfu). Of course, this iteration can be carried on ad infinitum. If we assume that every urban constraint taken from a GHG constraint leads to scenario with 30% of the NPC loss of the original scenario, and every GHG constraint taken from a urban constraint leads to a scenario with 46% of the loss, then we can extrapolate and estimate that the NPC loss actual GHG policy (minus the cost needed to achieve any urban gas reductions) is 2.03% and the loss from the urban policy is 1.92% as shown in Table 3-6. We can perhaps state therefore that 21% of the cost of a 550 ppm policy, and 34% of the cost of a similarly strict urban air pollution policy, is balanced by reductions in the other arena. Note that this not a statement about actual benefits, which would require valuing either health effects or climate impacts: this is balancing the cost of air pollution reduction with the cost it would take to achieve the ancillary ghg reduction, or vice versa.

	Net Present Consumption Loss	Modified NPC Loss
CCSP 550 ppm	2.58%	2.03%
Urban constraint	2.90%	1.92%
Simultaneous policies	3.34%	

Table 3-6: Net present consumption loss from the CCSP policy, the air pollution constraint policy, and both policies enacted simultaneously.
"Modified" loss refers to the loss after taking into account interaction effects between air pollution constraints and GHG constraints.

Therefore, the total NPC loss from the two policies enacted separately would be 3.95%. This cost is 0.61% of net present consumption higher than that of the two policies implemented simultaneously, which is $6.4 trillion of net present value. Implementing the policies in a way that does not allow for coordination would effectively lead to an 18% surcharge. Additional calculations show that this surcharge is fairly constant in any given time period in this calculation, plus or minus a couple percent.

We can examine how the 3 different policies impact energy demand in a different fashion. Table 3-7 shows the average demand in each sector over the period of the policy. The most obvious difference is the reliance on bio-oil for reducing CO_2 emissions, but the avoidance of bio-oil in the urban constraint case. This is a fairly obvious response to a technology which is carbon free but polluting. In addition to shifting away from bio-oil, adding an urban policy to a CO_2 policy also leads to shifting even further away from coal, which is a rather dirty technology, and compensating with small increases in gas, oil, and renewables. Again, this version of the model does not include CO_2 sequestration, which might otherwise give IGCC plants with capture an advantage over other technologies.

	Bio-oil	Coal	Gas	Oil	Renewable	Nuclear	Total
Ref	150	328	172	328	64	31	1073
CCSP 550	306	89	96	165	72	30	757
Urban	119	135	131	247	79	31	741
CCSP+Urban	221	75	102	176	78	31	682

Table 3-7: Average energy demand in quadrillion Btu from 2005 to 2100 by energy source

Table 3-8 shows the results of modeling these emissions scenarios in the earth systems component of the IGSM. This table shows that an urban constraint in and of itself leads to a 30% decrease in temperature. In our modeling of direct impacts compared to total impacts, about a quarter of the temperature reduction was due to direct impacts of air pollution reduction and three quarters was due to ancillary greenhouse gas reductions, and presumably this scenario has a similar breakdown (though a slightly larger temperature reduction due to the use of a slightly different model). However, the addition of the urban constraint to a fairly stringent greenhouse gas constraint only reduces temperature increases by a small amount. This occurs because there are no ancillary GHG reduction benefits because those emissions were already constrained, and in addition, as we showed in the previous section, the CCSP scenario by itself had already led to significant pollutant reductions. Therefore there are only small further decreases of black carbon reductions from the CCSP scenario by itself to the combination of a CCSP scenario coupled with the air pollution constraint.

	Ref	CCSP-550	Urb-Const	CCSP+Urb
2100 T (°C)	3.6	1.5	2.5	1.3

Table 3-8: Temperature increase from 2000 to 2100 in four scenarios

3.3.6 GHG and Air Pollution Policy Interactions: The case of GWP Trading

Another interesting way of looking at the interactions of GHG and air pollution policies is to consider the case of GWP trading. A priori, we expect CO_2 emission reductions and air pollution reductions to be complementary, but we expect that methane and N_2O reductions will have fewer interactions with air pollution policies because they are emitted in sectors that are not as polluting, and because methane and N_2O both have elasticities of subsitution within sectors to represent types of control options that do not exist for CO_2. Therefore if we run a CCSP scenario with GWP trading and no air pollution policy, intergas trading will lead to an optimal mix of CO_2, CH_4, and N_2O according to their GWP values. However, if we add an air pollution constraint to this scenario, the complementarities between air pollution constraints and CO_2 constraints will effectively reduce the cost of mitigating an additional ton of CO_2. Therefore, we would expect that additional CO_2 emissions would be abated, and the other GHG emissions would grow in response. And indeed, there is a 1.9% decrease of total CO_2 emissions over the century in the urban constraint case compared to the straight CCSP scenario, balanced by increases in CH_4 emissions of 6.9%, in N_2O emissions of 2.3%, and HFC emissions of 29%.

This adds an extra note to our methane analysis from Chapter Two. The result showing that a world with GWP trading will abate more CO_2 emissions in response to air pollution constraints does not detract from our contention that methane should be addressed separately from CO_2. However, when policymakers weigh methane reductions compared to CO_2 reductions, the realization that CO_2 constraints leads to ancillary air pollution benefits should encourage tighter CO_2 caps compared to caps of other gases (or increasing the GWP value of CO_2). This is in slight opposition to the various results in the previous chapter which had all indicated that methane was significantly undervalued by its current GWP estimation.

We have shown that there is an interaction effect between air pollution policy and GHG policies of 18% of the policy cost. What does this mean for actual policy coordination? On the one hand, policymakers could search for abatement options that reduce CO_2 and air pollutants simultaneously, and create legislation appropriately.

However, this not only creates a lot of administrative overhead, and requires picking "winners" which is a historically difficult task, but it would also open up opportunities for system abuse. On the other hand, there may be no need for an explicit policy creating incentives for solutions that abate multiple gases at the same time, but rather these efficiency benefits can be gained as long as the two policies are sufficiently flexible. If policies create a price for air pollutant emissions and for greenhouse gas emissions, then economic theory suggests that the market will arrive at an efficient solution – in much the same way as the EPPA model arrives at an efficient solution given a constraint on both kinds of emissions. Taxes or cap and trade policies would both achieve this purpose of creating prices. On the other hand, policies which mandate specific solutions to address only one issue at a time (eg catalytic converters, forest regrowth) will, if poorly designed, miss out on these coordination benefits. And constraining air pollution without a climate constraint or vice versa will naturally also lead to less adoption of these coordinated solutions.

3.4 Political Analysis of Air Pollution Policies and Climate

3.4.1 Motivation for Political and Geographic Analysis

There are many uncertainties involved in linking air pollution policy and climate impacts. Our computational analysis shows that there is significant potential for climate benefits resulting from pollution reduction, especially black carbon. We can perhaps conclude that the direct climate benefits of NOx and VOC reductions will be small, though the complexity of the ozone cycle and the contribution of these substances to aerosol chemistry both make it hard to state even this simple result with confidence. We also see that temperature increases resulting from global SO_2 reductions would be compensated in large part through balancing CO_2 reductions. Black carbon has more potential for direct temperature reduction, according to our modeling, but there is significant uncertainty involved in determining the forcing.

In our modeling analysis, we have not evaluated actual health impacts nor investigated uncertainty in a methodical fashion. And there are limits to disaggregation within EPPA. Diesel and gasoline are not modeled separately, and even if they were, within diesel we have potential differences between high-sulfur and low-sulfur diesel. Similarly, within coal there exist differences between high and low sulfur (O'Connor, 2000) – though these details, at least, are partially captured by the elasticities derived from the RAINS data. And when multiple pollutants co-vary we have problems in modeling them without the inclusion of separate sectors. Another critique of our reference scenario is that pollutant emission projections may be higher than realistic. A more realistic projection might have BAU emissions remain roughly constant over the century, as developed world technology diffuses into the non-Annex B nations even as their production continues to grow. In this case, we could then compare the "constant pollution" counterfactual to a policy reducing emissions below reference, and believe that it might not be too dissimilar from our modeling study.

However, one of the major reasons that estimates of complementarities and ancillary benefits vary so widely is regional heterogeneity. Source types, current pollution policies, and air basin characteristics all vary from city to city. This heterogeneity has significant implications for policy creation. We can examine diverse locations such as Mexico City, Beijing, and LA to see how the assumptions of homogeneity made in our modeling study breaks down. The dirtiness of local industry and sectoral balance, the inclusion of power generation close enough to impact air quality in major metropolitan areas, vehicle mix, local air pollution policies, and even the local geography are all vital to actually designing appropriate policies. In one location ozone abatement could be best served through NOx reduction, and in another through VOC reduction. This makes air pollution policy a very local issue in a way that GHG control is not. This was part of the reasoning behind examining air pollution policy: e.g., use local benefits to give incentives to implement policies with global implications, but this also creates problems when attempting to design scenarios that explore the implications of a globally coherent set of air pollution policies.

3.4.2 Analysis of Mexico City

Mexico City is one of the largest metropolitan areas in the world, and has historically been one of the most polluted, both because of its size and the fact that it is situated in a mountainous bowl which serves to trap pollution effectively. Mexico City's pollution issues are a result mainly of vehicular traffic, especially diesel freight and the taxi system. The power generation for the city mainly takes place outside the mountainous bowl of the city, limiting the impact of pollution from power on health. More than half of Mexico City's GHG emissions come from this consumption of electricity from outside the valley, which severely limits the opportunities for co-benefits. Of the GHGs generated inside the valley, more than 50% come from transport, 20% from industrial sources, 15% from residential sources, 8% from electricity produced within the city, and a couple percent from aviation. Given that transport is responsible for a large fraction of both the GHG emissions and the pollutant emissions, there seems to be an opportunity for co-benefits here, and in fact linear programming studies by West et al. (2004) show that the 3% reduction in CO_2 emissions resulting from PROAIRE measures in process of implementation for air pollution issues are mainly from transport related measures. The transport measures with good cobenefit potential are vehicle turnover programs, expansion of the metro and the new rapid bus transit system. Of course, if rather than being replaced with new vehicles, the 50% of the Mexico City automobile fleet that still lack catalytic converters are instead retrofitted, their miles per gallon rating would actually decrease. Similarly, switching from diesel to gasoline to meet standards would also likely increase CO_2 emissions. Meanwhile, the major GHG reduction policies involve cogeneration, forest management, renewables such as wind and hydro, efficient lighting subsidies, and various agricultural management programs, none of which serve to reduce pollution within the MCMA.

