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Climate Impacts and Mitigation Costs of Non-CO$_2$ Gases

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PEW CENTER
ON
Global CLIMATE CHANGE

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Prepared for the Pew Center on Global Climate Change

by

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

In the effort to understand and address global climate change, most analysis has focused on rapidly rising emissions of carbon dioxide (CO_2) and options for reducing them. Indeed, carbon dioxide, a byproduct of fossil fuel combustion, is the principal greenhouse gas contributing to global warming. However, other greenhouse gases including methane, nitrous oxide, and a number of industrial-process gases also are important contributors to climate change. From both an environmental and an economic standpoint, effective climate strategies should address both carbon dioxide and these other greenhouse gases.

Non-CO_2 gases account for 17 percent of total greenhouse gas emissions in the United States and a much larger percentage in developing countries such as India and Brazil. In addition, a host of local and regional air pollutant emissions interact in the atmosphere's complex chemistry to produce either additional warming or cooling effects. Understanding how these gases interact—and how to craft policies that address a range of environmental impacts—is vital to addressing both local and global environmental concerns.

In this report, authors John Reilly, Henry Jacoby, and Ronald Prinn of M.I.T. unravel some of the complexities associated with analyzing the impacts of these multiple gases and opportunities for reducing them. Emissions originate from a wide range of sectors and practices. Accurate calculation of emissions and emission reductions is easier for some sources than for others. For policy purposes, various greenhouse gases are compared on the basis of "global warming potentials," which are based on the atmospheric lifetime of each gas and its ability to trap heat. However, these do not yet accurately capture the climatic effects of all the substances contributing to climate change and so must be used with some caution. While scientists have recognized the various roles of non-CO_2 gases and other substances that contribute to climate change for some time, only recently have the various pieces of the puzzle been fit together to provide a more complete picture of the critical role these gases can play in a cost-effective strategy to address climate change.

Using M.I.T.'s general equilibrium model, the authors demonstrate that including all greenhouse gases in a moderate emissions reduction strategy not only increases the overall amount of emissions reductions, but also reduces the overall cost of mitigation: a win-win strategy. In fact, due to the high potency of the non-CO_2 gases and the current lack of economic incentives, this analysis concludes that control of these gases is especially important and cost-effective in the near term. The policy implications are clear: any attempt to curb warming should include efforts to reduce both CO_2 and non-CO_2 greenhouse gases.

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Executive Summary

Most discussions of the climate change issue have focused almost entirely on the human contribution to increasing atmospheric concentrations of carbon dioxide (CO_2) and on strategies to limit its emissions from fossil fuel use. Among the various long-lived greenhouse gases (GHGs) emitted by human activities, CO_2 is so far the largest contributor to climate change, and, if anything, its relative role is expected to increase in the future. An emphasis on CO_2 is therefore justified, but the near-exclusive attention to this single contributor to global warming has had the unintended consequence of directing attention away from the other GHGs, where some of the most cost-effective abatement options exist. The non-CO_2 GHGs emitted directly by human activities include methane (CH_4) and nitrous oxide (N_2O), and a group of industrial gases including perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6). When taken together with the already banned chlorofluorocarbons (CFCs), their climate significance over the past century is roughly equivalent to that of CO_2. Looking to likely emissions over the next half-century, it is also the case that feasible reductions in emissions of methane and other non-CO_2 gases can make a contribution to slowing global warming that is as large as or even larger than similar reductions in CO_2 emissions. To effectively limit climate change, and to do so in a cost-effective manner, thus requires that climate policies deal with CO_2 and non-CO_2 gases alike.

There are several reasons why attention has been focused so heavily on CO_2 even though the full list of GHGs has been targeted for control under international climate agreements. Emissions of CO_2 from fossil sources can be readily estimated from market data on fuel use, whereas the other gases present measurement difficulties. Also, the analysis of abatement options for fossil emissions benefits from decades of research on energy markets, energy efficiency, and alternative energy supply technologies—work that was spurred by concerns about the security of supply and prices of fossil fuels. The analytical capability developed to study energy markets was then readily applied to the climate issue. Now that the capability to measure and assess the non-CO_2 GHGs has improved, it is clear that their control is also an essential part of a cost-effective climate policy.

In addition to the main non-CO_2 GHGs identified above, there are other emissions from human activities that are not included in existing climate policy agreements but that nonetheless retard or enhance the greenhouse effect. Tropospheric ozone (O_3) is a natural greenhouse constituent of the atmosphere. Emissions of carbon monoxide (CO), nitrogen oxides (NO_X), aerosols, non-methane volatile organic compounds (NMVOCs), and ammonia (NH_3) all affect the chemistry of tropospheric ozone and methane. Black carbon or soot, though not well-understood, is thought to contribute to warming as well. Other human emissions have the opposite of a greenhouse effect. Sulfur dioxide (SO_2) and nitrogen oxides (NO_X), mainly from fossil fuel combustion, are converted by chemical processes in the atmosphere into cooling aerosols. These various gases and aerosols are related to one another by their common generation in industry and agriculture as well as by their interaction in the chemistry of urban areas, the lower atmosphere, and the stratosphere. Thus, policies that reduce CO_2 also may affect emissions of SO_2, NO_X, and CO, as well as the non-CO_2 greenhouse gases.

Designing a cost-effective approach for control of these multiple substances requires some way of accounting for the independent effects of each on climate. The current method for doing so is a set of indices or weights known as global warming potentials (GWPs). These have been developed for the main GHGs, but not for SO_2 and other local and regional air pollutants. By design, the GWP for CO_2 is 1.0 and the values for other GHGs are expressed in relation to it. These indices attempt to capture the main differences among the gases in terms of their instantaneous ability to trap heat and their varying lifetimes in the atmosphere. By this measure, for example, methane is ton for ton more than 20 times as potent as CO_2, while N_2O is about 300 times as potent, and the industrial gases are thousands of times as potent when taking into account the atmospheric effects of these gases over the next 100 years.

The relative value of controlling non-CO_2 gases, as expressed by these GWPs, is one key reason that inclusion of the non-CO_2 gases in policies to address climate change can be so effective in lowering implementation costs, particularly in the early years. Given the high carbon-equivalent values of the non-CO_2 gases, even a small carbon-equivalent price on these gases would create a huge incentive to reduce emissions. Another reason is that, historically, economic instruments (i.e., prices, taxes, and fees) have not been used to discourage or reduce emissions of non-CO_2 gases, whereas price signals via energy costs exist to curb CO_2 emissions from fossil fuels.

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If, for example, the total GHG emissions reduction required to meet a target were on the order of 10 or 15 percent, as would be the case if total GHG emissions in the United States were held at year 2000 levels through 2010, nearly all of the cost-effective reductions would come from the non-CO_2 greenhouse gases. Compared to a particular reduction achieved by CO_2 cuts alone, inclusion of the non-CO_2 abatement options available could reduce the carbon-equivalent price of such a policy by two-thirds. This large contribution of the non-CO_2 gases, and their potential effect on lowering the cost of a climate policy, is particularly surprising because it is disproportionate to their roughly 20 percent contribution to total U.S. GHG emissions. In developing countries like India and Brazil, non-CO_2 gases currently account for well over one-half of GHG emissions. Any cost-effective effort to engage developing countries in climate mitigation will, therefore, need to give even greater attention to the non-CO_2 gases.

Of course, these gases are only part of an effective response to the climate threat. Even if they were largely controlled, we would still be left with substantial CO_2 emissions from energy use and land-use change. Over the longer term, and as larger cuts in GHGs are required, the control of CO_2 will increase in its importance as an essential component of climate policy.

There remain a number of uncertainties in calculating the climatic effects of non-CO_2 gases, and one is the accuracy of global warming potentials. Analysis has shown that the GWPs currently in use significantly underestimate the role of methane, and any correction of this bias would amplify the importance of the non-CO_2 greenhouse gases. This error is due in part to omitted interactions, such as the role of methane in tropospheric ozone formation. The GWPs also fail to adequately portray the timing of the climate effects of abatement efforts. Because of its relatively short lifetime in the atmosphere, abatement efforts directed at methane have benefits in slowing climate change that take effect over the next few decades, whereas the benefits of CO_2 abatement are spread out over a century or more. To the extent one is concerned about slowing climate change over the next 50 years, therefore, the control of methane and HFCs—the gases that last a decade or so—has an importance that is obscured when 100-year GWPs are used to compare the contributions of the various gases. Economic formulations of the GWP indices have been proposed that would address these concerns, but calculations using these economic-based formulae are bedeviled by a variety of deeper uncertainties, such as how to monetize the damages associated with climate change.