In addition to the lack of power generation within the valley, one issue is that Mexico City has already implemented a large number of air pollution policies, thereby eliminating a lot of the low hanging fruit. The closing of the "18 de Marzo" oil refinery led to large drops in SO_2 emissions, fuel oil has been switched over to natural gas in many areas, other programs have significantly reduced the upper bound of NOx concentrations and kept the average concentration constant over the past decade, and ozone, CO, and particulates are all below their 1986 levels (Molina and Molina, 2002). According to one World Bank study, Mexico City has dropped from being widely considered one of the most polluted cities in the world in the 1980s to being 87th on the list of cities larger than 2 million people with the highest particulate matter concentrations by 2000 (Pandey et al., 2006).

Therefore, when West et al. ran their linear programming model for Mexico City they estimated that for Mexico City benefits from "integrated planning of urban-global co-control" were small (West et al., 2004). One issue that has not been treated is whether there are health benefits from reduction of pollution outside the MCMA. It is hoped that CDM will play a role in projects with ancillary benefits, but it seems from our analysis that there are few good opportunities in Mexico. And indeed, of Mexican CDM projects, the vast majority (by number) are wastewater management systems for methane capture, though a HFC treatment project had a similar magnitude of reductions in GWP weighted emissions. The remaining 20% of CDM credits are divided between landfill gas capture and renewables projects (hydro and wind). None of these projects will lead to much, if any, local air pollution reduction, and the wastewater projects do not seem to involving any actual treatment beyond methane flaring. Two plant retrofitting projects for sugar cane processing were actually rejected by the CDM commission. The reasoning was that barriers to implementation were not demonstrated. While these specific projects would not have yielded urban clean air benefits, being located in rural regions, they are similar to the kind of industrial upgrade project that might actually have some benefits in urban areas.

Politically, Mexico is a signatory of the Kyoto Protocol and a member of the Clean Air Initiative for Latin American Cities (CAI-LAC), but practically there is little political will to make significant climate policy happen. Even pollution abatement within Mexico City appears to be slowing down as the populace feels that the worst excesses have been solved and the remaining sources are more difficult to deal with. There will be continuing improvements in vehicle technology, but it is difficult to institute good maintenance practices. Also, given that there has already been a recent round of vehicle buybacks and upgrades for the microbuses, it is difficult to convince the drivers to cooperate with further such shifts. Therefore many of the efforts of Mexican environmental agencies have been to improve inventories, educate the public in order to build up more support, and coordinate available CDM and GEF funding with private industry where projects are available.

Interestingly, while much of the funding comes from EPA, a significant fraction of that was channeled through the Western Governors association because it was harder to work directly at the federal level (Instituto Nacional de Ecologia (INE), 2005).

3.4.3 Analysis of China

The mega-polluted cities of China are different in many ways from Mexico City. The first major difference is that much of the pollution has coal-based emission sources: coking, combustion, etc. Transport is also a rapidly growing source. China has many of the world's most polluted cities, according to the World Bank (Pandey et al., 2006)[12], and is therefore an obvious target for studying possible climate gains from air pollution policies.

Whereas in Mexico City a couple of percent CO_2 reduction is the best that can be gained from air pollution control measures, in China where many basic efficiency improvement measures remain untapped, there are many more opportunities for co-benefits measures with significant benefits. The Aunan et al study (2004) identified 3 different measures in Shanxi which would each independently reduce more than 10 million tons of CO_2, 30000 tons of particulates, and 100 thousand tons of SO_2. The issue is that these opportunities are the type of basic upgrades to equipment and improved techniques that are hard to sell as climate measures for outside funding because they would be expected to happen gradually over time in any case, much like the rejected Mexican projects. The fact that these upgrades might actually pay for themselves makes it even more difficult to qualify for funding. However, the plain fact is that there are sizeable numbers of these upgrades that have not happened, and additional funding would almost certainly speed up the process.

China expects 37 million CERs, the most of any participating nation (41% of total expected CERs). However, of its currently registered projects, 34.7 million are HFC decomposition related, with no co-benefits potential. Not only do these HFC reductions

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[12] I note here that many sources, including the Economist, the BBC, and Congressional Testimony, cite a World Bank study to back up the claim that 16 out of 20 of the world's most polluted cities are in China. In fact, the database that these respected sources cite is only a "selected" list of those cities: on the full list China has only 3 of the most polluted cities (by PM10 concentration) of greater than a million population.

lack co-benefits, but they may even have the perverse incentive of encouraging HCFC-22 production which produces HFC-23 as a byproduct, and even the choice of HCFC-22 production methods which will generate more HFC-23 (Bradsher, 2006; Hoffman, 2006; McCulloch, 2004; Schwank, 2004). Of the remainder of China's CERs, 461 thousand come from small hydro projects, 1224 thousand CERs come from wind projects, 608 thousand from landfill gas, and 106 thousand from a waste heat to power project (CDM Registry, 2006). All of these projects at least have the potential to displace coal power, though given China's voracious growth it seems likely they will only serve to displace some percentage smaller than 100% of their energy production. Note again that the registered projects are for the most part easily quantifiable and defendable in terms of CDM additionality. CDM, in its current form, is also not very appropriate for funding the construction of new, efficient capital projects. Carbon credits might be the difference between building a new efficient boiler and a new inefficient boiler, but if it can be difficult to show that retrofits are additional, it would be nearly impossible to be able to claim new boilers under current CDM rules. And in general, in the rapidly growing developing nations, the key point may not be the improvement of old facilities but rather constructing new facilities to be efficient. But in that case, incentives for modern methods will serve as incentives to actually increase emissions. The question is whether or not that increase would be more or less than the counterfactual. Though here, given that the subsidies would likely serve to increase local human welfare, there may be reason to err on the side of laxity rather than tight rules.

3.4.4 Analysis of Los Angeles

Finally, it is useful to address one of the more polluted cities in a highly developed country. Los Angeles continues to rank as having the worst air quality in the US by some measures (American Lung Association, 2005), despite being the testbed for new air pollution policies through CARB and the increased pollution levels of various cities in Texas and the southwest. Other measures (US Environmental Protection Agency, 2005) actually list Phoenix as having the worst PM levels in the country, but Los Angeles still ranks high and has the worst ozone levels in this database. Pollution in Los Angeles is also mainly vehicular, but here we have a very modern gasoline based fleet, mainly for passenger travel. After a fairly successful campaign to reduce pollution between the 1970s and the 1990s, pollution levels have stabilized recently as increasing popularity of SUVs and continued increase in vehicle miles traveled balanced improvements in catalytic converters and engine technology. This is true for both ozone and PM10 trends (California Air Resources Board, 2006).

Los Angeles also serves as a good example of the fact that high CO_2 emissions and low or moderate pollution emissions are quite compatible possibilities: major advances in pollution control for NOx, SO_2, particulate, and CO emissions occurred, without concurrent sizeable GHG decreases. There was, however, significant complementarity between reductions of different pollutants, where ozone reduction did lead to particulate reduction. And indeed, there have been efficiency improvements and decreases in open burning both of which may reduce some CO_2 emissions. In the transport sector in the US, emissions of hydrocarbons, CO, and NOx have all been reduced by a factor of 15 or more since 1973 (or a factor of more than 30 since pre-1968), with the last 50% occurring during the last decade with the Tier I to Tier II standard shift (Faiz et al., 1996). However, the fuel economy of the fleet increased by only 60% from 1975 to 1987, and has actually decreased since (US Environmental Protection Agency, 2006a). Actual vehicle miles traveled has, of course, increased dramatically over this time, leading to an increase in actual GHG emissions from the transport sector. California has even more stringent LEV and ULEV standards than Tier II, and is in the process of trying to implement CO_2 emission standards, but this last is in a potential conflict with federal prerogative to set fuel economy standards.

3.4.5 US State and Regional Policies

As in Mexico City, much of the power for Los Angeles comes from outside the air basin: coal plants in Utah and hydro from the northwest send a lot of their power into California. The state is currently implementing guidelines that will lead to demand for cleaner power, but that is not related to air pollution. Again, the state's requirement for more efficient transport may reduce air pollution slightly, but unless there is a shift towards electric vehicles (which seems highly unlikely) the incremental pollution benefit from efficiency improvements will be very small compared to continued end-of-pipe measures. And electric vehicles are only a solution to GHG emissions if the electricity comes from carbon free sources. However, if California does manage to institute a policy which leads to a CO_2 price (whether cap based, tax based, or credit/subsidy based), it will allow agents within the state to determine their own optimal co-benefit methodologies rather than requiring an outside agency to analyze them. Achieving such an optimal result from price based mechanisms presumes that good monitoring systems exist, which is a reasonable assumption for a state like California.

New England is the other major US region with a climate initiative, and there we see transport account for 37% of CO_2 emissions and electricity production another 28%. Interestingly, the Connecticut Climate Action plan recognizes black carbon as part of its GHG emission baseline, and expects black carbon reductions to meet 10% of the 2020 goal of the program. The Transport Working Group used Jacobson's work to assign black carbon a value of 220 to 500 CO_2 equivalents, if it is assumed that black carbon and organic carbon are emitted in a one to one ratio. Much of the proposed control comes from switch to ultra-low sulfur diesel fuel and upgrading diesel vehicles to include particulate traps. While other pollutants are not included in the GHG accounting, impacts on health through ancillary benefits are certainly used as partial compensation for GHG reductions. Many cities have implemented small scale climate projects, some in coordination with ICLEI's Cities for Climate Protection campaign, and presumably many of these local area programs take air pollution reduction goals into account. STAPPA and ALAPCO (State and Territorial Air Pollution Program Administration and Association of Local Air Pollution Control Officials) also released a report on "harmonized options" for reducing GHGs and air pollution, but their major recommendations all centered on shifts towards gas combined cycle power plants, with limited possibilities found in efficiency and demand side management measures, improved urban design and transport management, and similar programs. Nor were there clear recommendations on how to implement these measures outside of market mechanisms such as mandatory cap and trade constraints or GHG reduction subsidies.

3.4.6 International Cooperation

On an international level in the United States, we can see parallels between the formulation of M2M and the new Asia-Pacific Partnership on Clean Development and Climate which was inaugurated in January of 2006. The Bush administration proposed $52 million in funding. In the Whitehouse fact sheet (Office of the Press Secretary, 2005) the administration states that the Asia-Pacific Partnership builds on M2M as well as Carbon Sequestration and Hydrogen Economy initiatives. Similar to M2M, it seems its goal is to encourage private industry to engage in technology transfer to developing nations in order to implement clean technologies especially in the industrial area. Again, while the goal is worthwhile, the lack of actual funding and binding constraints makes it difficult to believe that there will be significant results from this initiative.

Involvement of air pollution control in future climate policies can occur in one of three environments. The first is a regime where GHGs are controlled, but air pollutants are not. The second is a regime where air pollution is controlled, but GHGs are not. And the third is a regime where both air pollutants and GHGs are limited by policy. In the first regime, air pollution abatement is an ancillary benefit to GHG control. If the ancillary health benefits and climate benefits from black carbon control are not taken into account, then the GHG policy will not be optimally strict. Moreover, the partitioning of the GHG policy into different gases, or the use of trading, will not properly weight the various gases. In this case, CO_2 reductions would be more desirable, on average, than otherwise expected. Of course, even within the realm CO_2 reductions, there might be a theoretical benefit from steering those reductions towards those solutions with the greatest co-benefits. However, given that any nation which is likely to take on GHG targets is virtually certain to already have implemented air pollution controls, this policy environment is unlikely to be represented in reality.

The second regime, that of air pollution control without GHG control, can be expected to apply to most developing nations, as well as those portions of the United States which are not implementing local GHG control measures. Here we have the opposite story from the above, with a difference. The ancillary benefits of pollution control apply towards a global commons and not the local good. Therefore, we expect to see co-benefits happen under two circumstances. The first is with subsidies from outside – CDM, GEF, etc. The second is where a country expects to join a climate regime, and the accession details are such that they encourage early action rather than perversely given incentives to increase GHG emissions baselines before joining.

In 2005, non-Annex B nations contribute nearly three times as much black carbon emissions as Annex B nations, and over the century our modeling runs project that their emissions will increase more than 6 times as much as Annex B emissions increase. While the magnitudes of the future increases may be uncertain, the fact is that there will be much more potential for BC reductions beyond the counterfactual in non-Annex B nations than in Annex B nations. As in the case of methane, non-Annex B nations are unlikely to take on significant constraints without international aid. Again, the question comes as to how to give this aid. GEF deducts some domestic ancillary benefits from grants for GHG control, but not "all" ancillary benefits (Pearce, 2000). This "frees up" moneys for more grants, but requires resources for analysis, introduces further uncertainty into the grant request process, and reduces incentives to seek out such dual-benefit policies. We have discussed CDM in the context of Mexico and China. The CDM already has over 1,200 projects in the pipeline and an overall emission reduction potential of about 1.4 billion tonnes by 2012. But additionality is not the only problem with CDM. Those projects that most clearly require CDM funding, and therefore can provide additionality, are also those that will most depend on continuous monetary flow for credits. This runs into problems both with the possibility that CDM will be discontinued post 2012, and the uncertainty in future carbon prices due to hot air and possible future accession of new nations. One must also consider the other side of additionality, the "additionality" of funding to normal development assistance. Developing nations continue to worry that increased contributions to GHG reductions will come at the cost of decreased economic aid. Given the magnitude of health costs in developing countries compared to global climate benefits from the reduction of these substances, perhaps the OECD should be stepping in to help reduce local air pollution on purely humanitarian grounds, and any climate benefits could be purely a side benefit.

There may also exist, in a few cases, potential for transboundary air pollution to play a role. Japanese investment in China (Evans, 1999) or US investment in Mexico could follow parallels to Nordic investment in Baltic States and the push towards a Convention on Long-Range Transboundary Pollution in Europe (Wettestad, 2002). The advantage here for Japan, at least, is that it gains both the local benefit of air pollution reductions and the CERs for Kyoto purposes. We will ignore for now the worry that foreign acquisition of CERs from developing country projects will make it more difficult for those nations when they take on GHG targets in the future.

The third possible environment is one where there exists both a climate policy and an air pollution regime: the Annex B Kyoto signatories all fall into this category, as will California and New England should their climate policies move forward. If the climate and pollution policies are both based on economic instruments which create prices for the substances in question (whether tax or cap and trade), then we can hope that independent agents will find optimal solutions without the need for significant top-level policy. Funding for research to find these solutions and then disseminate them will still be useful, but that is not as difficult a problem as how to devise the actual control policies in the first case. Note that when an air pollution cap exists, such as the SO_2 cap and trade policy, implementation of a new climate policy is unlikely to lead to further reductions in SO_2 emissions – there will likely be economic synergies, but as soon as SO_2 emissions are reduced in one sector due to a CO_2 policy, it is likely that emissions will rise in another sector due to the nature of cap and trade. At least until the CO_2 policy becomes so tight that the SO_2 cap is no longer binding. In the case where one of the policies is measure based (such as a hypothetical SO_2 policy that required scrubbers), then there would be few economic synergies from a new CO_2 policy, but environmental synergies might be created. One issue is that most of the economic instruments used in air pollution policies apply to large stationary sources: ideally smaller sources would also be dealt with in a way that could take advantage of complementarities. Fortunately, EPA standards for passenger cars and trucks are based on emissions per mile driven rather than emissions per gallon, which should complement CO_2 policies nicely should they ever be applied to the transport sector.

There are other issues in policy design as well. How much should black carbon reduction be rewarded (as in the Connecticut plan)? Like methane, there is significant uncertainty in emission estimates, but here there are additional uncertainties of impact. If it is included in a broad GHG target, what happens when future research rescales the GWP factor for the substance? In addition, should the impact of black carbon be discounted for international aid purposes because it has a much more regional impact than the well-mixed gases? How do we take advantage of so-called "green gold" solutions if they exist, where the win-win-win scenario of economic, health, and climate benefits from reducing energy use does not require a reduction in consumption?

3.5 Conclusions

In the chapter on methane we showed the potential disadvantages involved in climate policies that allowed trading between methane and CO_2 using GWP weightings. There are few serious proposals to use GWP weightings for air pollution policy: rather, there are significant benefits to be captured by allowing coordination between air pollution policy and climate policy. However, quantifying these benefits is a difficult problem because of the complexities of both the economics and the atmospheric chemistry involved. In this chapter we applied state of the art modeling tools to this problem, as well as political analysis to address issues that the models are still not able to resolve.

We first showed that the direct impacts of air pollution reductions on temperature change are fairly small. Policies that reduce ozone precursors tend to lead to increases in methane concentrations that almost exactly cancel out any temperature effects, though there is still some climate related value in terms of increased ecosystem uptake due to less ozone damage. Black carbon reductions lead to temperature reductions in our model, but black carbon impacts are still uncertain, we do not model organic carbon yet, and in any case, SO_2 reductions cancel out much of the black carbon effects. If we include all possible effects with a fairly significant reduction in emissions, we see an 8% reduction in the total temperature rise expected for the century.

However, much of the impetus for studying air pollution in a climate context is due to interactions between air pollution reductions and climate policy reductions – ancillary benefits or complementarities. In order to model these interactions, we introduced the capability to model air pollution constraints within the MIT EPPA model, basing our elasticities of substitution on empirical data. This enables a CGE model to capture end-of-pipe and other abatement techniques that are normally only accessible to bottom-up models, while continuing to have the capability to model economic shifts at the sectoral and demand levels in an equilibrium context. Using the new modeling system we show that an air pollution policy that costs a little more than 1% of net present consumption can lead to a decrease of 160 ppm in CO_2 in 2100 and almost 25% reduction in temperature rise over that same period. This indicates that there are indeed significant global climate advantages to encouraging stronger air pollution policy even in the absence of any direct incentives to reduce greenhouse gases.

This relation works in both directions, and we show that implementation of a 550 ppm scenario from the CCSP exercise leads to significant reductions in air pollutant emissions. However, this is misleading in that in actuality most climate policies will be enacted in regions that already have air quality standards, and therefore the GHG constraint will merely lead to a rebalancing of pollutant emissions rather than an absolute reduction. This does lead to the question of what the benefits are from implementing GHG reduction policies and air pollution emission constraints in a coordinated fashion. We use a novel approach to show that there is a 20% welfare penalty that results if the air pollution and climate policies have no flexibility that allows for coordination. This coordination can come from a command and control perspective of choosing measures with dual benefits, or from using market based mechanisms that allow individual economic agents to optimize their own behavior to meet simultaneous constraints.

Because of the existence of significant climate benefits that can result from air pollution policies we recommend that the OECD nations fund pollution reduction products in the developing world even in the absence of provable climate benefits. Concurrently, measures such as CDM should relax their additionality constraints when there are significant local air pollution benefits, otherwise there is a danger that the projects with the best potential for simultaneous abatement will go unimplemented. Within OECD nations that have both tight air quality standards and climate goals, we recommend that the policies are designed in such a way that they allow coordination in order to gain the benefits of complementarities.

4 Conclusions

Sound climate change policy making requires managing a complex, global integrated system composed of anthropogenic emissions, atmospheric chemistry, a number of different greenhouse substances, natural systems, uncertainties, technologies, and politics. Both the tools used to study the system and the policy recommendations that result from the analysis need to take into account this complexity. It is not obvious a priori how to properly balance two key issues: first, the advantages of a single, global, integrated policy which allows for economically beneficial “what, where, and when” flexibilities as well as a certain once and for all simplicity, and second, the fact that the complexities of the problem are not necessarily well served by a one-size fits all approach, and there are advantages to be gained from tailoring policies to individual regions and substances. In this thesis we used an integrated global modeling system to examine this balance between integrated and disparate policies as they relate to different climatically important substances. We showed how certain key characteristics of a gas like methane led to the conclusion that it should be treated separately from the other major GHGs. Conversely, we demonstrated the advantages of ensuring that coordination is possible between air pollution reductions and greenhouse gas reductions, even though air pollution policies will differ significantly on a regional level. We concluded that there are benefits to be gained from compartmentalization on the one hand, and from coordination on the other, and we showed this through application of novel modeling and other analysis methods.

In Chapter One we examined stabilization under Article 2 of the UNFCCC, which could be considered to be the cornerstone of the climate policy development. The Kyoto Protocol, the currently operative centerpiece of the UNFCCC, uses a GWP based trading mechanism to allow exchanges between the six primary greenhouse gases or gas groups. While CO_2 is the most important of the greenhouse gases, we showed how the emphasis on CO_2 has led to an under appreciation of other gases that can yield low cost yet significant reductions on the century timescale. We also showed the inherent disconnect between the concept of stabilization and the mechanism of gas emission trading. This analysis led us to concentrate on exactly how these other gases should be included in greenhouse policy.