A still more difficult issue is whether and how to compare efforts to control other substances that affect the radiative balance of the atmosphere, such as tropospheric ozone precursors, black carbon, and cooling aerosols. The main issue with these substances is that, even though their climatic effects are important, a more immediate concern is that they cause local and regional air pollution that affects human health, crop productivity, and ecosystems. Moreover, their climatic effects are mainly regional, or even local, and this feature creates difficulties for the use of a single index to represent their effects across the globe. In the end, it is essential to consider these substances as part of climate policy, but more research and analysis is needed to quantitatively establish their climate influence and to design policies that take account of their local and regional pollution effects.

Putting aside the local and regional air pollutants, the quantitative importance of the other non-CO_2 greenhouse gases has now been relatively well-established. One of the major remaining concerns in including them in a control regime is whether their emissions can be measured and monitored accurately so that, whatever set of policies are in place, compliance can be assured. In fact, the ability to monitor and measure has less to do with the type of greenhouse gas than with the nature of its source. It is far easier to measure and monitor emissions from large point sources, such as electric power plants, than from widely dispersed non-point sources, such as automobile and truck tailpipes or farmers' fields. Methane released from large landfills can be easily measured, and is in the United States. But, it is impractical to directly measure the methane emitted from each head of livestock, or the N_2O from every farmer's field. The difficulty of monitoring and measuring emissions implies that a different regulatory approach may be desirable for different sources, at least initially.

Scientists have long recognized the various roles of non-CO_2 greenhouse gases and other substances that contribute to climate change. It is only in the past few years, however, that the various pieces of this complex puzzle have been fit together to provide a more complete picture of just how critical the control of these gases can be in a cost-effective strategy to slow climate change. Control of non-CO_2 greenhouse gases is a critical component of a cost-effective climate policy, and particularly in the near term these reductions can complement early efforts to control carbon dioxide.

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I. Introduction

Human activities are contributing a complex mix of greenhouse gases (GHGs) to the atmosphere, perturbing the radiation balance of the Earth and to some degree modifying its climate. Carbon dioxide (CO_2), mainly from fossil fuel burning, is the most important single anthropogenic source of these emissions. Of critical importance, however, are emissions of non-CO_2 gases—including methane (CH_4) and nitrous oxide (N_2O)—that are naturally present in the atmosphere, and a group of industrial gases (hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulfur hexafluoride, SF_6) not found in nature. Taken together, their historical significance is roughly equivalent to that of CO_2. To effectively limit climate change, and to do so in a cost-effective manner, climate policies need to deal with CO_2 and non-CO_2 gases alike.

For scientists, policymakers, and analysts who deal closely with the climate change issue, the importance of these many other substances is largely non-controversial, even though uncertainties in the specific estimates remain. Indeed, the United Nations Framework Convention on Climate Change (UNFCCC), the original international treaty that set out the goal of stabilizing atmospheric concentrations of GHGs, explicitly recognizes the multiple substances contributing to climate change. Often, however, and for a variety of reasons, even those quite knowledgeable about the climate issue focus the discussion almost exclusively on CO_2 emissions from fossil fuels when discussing climate policy. Doing so risks misinforming the public and policymakers and creates the chance that climate policies may be more costly and less effective than they need to be.

In addition to the main non-CO_2 greenhouse gases, which are covered in the Kyoto Protocol, there are other human emissions that are not included in existing climate policy agreements but that nonetheless retard or enhance the greenhouse effect. Ozone (O_3) is a natural greenhouse constituent of the atmosphere, and its concentration is being influenced by chemical reactions involving some of the GHGs and other gases that have no direct effect on climate. Carbon monoxide (CO) is converted to carbon dioxide (CO_2) in the atmosphere, but in the process influences the chemistry of tropospheric ozone and methane. Black carbon or soot, though not well-understood, is thought to be a warming influence as well.