The primary non-CO_2 gas of interest is methane, because it has the greatest contributions to past and probably future forcing, and because methane has significantly different properties than carbon dioxide both in terms of emission sources and atmospheric characteristics such as lifetime for removal. We propose that methane should no longer be traded with CO_2 on a GWP basis for four major reasons. While any one of these four might be a cause for concern in and of itself, perhaps to be solved by an adjustment to the GWP number or other similar correction, the sum of all four leads us to conclude that continuing to include methane in the standard GHG trading basket is not wise. The first and perhaps the most important reason is the difficulty in estimating anthropogenic methane source inventories compared to the relative ease of estimating CO_2 emissions from fossil sources, leading to possibilities for "creative accounting" in trading, errors in emissions estimates, or having national constraints depend on changes in inventory methodology.[13] We have additionally used modeling to show that methane policies alone can easily lead to a reduction of more than 15% of the expected temperature rise in the 21st century, and this temperature reduction is greatly decreased by allowing trading with CO_2. Therefore we believe that methane is significantly undervalued by its GWP, due in part to lifetime and ozone effects. Third, modeling also demonstrates that interaction effects with underlying taxes means that the welfare impact of reducing a ton of carbon dioxide at a given price will be greater than the welfare impact of reducing a carbon equivalent ton of methane at the same price. Finally, political analysis leads us to believe that methane policy can advance faster, and include more nations, without the millstone that is current international CO_2 policy. By addressing methane with a separate policy, significant temperature abatement can be realized in the near future.

Again, it must be stressed that the recommendation to address methane using a policy separate from a CO_2 policy should not be used as an excuse to delay CO_2 policy implementation. But the two gases are best suited to different strategies and policy tools. CO_2 abatement will eventually require significant capital investment and long term research and development of zero carbon technologies. Near term CO_2 abatement is also well suited to market signals through cap and trade or tax instruments. Most methane

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[13] Of course, emissions and sinks of CO_2 from land-use change do share this quantification difficulty with methane.

abatement, on the other hand, can be achieved through low cost measures already available. Difficulties in monitoring and verification of methane reduction may mean that methane control is best achieved through non-market instruments: policies and measures, best practices, and information transfers. Non-fossil CO_2 should also be addressed separately: a coherent land-use change policy is necessary but may also be better managed through non-market mechanisms.

In a contrasting case, we examine air pollution, which is currently controlled almost completely separately from greenhouse gas emissions. Here we show the benefits of increased coordination in reductions. We show that the direct impact of most air pollution reduction on climate is small, with the exception of SO_2 and BC. The warming influence of SO_2 reductions counteracts some of the cooling due to BC carbon reductions. Despite assumptions that may overestimate potential reductions due to high reference emissions, and including ozone impacts on ecosystem carbon uptake, we show a potential for only an 8% reduction in temperature rise over the century from these direct reductions. There may be some climate benefit from greater black carbon reductions, but the main interaction of air pollution and climate is the possibility for complementarities between air pollution reductions and CO_2 reductions. We have introduced into the EPPA model the capability to model air pollution control using elasticities of substitution. With this tool, we were able to explore various aspects of the interactions between air pollution reductions and greenhouse gas reductions. We showed that with an air pollution policy that costs a little more than 1% of net present consumption, we not only get cleaner air but a 160 ppm decrease in CO_2 and a total of almost 25% temperature reduction. For simultaneous policy implementation, we show that there is a 20% welfare penalty to not designing policies that allow coordination between reductions of pollutants and greenhouse gases. This coordination could be as simple as implementing cap and trade or taxes on both kinds of emissions and allowing autonomous agents to reach their own optimal mix of reductions. However, current policy, especially with regards to the developing world, seems to be focused on project based mechanisms such as the Clean Development Mechanism. And because of the CDM additionality clauses, the very projects which best coordinate local benefits and GHG reductions are the ones which have the most risk of being rejected, and therefore the coordination benefits are likely to be lost.

This thesis was not able to address all climate substances, nor account for all details of the substances it did address. However, there are some generalizations that can be made with regards to what substance characteristics may be important. Differences in lifetime are a major issue, and our work indicates that GWPs are not a good way to address these differences. Ability to accurately measure emissions is also important. This applies to issues such as carbon sequestration and forest sinks, which are less well understood than the direct CO_2 emissions from fossil fuel consumption, and therefore caution should be taken when trying to address well quantified and poorly quantified emissions with the same policy. Interactions between policies are also important, whether it be CO_2 policies and fuel taxes or air pollution policies and greenhouse policies. The ability to estimate the magnitude of potential reductions is necessary in order to determine whether a given substance is worth the effort to address by itself, or if including it in a larger mix is acceptable because errors will be small.

This analysis could not have been done without the full tool set of economic analysis, both modeling and theoretic, atmospheric modeling capabilities including full chemistry, ecosystem, and radiation codes, and analysis of the political realities on the ground. Truly complex problems require a broad spectrum of scientific and political tools in order to properly understand and devise appropriate solutions. Each tool has inherent limitations: integrated approaches can overcome some of these constraints.

While this thesis demonstrates improved methodologies for analyzing policies involving multiple substances, it is important to remember that the main thrust of climate policy needs to be near term action. This thesis should not be interpreted as a call to step back and reevaluate, but rather to push ahead and implement methane policies and air pollution policies immediately while continuing to work on carbon dioxide reductions. As Nicholas Mabey stated[14], “The challenge is change, not setting targets or developing optimal solutions if said targets/solutions are not actually met”.

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[14] 6th TPP Symposium, Leadership for 2050: Technology, Policy, and Education, 2006.

Appendices

A. The MIT Emissions Prediction and Policy Analysis (EPPA) Model

The EPPA model is a computable general equilibrium (CGE) model designed to simulate the global economy. The model was designed with two primary purposes. The first purpose is to project emissions into the future for use in the earth systems component of the IGSM. The second purpose is to analyze the costs and effects of imposing climate policies on the economy. To achieve these purposes requires a global model with multiple regions and sectoral detail. EPPA version 4 (Paltsev et al., 2005b) has 16 separate regions (Table A-1) and sectoral splits with special detail in the energy and electricity generation because of the importance of fuel choice and generation technology to greenhouse gas emissions (Table A-2). The model is calibrated based on the GTAP dataset in 1997, and then simulated forward from 2000 to 2100 in 5 year increments. The versions of EPPA used in this thesis are recursive-dynamic, meaning that they are myopic rather than forward looking. Emissions of the 6 major greenhouse gases (carbon dioxide - CO_2, methane - CH_4, nitrous oxide - N_2O, hydrofluorocarbons - HFCs, perfluorocarbons - PFCs, and sulfur hexafluoride - SF_6) are calculated, along with air pollutants which have direct or indirect impacts on radiative forcing (sulfates - SOx, black carbon - BC, organic carbon - OC, nitrogen oxides - NOx, carbon monoxide - CO, ammonia - NH3, and non-methane volatile organic compounds – NMVOCs).

Annex B	Non-Annex B
United States (USA) European Union (EUR) Eastern Europe (EET) Japan (JPN) Former Soviet Union (FSU) Australia & New Zealand (ANZ) Canada (CAN)	China (CHN) India (IND) Higher Income East Asia (ASI) Middle East (MES) Indonesia (IDZ) Mexico (MEX) Central & South America (LAM) Africa (AFR) Rest of World (ROW)

Table A-1: Countries and Regions in the EPPA Model

Non-Energy Sectors	**Electric Generation Technology**
Agriculture (AGRI)	Coal
Energy Intensive (EINT)	Pulverized Coal (PC)
Transportation (TRAN)	Gas
Other Industry (OTHR)	Refined Oil
Services (SERV)	Hydro
Energy Sectors	Nuclear
Electricity (ELEC)	NGCC
Coventional Crude Oil (OIL)	NGCC-CCS
Oil from Shale (SOIL)	IGCC-CCS
Liquid Fuel from Biomass (BOIL)	Wind & Solar
Refined Oil (ROIL)	Biomass
Coal (COAL)	**Primary Input Factors**
Natural Gas (GAS)	Capital
Gas from Coal (SGAS)	Labor
Household Sectors	Land
Own-Supplied Transport	**Energy Resource Stocks**
Purchased Transport	Crude Oil
Other Goods & Services	Shale Oil
	Natural Gas
	Coal
	Hydro
	Nuclear
	Wind & Solar

Table A-2: Sectoral Breakdown and Resource Factors in the EPPA Model
NGCC: Natural Gas and Combined Cycle. CCS: Carbon capture and sequestration. IGCC: Integrated Gas Combined Cycle

The structure of the model involves a representative consumer providing primary factors to the production sectors, which then sell goods and services back to the consumer. Every production sector has a corresponding production function formulated as a set of nested constant elasticity of substitution functions that determine the mix of primary factors and intermediate inputs that are necessary to produce the output of the sector. These factors and inputs can potentially be substituted for one another, depending on the given elasticities of substitution. These elasticities are vital for determining the manner in which the model can respond to policy constraints, as they control how easy it is to substitute labor or capital for energy based inputs. The model then optimizes the welfare of the representative consumers (consumption plus saving) while meeting market clearance conditions.

The evolution of the model between periods involves several factors. First is that savings equal investments, which contribute to capital in the subsequent period offsetting depreciation. Population trends over time are based on United Nations projections (United Nations, 2000; United Nations, 2001). Labor productivity is assumed to increase over time, and an autonomous energy efficiency improvement (AEEI) index is used to represent the change in energy use per unit output over time as technology changes. Natural resources have a finite stock, and the cost of extraction increases as that stock is depleted. The nuclear sector is also modeled with a limited resource in order to represent political limits to expansion of this sector – this assumption has been explored in more depth in the Future of Nuclear Power report (Deutch et al., 2003). Finally, new technologies (such as the carbon capture and sequestration – CCS – technologies) are modeled such that they become available in a given time period, but there is a limit on the rate at which these technologies can penetrate the economy.

In the reference scenario, the combination of reference parameters used in this thesis leads to a total GDP growth over the time period of more than a factor of 10. This growth leads to significant emissions growth of greenhouse gas emissions as shown in Figure 1.4 in Chapter 1.

The models used in this thesis had some modifications from the model described in Paltsev et al. 2005. The addition of air pollutant abatement has been described in detail in Chapter 3, however there were other minor changes made for the model used in that chapter. First is that the standard version of EPPA4 had a strict cap on SO_2 emissions in developed nations that was implemented by artificially reducing the SO_2 emissions after the model solution. This clearly would conflict with attempts to model SO_2 abatement response to policy, so the artificial cap was replaced with an exogenous improvement in the base emission factors that reproduced the appropriate SO_2 emissions path in the reference case. Additionally, the advanced pulverized coal technology had higher NOx emissions than the base coal technology, so the emission factors of the pulverized coal technology were adjusted to match the intuition that the advanced technology should be at least as clean as the older technology. The new numbers were within literature ranges (Marion et al., 2004). This version of the model also used the baseload and shoulder details developed by (McFarland and Herzog, 2006).