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Other human emissions have the opposite of a greenhouse effect. Sulfur dioxide (SO_2) and nitrogen oxides (NO_X), mainly from fossil fuel combustion, are converted by chemical processes in the atmosphere into cooling aerosols. These gases and aerosols are related to one another by their common generation in industry and agriculture as well as by their interaction in the chemistry of urban areas, the lower atmosphere, and the stratosphere.

The non-CO_2 gases are important for climate policy not only for their contribution to the greenhouse effect, but also because they present attractive targets for control. Some of these gases have very powerful radiative effects and long residence times in the atmosphere, so the abatement of a ton of emissions may be worth hundreds or even thousands of times as much, in terms of reduced warming influence, as the prevention of a ton of CO_2 emissions. Even the weaker ones like methane, which is only roughly 20 times as potent as CO_2, offer control opportunities that are comparatively cheap when relative radiative strength and lifetime are taken into account. Thus, to achieve a climate policy that is economically efficient as well as environmentally effective, it is necessary to give balanced attention to CO_2 and these non-CO_2 contributors.

Designing such a cost-efficient approach faces a number of hurdles, however. Because of the complex chemistry and physics of the atmosphere, and the sequence of climatic, environmental, and economic consequences of human-induced change, precise comparison of the effects of the different gases is a challenging task. Moreover, whereas CO_2 emissions can be measured and monitored relatively well by the use of fossil fuels, some sources of the other gases are difficult to quantify. Particular cases are the agricultural sources of methane and N_2O, and they face difficulties not unlike the problems of measuring and monitoring uptake or emissions of CO_2 by agricultural soils. Such dispersed sources are always difficult to monitor, and these emissions are the product of biological processes that introduce additional uncertainties. Nonetheless, opportunities for cost-efficient control exist in these areas, and efforts to develop monitoring methods adequate to the task should yield high returns.

Discussion of the non-CO_2 gases begins in Section II with a brief summary of the science of the Earth's radiation balance and the role of GHGs, both natural and anthropogenic. Given this background, Section III shows how important these gases are as a target of climate policy. The relative costs of reductions of carbon dioxide and the non-CO_2 gases are then analyzed in Section IV, which uses examples of control regimes to demonstrate the relative roles of the different gases in an economically efficient implementation. Some of the difficulties of including these gases in a control program are explored in

Section V, with particular attention to problems of measurement and monitoring of agricultural emissions, and the difficulty of developing a scheme of relative weighting to allow implementation of a "basket" approach in emissions control agreements.

Section VI draws some important conclusions from the discussion. The main point to be stressed is that understanding the full range of human greenhouse interventions, including all the GHGs and their integration into an all-gas policy approach, is essential to the design of effective and efficient strategies for limiting the risk of global climate change.

II. The Science of Radiative Forcing

For the globe to maintain a stable temperature, energy from the Sun must be balanced by energy transmitted back to space (as reflected sunlight or emitted infrared radiation). While the Sun's input varies slightly over decades or centuries, the modern threat of climate change comes from human-induced modification of the radiation flow of energy to space by changing the Earth's surface and the composition of its blanket of atmospheric gases and clouds. The condition of the surface landscape matters because its brightness, or "albedo," helps determine how much of the Sun's input is reflected back through the atmosphere. Bright/smooth areas, like snow and ice, reflect incoming radiation while dark/rough surfaces absorb the short-wave solar energy and then re-emit it as long-wave infrared radiation. Materials in the atmosphere have two competing effects. Some absorb infrared radiation and re-emit some of it downwards, causing the Earth to warm. These are the greenhouse substances, which include greenhouse gases (water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other trace gases) as well as clouds. Clouds, and other suspended particles called aerosols, also reflect solar radiation. Like the bright components of the surface, they return some of the incoming solar radiation immediately back to space and thus cool the planet.

Human activities are modifying this input-output energy balance in several ways, but here the focus is on our most important current influence, which is the composition of the atmosphere.

A. The Earth's Radiation Balance

Even before human activities began changing the composition of the atmosphere, GHGs exerted a strong influence on the global climate. Without the natural level of GHGs, the Earth would be 33°C (60°F) cooler than it is now and largely covered by ice (see Box 1). By far the most important of all the GHGs is water vapor. Because of the importance of water, the other gases produce a complicated set of feedbacks—most positive, but some negative. To the degree they warm the globe, they cause more evaporation, and a warmer atmosphere can hold more water vapor, which in turn causes more warming. With more water vapor in the atmosphere, there is a good chance, however, that there will also be more clouds, and in this form water has a complex set of effects. Cloud particles reflect energy into space, an effect we experience when passing clouds block the Sun's energy.

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Box 1

Radiative "Forcing" and Climate Change

Most of the Sun's energy that reaches the Earth is absorbed by the oceans and land masses and radiated back into the atmosphere in the form of heat or infrared radiation. Most of this infrared energy is absorbed and re-radiated back to the Earth by atmospheric gases such as water vapor and carbon dioxide. This phenomenon, referred to as the greenhouse effect (figure below), serves to keep the Earth some 33°C (60°F) warmer than it would otherwise be. As concentrations of gases that absorb and re-radiate infrared energy (i.e., greenhouse gases) increase, the warming effect increases. The increase is called radiative "forcing" and is typically measured in watts per square meter (W/m^2), and the scientific basis for this estimate is relatively firm. The more controversial aspects of the effect of increases of radiative forcing on global temperature are that these gases have many indirect effects and feedbacks. Together they affect, for example, the level of water vapor, itself a greenhouse gas.

The **Greenhouse Effect**
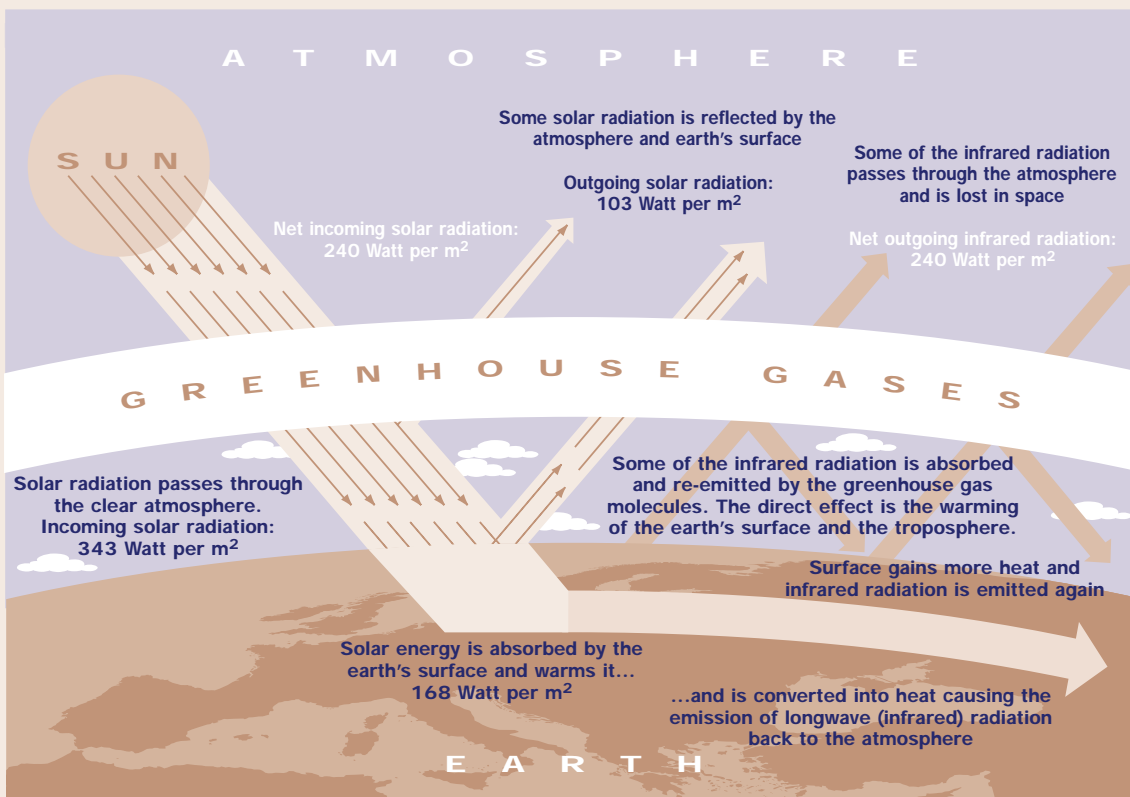
Note: Greenhouse gases are shown as a layer to simplify the drawing. In reality, they are dispersed throughout the atmosphere. Although the atmosphere consists largely of oxygen and nitrogen, neither absorbs infrared energy; thus, they do not play a role in warming the earth and are not greenhouse gases.