B. The MIT Integrated Global Systems Model (IGSM)

The earth systems component of the MIT IGSM is designed to simulate the global atmospheric, land, and ocean system over the next century using emissions inputs from the MIT EPPA model. Two major versions of the IGSM have been used in this thesis: IGSM1 (Prinn et al., 1999), a 2D land/2D ocean model with 7.8 degree resolution latitudinally and 9 vertical atmospheric levels, and IGSM2.3 (Sokolov et al., 2005) which has a finer 4 degree resolution and 11 vertical levels, a 3D ocean general circulation model, and an improved land process component (Schlosser and Kicklighter, 2007) based on the Community Land Model (Bonan et al., 2002). The nature of the problems studied in this thesis require a detailed chemistry model. The IGSM includes 33 chemical species, with 41 gas-phase and twelve heterogeneous reactions in the background chemistry module. Both models include an urban air pollution module based on fitting a 3D California Institute of Technology Urban Airshed model (Mayer et al., 2000), though this urban module is in the process of being replaced with an improved version. Natural systems are represented by a Terrestrial Ecosystems Model (TEM) (Melillo et al., 1993) and a Natural Emissions Model (NEM) (Liu, 1996). Table B-1 shows which model version has been used in which portion of the thesis.

Chapter	Model Used
One (Stabilization)	IGSM1 IGSM2.3 for CCSP exercise
Two (Methane)	IGSM1 for M2M analysis IGSM2.3 otherwise
Three (Air pollution)	IGSM2.3

Table B-1: IGSM Model usage in this thesis

The IGSM is considered to be an Earth Model of Intermediate Complexity (EMIC). The two dimensional nature of the model leads to some differences with 3D state-of-the-art atmosphere-ocean-land general circulation model (AOGCM): there may be some sacrifice of detail, most obviously in the lack of longitudinal resolution, but the IGSM has advantages in computational speed, flexibility of parameterizations allowing for exploration of the space of climatic uncertainty, and more complete chemistry and earth systems linkages. The parameterization flexibility enables ocean heat uptake and the ocean carbon sink to be adjusted by modifying Kv (effective diffusion coefficient for parameterizing all mixing processes) in the IGSM1 2D ocean or Kz (coefficient for vertical diffusion for parameterizing only the small-scale mixing processes) in the 3D ocean. Because the 3D ocean has explicit modeling of the biogeochemical cycle the carbon uptake in the 3D model is less responsive to Kz changes than in the IGSM1 2D version. The climate sensitivity (CS) can be adjusted by the use of a cloud feedback parameter, and the aerosol forcing (Faer) is also adjustable. The default parameters used in this thesis are shown in Table B-2. The change in Kv is due to improved attribution studies (Forest et al., 2006), leading to a ocean with slower heat uptake and correspondingly slower sea level rise. The Forest (2006) study also led to a prediction of slightly higher climate sensitivity (not used in the CCSP study). The aerosol forcing parameter required updating due to the inclusion of the radiative impact of black carbon in the climate model, and therefore a compensating increase in the cooling effectiveness of sulfate aerosol was necessary to match historical data in the 1980s. Work on updating best estimates of these parameters is ongoing.

	Kv (cm^2/s)	CS (ºC)	Faer (W/m^2)
IGSM1	9.2	2.4	-0.61
	Kz (cm^2/s)	CS (ºC)	Faer (W/m^2)
IGSM2.3 (CCSP)	0.4	2.0	-0.35
IGSM2.3	0.4	3.0	-0.85

Table B-2: Climate parameters chosen for use in this thesis

C. Kyoto gases other than CO_2 and CH_4

A brief digression to address well-mixed gases other than methane and CO_2 is appropriate here. We have chosen to focus on methane because it is the 2nd largest contributor to radiative forcing of the greenhouse gases, but the historical contributions 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). We analyzed the benefits of reductions of all non-CO_2 gases together in Reilly et al. (2006).

This study did support our intuition that of these gases methane was clearly the most important in terms of cost effectiveness and near term temperature impact. However, some of the findings of the study are still worth noting here for reasons of completeness. Should near term policy move in the direction of addressing gases such as methane individually rather than in larger, more comprehensive programs, it would be remiss not to address smaller contributors that nonetheless have simple abatement options available.

Much of the historical forcing of these industrial gases 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 (Mayer et al., 2001; Reilly et al., 2003a; Reilly et al., 2000; Reilly et al., 2002; Reilly et al., 1999; US EPA, 1999; US EPA, 2001a; US EPA, 2001b; US EPA, 2001c). 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, 2001c). 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 their atmospheric concentrations because of their very long lifetimes.

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.

Currently, because HFC is covered under the Kyoto Protocol, and because destruction of HFC is fairly simple to quantify and is arguably always "additional", the majority of CDM credits have been allocated to HFC combustion projects. However, the problem is that there is not a constant rate of production of HFC-23 as a byproduct of HCFC-22 manufacture. Therefore, by giving credits for HFC-23 destruction, this creates perverse incentives for designing a plant that creates more HFC-23 byproducts than would be maximally efficient – at least, as long as destruction of HFC-23 is credited, and not avoided production (Hoffman, 2006). This characteristic indicates a need to examine HFC-23 credits more closely, and perhaps to create a separate mechanism for non-Annex B nations to gain credits for HFC-23 reduction (perhaps from a baseline cap, rather than per ton of destruction).

N_2O has similar emissions characteristics to methane, but lifetime closer to that of CO_2. Therefore, if accurate quantification of emissions were possible, there would be few reasons not to allow GWP based trading between N_2O and CO_2, though there still might be reasons why some nations might be willing to implement an N_2O policy but not a CO_2 policy. Further analysis would be interesting, but is not included within this thesis, especially given that projections indicate that N_2O emissions will contribute less than methane to warming over the next century.

D. Global Warming Potentials

Because GWPs are central to some of the major conclusions of this thesis, we include an appendix discussing their basic properties and a few of the alternatives that have been proposed over the years. The Global Warming Potential concept was adopted by the first IPCC Assessment Process in 1990. There was a need for intercomparisons between different gases, and the obvious parallel was the Ozone Depletion Potential used within the Montreal Protocol (Shine et al., 1990). A single number was necessary for policymakers to be able to evaluate the relative merits of different greenhouse gas mitigation strategies. Several of the possible drawbacks to GWPs were noted in the original discussion, including the problem resulting from using CO_2 and its complicated lifetime as a reference gas.

The basic definition of a GWP is the time integrated climate forcing resulting from a release of 1 kg of a trace gas relative to the forcing resulting over that time period from an emission of 1 kg of the reference gas (CO_2) as in the following equation:

$$GWP(x) = \frac{\int a_x * [x(t)]dt}{\int a_{CO_2} * [CO_2(t)]dt}$$

We include a table of the 20 year, 100 year, and 500 year GWP values here (from the IPCC Third Assessment Report in 2001), along with the old 100 year values from the IPCC Second Assessment Report in 1996.

	20 year	100 year	500 year	IPCC 1996 (100 year)
CO_2	1	1	1	1
CH_4	62	23	7	21
N_2O	275	296	156	310
CF_4	3900	5700	8900	6500
SF_6	15100	22200	32400	23900
HFC-134a	3300	1300	400	1300

Table D-1: GWPs by gas and integration time period from IPCC TAR (Ramaswamy et al., 2001) and IPCC SAR (Schimel et al., 1995)

The 1996 IPCC values for GWPs are used in Kyoto for the first commitment period, and therefore have been used as the trading metric for EPPA. However, the Protocol indicates that updated GWPs may be used for future commitment periods.

The table above shows the importance of the time threshold chosen for the calculation, where the GWP of methane varies from 62 to 7. Naturally, the closer the lifetime of the gas in question comes to that of CO_2, the less difference results from the chosen time period. However, since the carbon cycle has unique properties, it is not obvious exactly what lifetime to use for CO_2: the IPCC uses the Bern carbon cycle model as a base. This complexity in CO_2 lifetime properties immediately leads to potential complications in calculating GWP values. Also, the radiative forcing per unit CO_2 decreases logarithmically as CO_2 concentrations in the atmosphere increase, differing from most other gases because the radiative forcing bands of CO_2 are more highly saturated. Therefore, it is might be expected that a repeat of the GWP calculation in 50 years when CO_2 concentrations are higher will lead to a higher GWP for all the non-CO_2 gases due to this forcing relationship.

Alternate formulations of GWPs have been proposed. One approach, suggested by Shine et al. (2005) was to use a simple energy balance model and look at temperature change at a given date resulting from a pulse of gas, rather than integrated forcing. Additionally, they also examined the effect on temperature at a given date of a sustained reduction of a given gas. Their 100 year "GTPs" (Global Temperature Change Potential, Sustained Reduction) for methane is about 25, not much larger than the same GWP, which does not seem to match our experience with methane reductions compared to CO_2 reductions in the IGSM. However, there is likely a relationship between a calculated GWP or GTP and the counterfactual, the size of the reduction pulse, and the effect of methane emissions on its own lifetime. In our scenario we have increasing CO_2 concentration in the counterfactual which effectively leads to an increase in other GWPs over time as the radiative forcing per unit CO_2 decreases, we have a fairly large reduction of methane between the reference case and the policy case, and we have an elaborate chemistry model, all of which could lead to different evaluations than the IPCC or Shine et al. approaches.

Manne and Richels offer yet another approach (Manne and Richels, 2001b) by choosing a temperature change target and using a forward looking model to determine optimal abatement (and price) paths. With a pure temperature target they get the result that methane price is low at the beginning of the period, rising rapidly as the target is approached. This is a natural consequence of the constraint: methane abatement in the early periods does nothing to forcing at the time that the constraint is taking effect (this result is also seen in Aaheim et al. (2006)). If a rate of change constraint is added, then the price of methane becomes higher. A 2 degree temperature target, with a 0.2 degree/decade rate of change, leads to a methane price not dissimilar from the standard GWP. N_2O prices, however, are higher than their GWP values in all the scenarios that the authors considered. Indeed, in their recent paper for EMF-21 (Manne and Richels, 2006), they used a radiative forcing ceiling rather than a temperature target, and observed the same behavior where methane abatement was delayed until the end of the period. However, in a radiative forcing ceiling scenario, this allows radiative forcing to rise quickly and then stabilize, leading to a higher temperature in 2100 than would result if methane were not reduced at all.

Note that GWPs are expressed in CO_2 equivalents, and therefore care must be taken when converting emissions of a non-CO_2 gas to carbon equivalents instead. The CO_2 equivalents to C equivalents conversion factor is 12/44, and therefore it is important to understand when C equivalent, CO_2 equivalent, or actual mass of a given gas is being reported. This applies equally well to \$/tonC, \$/tonCO_2, etc.

E. Methane properties

To understand the place of methane policies, we need to understand the relevant characteristics of methane: its sources, sinks, and radiative properties. These are important both for modeling reasons and for policy creation. The radiative properties of methane are important for determining the benefits of reducing its concentrations. Understanding the sources of methane is necessary to determine where to concentrate policies in order to yield the best effect, and how to best craft such policies. Understanding of sinks is important both because the manner in which sources are estimated sometimes depends on assumptions about the rate of decomposition of methane, but also because we need to understand how such sinks may change in the future which may change the relationship between emissions and concentration.

Among the greenhouse gases, methane (CH_4) is the most important direct anthropogenic source of increased radiative forcing after CO_2. The concentration of methane in the atmosphere in 2004 was 1783 ppb according to the WMO (World Meteorological Association, 2006), though the abundance of CH_4 measured by NOAA/GMD was 1775 ppb. Different measurement scales can lead to different results: the NOAA number used to be 1751 ppb (Dlugokencky et al., 2003), but now NOAA uses a new scale used for measurement (NOAA04) which is designed to bring NOAA estimates into agreement with the AGAGE network (Cunnold et al., 2002; Dlugokencky et al., 2005). There is significant variability between regions – the 5 AGAGE monitors registered annual average concentrations ranging from 1730 to 1852 ppb in 2004. In any case, methane concentrations are less than 1% that of CO_2. However, each molecule of methane has a radiative forcing approximately 21 times that of a molecule of carbon dioxide, or a forcing of 60 times that of CO_2 by weight. Methane concentrations have also increased by a factor of 2.3 since preindustrial times, compared to an increase of 30% in CO_2 concentrations in the same time period. The Intergovernmental Panel on Climate Change (IPCC) estimated methane's 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 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 not the only contributor to past increases in O_3. CO, NOx, and VOCs are all involved in the O_3 cycle, and clearly identifying the contribution of each is difficult both because the chemistry of O_3 formation in the troposphere is complex and non-linear in precursor emissions and atmospheric conditions, and also because the emissions in some of precursors are highly uncertain. One estimate (Lelieveld et al., 1998) is that anthropogenic CH_4 emissions contributed to one quarter of the tropospheric O_3 rise since 1850. We plan to address this issue further in future work on historical emissions as inputs into the IGSM.

Naturally, GWP calculations have been made in order to compare methane emissions directly to other greenhouse gas emissions for trading purposes. Methane's comparatively short lifetime of 14.5 years (including adjustment) (Seinfeld and Pandis, 1998) or 8.4 years (direct lifetime) (Prather et al., 2001) results in it having a 100 year GWP of only 21 (or 24 in the TAR estimate) despite its factor of 60 increase in radiative forcing by mass. This short lifetime also means that methane concentrations will adjust very quickly to changes in emissions, and the comparatively high radiative forcing results in fast reactions of the climate system. Adjustments to methane's GWP include the fact that its end oxidation state is CO_2 (regardless of whether it is burned by flaring or in gas turbines, or oxidized in the atmosphere), its contribution to O_3 concentrations, and the fact that emissions of methane lead to an increased lifetime for atmospheric methane by reacting with hydroxyl radicals. These adjustment factors are usually included by multiplying a calculated GWP from CH_4 forcing alone by a factor of 1.3.

These hydroxyl radicals are the main determinant of the oxidative capacity of the atmosphere. This means that methane's lifetime will grow if there are significant emissions of hydroxyl radical sinks such as carbon monoxide, volatile organic compounds, or methane itself. In order to measure OH concentrations (Prinn et al., 1995) used chlorinated compounds as tracers. While there have been variations in OH trend estimations (Krol et al., 1998; Krol et al., 2003; Prinn et al., 2001) the most recent publications include better estimates of methyl chloroform emissions (Reimann et al., 2005) and indicate that long term OH trends have been fairly small though interannual variability can be larger, with a minimum in 1998 (Prinn et al., 2005b). Accurate determination of OH concentrations is vital for accurately determining the CH_4 sink, which is then used for determining the total CH_4 source using inverse methodologies. There are also small methane sinks due to bacterial oxidation (20 to 51 Tg) and stratospheric degradation that may amount to on the order of 10 % of the total sinks (Lelieveld et al., 1998; Ridgwell et al., 1999).

Methane is generated from various sources, including incomplete combustion, fossil outgassing, and biological anaerobic decomposition. Estimates for the total source term for methane have improved over time: Seinfeld and Pandis (1998) estimated a range of 410 to 660 Tg (median 535 Tg), of which they attributed 160 Tg to natural sources (mainly wetlands). Of the 375 Tg of anthropogenic emissions they attribute 100 to fossil fuels and the remainder to biological sources, including enteric fermentation (livestock), rice paddies, biomass burning, landfills, and various sewage sources. Lelieveld et al. (1998) estimated a total source of 600 Tg yr-1 (±80 Tg), determined by inverse calculations, with a fossil contribution of 110 Tg (± 45 Tg) determined by 14C/12C ratio, for an anthropogenic total of 410 Tg. They estimated that the pre-industrial natural methane source was 190 ± 70 Tg/yr. Various bottom-up estimates of anthropogenic emissions exist, but generally yield lower emission totals. The US EPA estimates anthropogenic sources at only 287 Tg in 2000 of which 30 Tg was due to rice (US EPA, 2006) and the EDGAR database lists 321 Tg emissions of anthropogenic emissions of which 39 Tg is due to rice cultivation and 104 Tg from fossil fuels (Olivier, 2005; Olivier et al., 2005).

However, the most recent inverse calculations (Chen and Prinn, 2006) provide slightly different numbers: only 48 ± 3 Tg of fossil fuel emissions, with 112 ± 29 Tg from rice, 189 ± 3 from animals and waste, 43 ± 18 from biomass, and 36 Tg from industrial/biofuel combustion, for about 430 Tg total anthropogenic emissions. Natural emissions are attributed to wetlands (143 Tg) and termites (23 Tg), for a total of 597 Tg.

There have been several results in recent years that may require a reevaluation of some of these source terms, with some amount of involved controversy. A recent paper by Keppler et al. (2006) claimed that there may be a 62 to 236 Tg source from living plants. Some experts in the field are dubious about both the extreme conditions of the original experiments and the validity of the extrapolation showing it to be a major worldwide source, and many others are waiting for validation of the results from new studies. However, the fact that this claim is not dismissed out of hand is another indication of the uncertainty involved in methane inventories. Another paper (Kvenvolden and Rogers, 2005) has taken issue with the oversight of geological sources of CH_4: they estimate that seeps, volcanoes, mid-ocean ridges, and similar non-biogenic nor anthropogenic sources account for 45 Tg of CH_4 per year. Geological sources are also addressed in Etiope and Klusman (2002) as a source of “missing” old methane, because bottom-up fossil source estimates were smaller than top-down $^{14}C/^{12}C$ ratio fossil estimates. Finally, there has been discussion about whether dams might be potential methane sources. While it would be expected that methane would oxidize in the water column before reaching the surface, perhaps it is possible that methane can escape along with releases of water from the depths of the reservoir through the spillway, or through ebullitive emissions (bubbles), and some measurements have shown that some dams do have significant emissions (Fearnside, 2004; Giles, 2006; Rosa et al., 2004). Shallow dams for irrigation purposes could be expected to contribute more to emissions than would deep dams for power, as any standing vegetation that breaches the surface could serve as a "channel" for methane escape from depth.

Another issue revolves around recent estimates of rice paddy emissions. Methane in rice paddies is generated by decaying plant matter in flooded fields, and the rice plants themselves serve as channels for methane to diffuse into the atmosphere. Emissions vary with season, soil types, and various agricultural practices. An old paper by Sass and Fisher (1997) put a limit of 25 to 54 Tg on global methane emissions from rice using bottom-up methodology. The EPA's inventory methodology follows the general pattern of the Sass papers, with total global methane emissions from rice much closer to 20 Tg than to 100. Lelieveld listed estimates of annual emissions ranging from 20 to 150 Tg, but suggested that the lower end of the range would not be consistent with their model calculations. The inverse methodology of Chen and Prinn (2006) attributed 112 ± 29 Tg of methane emissions to rice paddies, far larger than the bottom-up estimates. Some bottom up modelers acknowledge the limitations of their approach: (Sass et al., 2002) state that "reliance on single-field studies for determination of global methane budgets may be questionable." Given that in the IGSM model system we encountered problems using numbers based on the EPA inventories because methane concentrations were dropping through the 90s, we have chosen to increase the emissions to match the estimates from Chen and Prinn (2006). This led to much more realistic concentration profiles, though there are still issues to be resolved about even present day emissions and chemistry estimates in our modeling system.

However, if the Keppler et al. study bears out, it is possible that the emissions from tropical forests may mask the lack of emissions from rice paddies. Similarly, large emissions from dams used to flood rice paddy fields may be another way to reconcile the low bottom-up estimates from the EPA and the large inverse modeling estimates from Chen and Prinn (2006), as these emissions could potentially have similar geographic and temporal patterns.

Calculated emissions in 2005 from running the IGSM in a standard reference run (IGSM2, EPPA4) were 133 Tg of CH_4 from NEM, 40 Tg of CH_4 from the preprocessor (attributed to termites, oceans, and other processes), and 374 Tg from anthropogenic sources, for a total of 547 Tg (emissions were similar in 2000 except for 26 Tg less from anthropogenic sources).

Methane emissions from landfills is quite temperature dependent. The GAINS model uses different emission factors for cool, temperature, and warm climates. Occasionally, there are significant differences even between different inventories. GAINS and the UNFCCC both separately estimated emissions for the EU-25. For a half dozen countries, "GAINS estimates for 1990 deviate by more than 30 percent from the figures reported by countries to UNFCCC (2005)" (GAINS methods report, 2005, pg. 56) These differences were attributed to the waste sector and coal mining emissions, as well as the agricultural sector in Germany only. In the waste sector, the UNFCCC assumes that all waste is created equal and therefore has identical methane emission profiles, whereas GAINS separated paper and organic waste. This meant that methane emissions in nations with high paper consumption and low recycling and incineration rates were, according to GAINS, being underreported to the UNFCCC. Similarly, in Austria a study showed that the standard deviation in methane estimations was up to 25% of the mean emission estimates (and even worse for N_2O) (Winiwarter and Rypdal, 2001). If this is true in the EU-25, it could be expected that errors of that magnitude or larger may be common in developing nation inventory reports.