Source: Rekacewicz, 2000.

They also trap outgoing infrared energy and re-emit some of it toward the surface, which is why the temperature of the surface tends to drop much less on a calm, cloudy night than on a clear one. Because of these warming and cooling effects, the overall influence of clouds poses one of the greatest uncertainties in climate forecasts.

Various substances in the atmosphere affect climate (Box 2). Although, as mentioned above, the greenhouse effect is predominantly attributed to water vapor, other naturally occurring greenhouse gases (GHGs) such as CO_2, methane, nitrous oxide, and tropospheric ozone also contribute. CO_2 is constantly exchanged between the atmosphere and terrestrial vegetation through the processes of photosynthesis (CO_2 uptake) and respiration (CO_2 release), as demonstrated by the seasonal cycle of atmospheric CO_2 concentrations. Similarly, there is a constant exchange of CO_2 between the atmosphere and the ocean surface. On average, molecules of CO_2 in terrestrial vegetation or the oceans cycle back and forth to and from the atmosphere every 5 to 15 years. However, if CO_2 is transported into the deep ocean, it may take decades to millennia for it to return to the atmosphere. Carbon deposited in geologic reservoirs (e.g., ocean sediments, coal, or petroleum deposits) may remain trapped for millions of years before being released through volcanic activity or erosion. In the absence of human activities, the cycling of carbon has been approximately balanced (at least over the past few thousand years), preventing the disproportional accumulation of carbon in the atmosphere, such as that observed during the industrial era.

Box 2

Greenhouse-Relevant Material in the Atmosphere

Materials that influence the Earth's radiation balance come in various forms. Some are gases, which remain in the atmosphere for periods ranging from days to millennia, trapping heat while they are there. Other gases have no direct greenhouse effect, but they are components of the atmospheric chemistry that determines the lifetime of many of the heat-trapping gases. Various forms of particles or aerosols may have a positive or negative effect, depending on their relative brightness. Some present a white surface and reflect the Sun's energy back to space; others are black and absorb solar energy, adding to the solar warming of the atmosphere. Aerosols also have an indirect effect on climate in that they influence the "seeding" of clouds, which has a strong influence on the radiation balance.

Methane is produced naturally by bacteria in the digestive systems of animals, particularly ruminants (such as cattle, sheep, or goats), in soils, and in the sediments of wetlands and oceans. Meanwhile, methane is continuously destroyed on an approximately ten-year time scale by chemical reactions in the atmosphere. The exact pace of destruction of methane is determined by complex reactions in the lower atmosphere. It is destroyed by reaction with the hydroxyl radical (OH). This radical is so important in the destruction of methane and other pollutants that it is often referred to as the "cleansing agent" for our atmosphere. OH is produced by the action of ultraviolet (UV) radiation on a mix of other atmospheric gases and is itself destroyed as it "cleanses" the atmosphere. The lifetime of methane thus depends on how much OH is produced and how much is used in all the cleansing processes it performs. Important among the other substances that affect the amount of OH are nitrogen oxides (NO_x) and carbon monoxide (CO) produced by natural fires, ammonia (NH_3) and non-methane volatile organic compounds (NMVOCs) produced during various biological processes.

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Nitrous oxide (N_2O) also occurs naturally, produced by bacteria in soils. It is destroyed mainly by UV radiation. The lifetime of N_2O is determined by the time it takes for the gas to diffuse to high levels in the stratosphere, where the UV radiation is strong enough to break apart the molecule. The process of diffusion to high altitudes is fairly stable over time, and so, in contrast to methane, the lifetime of N_2O is fairly constant at about 120 years.