While uncertainty in anthropogenic emissions inventories may be most relevant for policy purposes, uncertainty in natural emissions is important for climate projections. Especially important are possible feedbacks between temperature and natural emissions due to possible carbon release from northern latitude land ecosystems or ocean methane hydrate destabilization. Zhuang et al. (2006) estimate a current methane emission source of 36 Tg, with a doubling of emissions over the 21st century in a scenario where high latitude temperatures increase by 7 °C. This increase is small compared to projected anthropogenic emission increases, but there are still mechanistic uncertainties. Other sources of uncertainty include wetlands, which are as hard or harder to measure as rice paddies, and possible sources such as ebullition of methane from lakes (Walter et al., 2006) which are difficult to measure due to spatial and temporal non-continuity in much the same way that it is difficult to measure possible methane emissions from water trapped behind dams.

F. Complementarity Literature Analysis

Since the "Killer Fog" of London in 1952 more and more attention has been paid to the hazards of local air pollution. In the developing world, India, China, and Mexico have the most polluted cities in the world, some of which reach particulate levels of nine times the World Health Organization guidelines, and indoor air quality can be even worse. 50,000 deaths a year in 11 large Chinese cities are attributed to smoke and fine particles from coal combustion (or 180,000 annual deaths in urban areas from all air pollution sources) (Hughes, 1997; World Bank, 1997). The United States, the world's largest emitter of greenhouse gases, has much lower local pollution levels after several decades of regulation. However, heightened environmental awareness continues to lead to calls to further reduce pollution, and research such as the Six Cities Study demonstrate the dangers of PM2.5 and other pollutants (Daniels et al., 2004; Dockery et al., 1993; Health Effects Institute, 2000; Pope et al., 1995). Given the incentives to reduce local air pollution in the developed and developing worlds, and given that the sources of air pollution are often also the source of greenhouse gases, it appears that there is a potential complementarity that can be exploited to global advantage.

While the link between climate change mitigation and air pollution reduction seems reasonably evident, numerical estimates of these benefits have only become widespread recently. One of the early reviews of these estimates was published in 1996, and stressed "the preliminary and tentative nature" of the secondary benefits studies (Ekins, 1996). Now, however, policy makers in the climate change field regularly cite non-climate benefits as a justification for climate policy. For example, the IPCC 2nd Assessment Report claims that reduced air pollution damages will equal 30 to 100 percent of the costs of GHG emission reductions (Pearce et al., 1995). The 3rd Assessment report went further, discussing the difference between "ancillary benefits" – benefits arising from climate-only policies – and "co-benefits", where the policy is designed to be a cost-benefit optimal mix of air pollution and GHG reduction (Hourcade et al., 2001). The Working Group on Public

Health and Fossil Fuel Consumption calculated the number of lives saved because of secondary air pollution benefits from a climate change reduction policy on the order of 700,000 annually by 2020 (Davis et al., 1997). These results lead groups like the WRI to call for immediate implementation of GHG reduction policies because "small reductions in carbon emissions over the next two decades can yield big benefits to public health worldwide" (Repetto and Austin, 1997; World Resources Institute, 1997). The Working Group report and other similar studies often make broad assumptions about the relationship between PM2.5 and GHG reduction in order to make their predictions of lives saved (Cifuentes et al., 2001a; Cifuentes et al., 2001b). Other approaches have involved using CGE models in order to calculate marginal abatement curves and therefore predict "optimal" and "no-regrets" levels of CO_2 reduction, where CO_2 abatement costs are canceled with ancillary benefits (O'Connor, 2000). Jorgensen et al. examined the results of carbon emission reduction in China, but in their case using a dynamic recursive model to look at the health benefits of a carbon tax (Garbaccio et al., 2000). However, one problem many of these studies share is that they do not include sufficient detail to examine all the different possible technologies that achieve similar levels of carbon reduction. The studies that look at air pollution benefits derived from GHG reduction also miss some of the major problems involved with this complementarity.

For example, in many developing countries, the largest GHG producers may not be the largest pollution emitters. Power plants may produce the most GHGs, but indoor stoves produce pollutants where they have the largest health impacts (as well as being dirtier). In China, for example, health benefits from household stove PM10 reductions were calculated to be forty times that of health benefits from an equivalent PM10 reduction in large power plants (Wang and Smith, 1999). The approach of the Wang study was to create a GHG reduction target, and examine the ancillary benefits of various technological and policy options for meeting that target. One interesting note in the study was that when replacing coal stoves, there was a large GHG emission difference between the alternatives – with electric stoves being little improvement over coal stoves, but coal gas and especially natural gas being significant improvements. Another problem regards diesel vehicles. Diesel is considered to be a dirty fuel, but is more fuel-efficient than gasoline. Therefore, proposals to clean the air by switching from diesel to gasoline may actually increase GHG emissions. The issue is made more complicated by the possibility that soot from diesel emissions actually has a major greenhouse impact in its own right (Jacobson, 2002).

The flip side of the developing country issue is that in industrialized economies pollution control measures are often tight enough already that CO_2 reduction measures may not have a significant effect on air pollution. The IPCC predicts that some CO_2 measures will merely reduce SO_2 abatement costs until a certain threshold has been reached. After that threshold, further CO_2 reduction measures will then have much larger marginal benefits, leading to a significant discontinuity (Hourcade et al., 2001). This is in large part due to the SO_2 trading regime in the US. Of course, decreases in SO_2 abatement costs may lead to more stringent caps in the future, as are already being considered.

There has been recognition that addressing multiple pollutants simultaneously is often more efficient than addressing the pollutants individually. This has been noted for the separation of air and water policy in the EPA, as well as in climate change where models (and common sense) show that targeting multiple gases is more efficient than achieving climate control through CO_2 reduction alone (Reilly et al., 1999). Congress and the Bush administration have also recognized the value of multipollutant strategies, though CO_2 may not be included in their mix of SO_2, NO_x, and Hg. However, the debates highlight many of the difficulties involved in any environmental legislation – and additional complexity only exacerbates those problems, so there may be political reasons to keep pollutants separate (Hogue, 2001).

Because of the lack of federal action in GHG reduction, there has been a movement by state and local agencies such as STAPPA and ALAPCO to create “harmonized strategies” of air pollution reduction and GHG reduction (State and Territorial Air Pollution Program Administrators and Association of Local Air Pollution Officials, 1999). They recommend switching from coal to gas-fired combined cycles plants at a CO_2 saving of 66 percent, a NO_x saving of 99 percent, and an SO_2 saving of 100 percent. They estimate the cost of the switch as being under \$39 per ton of CO_2 saved, not taking into account complementarities. There are recommendations to improve end-use efficiency (citing the Five-Labs Study), downsize motors in the commercial sector, and reduce emissions in the transportation sector. The problem is that these organizations have no real mandate to act, and therefore have not implemented the market based GHG reduction plans that were suggested in their report.

There has been a small body of work on taking air pollution reduction as a primary goal and examining how to derive a GHG benefit from that reduction, which is closest in direct relevance to the work in this thesis. A CICERO study in Oslo looked at the Chinese Shanxi province (Aunan et al., 2004). Their motivation was that local reductions in air pollution often did not imply significant reductions in GHG emissions, as exemplified by studies in Mexico City and Santiago, because 1st generation measures for SO_2 and particulate reductions do not include shifting of fuel types, efficiency measures, or renewable use. Because Shanxi is a major center for coal mining, coke production, power plants, and metallurgy, the majority of the analysis was aimed at coal emission reduction technology. The study found that the most cost efficient way to reduce CO_2 (co-generation) was no longer the most cost efficient when local environmental damages were introduced into the calculation, leading to a recommendation for briquetting as a means to reduce both CO_2 and local air pollutants.

There was also a study using a linear programming model for the Shanghai energy system (Gielen and Chen, 2001). This study examined the difference between a base case of economic efficient action, a case where local pollution policies were implemented, and a case where an additional $12/ton carbon tax was placed on top of the pollution policies. This additional tax resulted in an 11% CO_2 reduction (or 22 Mt CO_2). This is on top of 24% for the local pollution measures, and 10% for inclusion of "no-regrets" measures. The recommendation of the authors was to be careful to use only the final 10% CO_2 reduction costs in any CDM measures funded by outside nations, as they consider it likely that China will be installing local pollution measures on its own.

Finally, the third study of direct relevance is a World Bank six cities study on environmental fossil fuel damages that concluded (given a $20/ton carbon shadow price) that optimal policies taking both health and global climate into account were almost identical to straight air pollution reduction policies (Lvovsky and Hughes, 1999; Lvovsky et al., 2000). They analyzed costs to reach certain PM10 levels focused on PM10 alone, or given a strategy focusing on CO_2. They state a value of $80/ton necessary to make CO_2 reduction a priority over local pollution reduction. Specifically, the authors believe that the priority is local pollution measures, especially focused on household pollution, using cleaner fuels and cleaner combustion technology incentives. Interestingly, of course, the European ETS trading price did peak over $80/ton carbon in the early periods of the system, and if the trading system returns to such a price the authors could possibly change their recommendations to meeting air pollution targets using approaches optimized for CO_2 reductions, with the increment in cost funded by emissions credit purchases.

G. Black Carbon

Our modeling simulations show a large global mean surface temperature response to black carbon reductions. In order to stay consistent with past observations, this requires a larger sulfate aerosol cooling factor. There is some doubt as to whether or not a response of this magnitude is reflective of reality. There are some studies which might indicate that it is not out of the bounds of consideration: we have already cited the Bond estimate, but additionally the well publicized work by Hansen et al. and Jacobson et al. indicate that there are some researchers who believe that the absorptive properties of elemental carbon are actually a major contribution to global scale warming patterns. Jacobson believes that black carbon is mainly internally mixed with other aerosols, thereby increasing its absorption potential to 0.55 Wm^{-2} compared with 0.27 Wm^{-2} for an external mixture (Jacobson, 2001). Hansen goes further to state that including BC indirect effects (through ice and snow melt) may "increase its net forcing to 0.5-1 W/m^2" (Hansen and Sato, 2001). Under the Jacobson hypothesis, unless diesel vehicles become significantly cleaner, then switching from gasoline to diesel in order to reduce CO_2 emissions would actually warm the climate in the 13 to 50 year timescale.

These estimates are highly controversial for various reasons. First, the black carbon forcing numbers are controversial in themselves. Second, black carbon is often emitted along with organic carbon, which is much more reflective, and therefore the two types of particle may cancel each other out to a large extent. The Jacobson study did eliminate both organic and black carbon when running comparisons with CO_2 and CH_4 reductions

(Jacobson, 2002). However, the MIT IGSM does not yet include organic carbon in the climate/chemistry component of the model.

In addition, emissions estimates for black carbon are highly uncertain. Cooke et al. (Cooke et al., 1999) attempt to construct an equivalent 1x1 degree emission data set for black and organic carbon but acknowledge that there is "at least a factor of 2 uncertainty" due to problems with emissions data. In addition, despite the 1x1 degree resolution, in fact the emissions are only calculated at the national level, and then a simple mapping to population density is made from there. We can see some of the uncertainties involved in calculating activity and emissions factors when we note that for biomass burning, the EDGAR database tentatively, and somewhat arbitrarily, assumes that 50% of the biomass is burned. Finally, there is significant uncertainty involved in even the characterization of what constitutes black carbon versus organic carbon versus non-carbonic impurities.

The temperature change resulting from black carbon may be unrealistically large (Wang, C, personal communication), and further investigations into the model structure leading to this large black carbon impact are ongoing. Because the sulfate aerosol forcing constant is set such that all forcing from all aerosol in the 1980s approximates best estimates for that decade, any changes in black carbon forcing are likely to be partially compensated by opposing changes in sulfate aerosol forcing (in the case where all pollutants are controlled). This does mean that both sulfate and black carbon impacts may be currently overestimated. However, there are some researchers (Tami Bond) who believe that black carbon has a significant impact on global mean surface temperature, and therefore the black carbon results from the current model version are not outside the realm of believability.

H. Fictionistan

In the analysis of effiency losses due to lack of coordination between air pollution and climate policies we showed that there was a danger of taking a "naive" approach. This approach would involve adding the cost of an air pollution policy to the cost of a climate policy and comparing that sum to the cost of the two policies implemented simultaneously (and therefore, presumably efficiently, in the context of a general equilibrium model, though as we have showed that there is not always a perfect correspondence between minimizing prices of pollutants and minimizing consumption loss). In order to solve this problem, we devised an iterative method involving setting constraints at a level equal to that of the ancillary impact on the non-constrained gas. The cost of the original GHG control run minus the cost of achieving the ancillary control would allow us to add the cost of GHG control to the cost of air pollution control more accurately than the original "naive" approach. In order to demonstrate the value of this iterative methodology, we created a fictional nation 'Fictionistan' which has available a set of nine reduction measures which control CO_2, BC, or both, each at a given cost (Table H-6). We then attempt to choose a set of measures to achieve at the lowest possible cost a CO_2 reduction of 50 units, a BC reduction of 50 units, or both reductions simultaneously. The results are shown in Table H-1.

Constraint	Options	CO_2 red.	BC red.	Cost
CO_2	TBNW	53	15	61
BC	TMYQS	20	56	77
CO_2+BC	TOMWNY	53	50	90

Table H-1: Optimal set of options for achieving constraints to CO_2, black carbon, or both simultaneously.

We note that there are ancillary BC reductions from the CO_2 constraint, and ancillary CO_2 reductions from the BC constraint. The "naive" approach would compare the sum of the two constraint costs (61 + 77 = 138) and compare that to the cost of the combined policy (90), and show that the welfare penalty for not allowing coordination between policies is 53%. There are two obvious reasons why this "naive" approach is wrong. The first is that option "T" is used in both the CO_2 constraint case and the BC constraint case, and therefore its cost is being double counted. If we just take the option set TBNWMYSQ then the cost of the combined policy is 131, not 138. The other problem is that this combined option set actually far exceeds the actual constraint levels. As can be seen in Table H-2, the combined set has 66 units of CO_2 reductions rather than 50, and 64 units of BC reductions. If we take the minimal set required to meet the constraint by removing the least cost effective CO_2 reduction (option W) and the least cost effective BC reduction (option S), the cost of meeting the constraint drops to 105. This is the number that should be compared to the combined policy cost of 90, or only a 17% welfare penalty for lack of coordination. This difference mainly comes because option O is the second most efficient option for reducing both pollutants simultaneously, but not efficient for reducing either pollutant individually. Also, option W was left out of the minimal set, as the most expensive per unit reduced of the CO_2 options, but is actually more efficient than Option N if pollution reduction is also a goal.

Constraint	Options	CO_2 red.	BC red.	Cost
CO_2+BC – all	TBNWMYQS	66	64	131
CO_2+BC – minimal	TBNMYQ	53	53	105

Table H-2: A comparison of the combination of all of the options necessary to meet the CO_2 constraint and BC constraint individually to the minimum set of those options that is required to meet the two constraints.

The above analysis is fairly straightforward: however, it is impossible to determine the "minimal set" doing a CGE analysis. We can, however, set constraints to try to meet the ancillary benefits level, thereby having a CO_2 constraint at 20 and a BC constraint at 15, as seen in the Table H-3.

Constraint	Options	CO_2 red.	BC red.	Cost
CutOff: CO_2 20	TB	27	7	29
CutOff: BC 15	TM	10	16	18

Table H-3: Meeting constraints equal to the ancillary benefits of the original policy

These two scenarios have their own ancillary benefits, and so another iteration was performed (Table H-4).

Constraint	Options	CO_2 red.	BC red.	Cost
CutOff: BC 7	T	7	7	7
CutOff: "CO_2 10"	(10/27*TB)	10	2.6	10.7

Table H-4: Second iteration of setting constraints equal to ancillary benefits

So, we can now look at the cost of the original policies (CO_2 constraint of 50 or a BC constraint of 50), and the first and second iterations of corrections in Table H-5.

Constraint Combination	Cost
CO_2 50	61
CO_2 50 - BC15	43
CO_2 50 - BC15 + "CO_2 10"	53.7
BC 50	77
BC 50 - CO_2 20	48
BC 50 - CO_2 20 + BC 7	55

Table H-5: Cost of original two policies and the cost of those policies after one and two iterations of the adjustment scheme described in this chapter

At zero iterations, the sum of the cost of the two individual policies is 138, which we showed is a tremendous overestimate of the "true cost" of 105. At one iteration, the sum is

91, which is rather an underestimate of the true cost. After two iterations, the sum is 108.7, which is now approaching the right number. Unfortunately, the resolution of this exercise does not allow us to prove that the convergence will lead to the exact right number. Given that this exercise is a simple linear programming model and not a full CGE model, even such perfect convergence would not be proof. However, it should serve as a logical demonstration of the methodology and why this method was necessary.

Option	CO_2 red	BC red	Cost	Cost/CO_2	Cost/BC	Cost/SUM
B	20	0	22	1.10	NA	1.10
M	3	9	11	3.67	1.22	0.92
N	14	4	17	1.21	4.25	0.94
O	13	14	23	1.77	1.64	0.85
Q	5	21	31	6.20	1.48	1.19
S	1	7	11	11.00	1.57	1.38
T	7	7	7	1.00	1.00	0.50
W	12	4	15	1.25	3.75	0.94
Y	4	12	17	4.25	1.42	1.06

Table H-6: Full Set of Reduction Options available in Fictionistan

Glossary

AGAGE – Advanced Global Atmospheric Gases Experiment
AGGG – Advisory Group on Greenhouse Gases
Annex B – As defined in the Kyoto Protocol, nations that agreed to emission constraints
AR4 – Fourth Assessment Report of the IPCC
BAU – Business As Usual
BC – Black Carbon
CCSP – Climate Change Science Program
CDM – Clean Development Mechanism, a method by which Annex B nations in Kyoto can gain CERs by implementing emission reducing projects in non-Annex B nations
CER – Certified Emission Reduction
CFC – Chlorofluorocarbons
CH_4 – Methane
CGE – Computable General Equilibrium
CLM – Community Land Model
CO_2 – Carbon Dioxide
CO_2eq– Carbon Dioxide equivalents (using GWP weightings)
CS – used in this thesis to refer specifically to equilibrium Climate Sensitivity – change in global mean temperature at equilibrium resulting from a doubling of CO_2
EINT – Energy intensive industries
EMF – Energy Modeling Forum
EMIC – Earth Model of Intermediate Complexity
EPA – Environmental Protection Agency
EPPA – Emissions Prediction and Policy Analysis (CGE economic modeling tool developed by the MIT Joint Program: Appendix A)
ETS – Emission Trading System (EU carbon trading)
EU – European Union
Faer – aerosol forcing parameter
GAINS – Greenhouse Gas and Air Pollution Interactions and Synergies
GCM – Global Climate Model
GHG – Greenhouse Gas
GTAP – Global Trade Analysis Project
GtC – Gigatons of Carbon
GtCeq – Gigatons of Carbon equivalent (using GWP weightings)
GWP – Global Warming Potential
HFC – Hydrofluorocarbons (HFC-134a is the representative species used in the IGSM)
H_2O – water
ICLEI – International Council for Local Environment Initiatives
IGSM – Integrated Global Systems Model (modeling tool developed by the Joint Program: Appendix B)
INE – Instituto Nacional de Ecologia (Mexican environmental agency)
IPCC – Intergovernmental Panel on Climate Change
JI – Joint Implementation
Kv – effective diffusion coefficient (a parameter to capture mixing by all processes, used in 2D model)

Kz – coefficient for vertical diffusion (small scale mixing parameter, used in 3D ocean model)
LDC - Least Developed Country
LEV – Low Emission Vehicle
LULUCF – Land Use, Land Use Change, and Forestry
M2M – Methane to Markets
MAC – Marginal Abatement Cost
MERGE - Model for Evaluating Regional and Global Effects
MIT – Massachusetts Institute of Technology
MMT – Million Metric Tons
N_2O – Nitrous Oxide
NEM – Natural Emissions Model
NGCC – Natural Gas Combined Cycle
NGCC_S/B – Shoulder or Base load
NMVOC – Non-Methane Volatile Organic Compounds
NOAA – National Oceanographic & Atmospheric Administration
NO – Nitrogen Oxide
NO_2 – Nitrogen dioxide
NOx – Nitrogen Oxides (usually NO + NO_2)
Non-Annex B – nations not included in Annex B
OC – Organic Carbon
OECD - Organization for Economic Cooperation and Development
OH – hydroxyl radical
PC – Pulverized Coal
PC_S/B – Shoulder or Base load
pdf - probability distribution function
PFC – Perfluorocarbon (CF_4 is the representative species used in the IGSM)
PNNL - Pacific Northwest National Labs
PPP – Purchasing Power Parity
SAR – Second Assessment Report of the IPCC
SF_6 – Sulfur hexaflouride
SO_2 – Sulfur dioxide
SOx – Sulfur Oxides
SRES – Special Report on Emission Scenarios
TAR – Third Assessment Report of the IPCC
TCR - Transient Climate Response - temperature change at the time of doubling CO_2 in a 1%/year increase scenario
TEM – Terrestrial Ecosystem Model
Ton – Throughout the thesis, ton refers to metric tonne
ULEV – Ultra Low Emission Vehicle
UN – United Nations
UNEP – UN Environment Program
UNFCC – UN Framework Convention on Climate Change
US – United States
VOC – Volatile Organic Hydrocarbons
W – Watt, equals joule/second

WMO – World Meteorological Association

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