Some of these gases also serve as precursors of other substances that influence the radiation balance. Ozone (O_3) is not released in significant amounts through biological processes, but is created by chemical processes in the atmosphere. In the lower atmosphere (the troposphere), the available NO_X and organic compounds, plus UV radiation, are the main determinants of tropospheric ozone concentrations. Its lifetime is on the order of hours, and concentrations rise in heavily polluted areas during the day when the UV radiation from sunlight is present, and fall at night as it is destroyed by chemical reactions. Ozone also occurs naturally in the upper atmosphere or stratosphere. There, in addition to being a greenhouse gas, it fortunately blocks UV radiation from the Sun, limiting the amount reaching the Earth's surface to levels to which plants and animals have adapted over time.

Climate is also influenced by atmospheric aerosols. These are solid or liquid particles that are small enough to remain suspended in the atmosphere for periods of days to weeks before being washed out by precipitation or brought down simply by the force of gravity. For example, sulfur oxides (SO_X) and nitrogen oxides (NO_X) are converted into acid aerosols. SO_X is produced naturally by the oxidation of sulfur gases produced biologically in oceans and swamps. Dust blown from the Earth's surface, the smoke and ash from volcanic eruptions, and carbon-rich particles (i.e., soot) from natural fires also add to the natural aerosol load. Some of these aerosols are bright and reflect solar radiation back to space. Others are dark and absorb the incoming solar radiation and warm the air around them.

B. Large-Scale Human Intervention

Using data from ice cores and other sources, scientists have been able to estimate past GHG concentrations. While over its longer history the Earth has experienced large and even rapid changes in the atmospheric concentrations of these gases, they have remained relatively stable for the past 10,000 years—that is, until the industrial revolution. Human settlements have been around for several millennia, and these populations cleared forests, drained wetlands for agriculture, and otherwise altered the Earth's landscape in ways that affected GHG emissions and surface albedo. Until the industrial revolution, however, the small and slowly growing population had only a minor influence on the Earth's atmosphere.

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The mark of the industrial revolution, beginning around 1850, was the replacement of human and animal power with energy from fossil fuels. The general expansion of economic activity and improvements in technology made it possible to support larger populations, which in turn contributed to larger-scale changes in the landscape. These forces accelerated, particularly in the 20th century with the growth of the economies of European and North American countries, and then the spread of industrialization worldwide. The primary GHGs and other pollutants that affect climate directly and indirectly, and the many activities that emit them, are listed in Table 1.

Table 1

Anthropogenic Sources of the Primary Non-CO$_2$ Emissions

Substance	Major Sources
Greenhouse Gases	
Methane (CH$_4$)	Many sources with no single dominant one: Petroleum and coal production, gas distribution, landfills, livestock (manure and enteric fermentation), rice production, decomposition or burning of other waste.
Nitrous Oxide (N$_2$O)	The major source is agricultural soils through enhanced levels of nitrogen (from either natural or synthetic sources). Chemical production and fuel combustion are important secondary sources.
Chlorofluorocarbons (CFCs)	A family of industrially produced substances, they have now been nearly phased out of use because they deplete stratospheric ozone. They were widely used in air conditioning, as propellants, and in many other minor uses.
Hydrofluorocarbons (HFCs)	A family of industrially produced gases with the largest uses in air conditioning and foam blowing. Developed as a replacement for CFCs which were phased out because they deplete stratospheric ozone.
Perfluorocarbons (PFCs)	A family of industrially produced gases used in semi-conductor production, for plasma etching and chemical vapor disposition, and released as a byproduct of aluminum smelting.
Sulfur Hexafluoride (SF$_6$)	Industrially produced and used as an insulator in electrical switchgear and as a cover gas in magnesium smelting.
Ozone (O$_3$)	Occurs in the stratosphere, where it is depleted by CFCs, and in the troposphere (the main ingredient of smog). NO$_X$, SO$_X$, CH$_4$, NMVOCs, and CO are all involved in its formation and destruction in the troposphere.
Other Climatically Important Substances	
Sulfur Dioxide and other oxides of sulfur (SO$_X$)	Main source is from coal burning, but other important sources are combustion of oil products, ore smelting, and biomass combustion.
Non-Methane Volatile Organic Compounds (NMVOCs)	Many different volatile components of fuels, chemicals, and solvents that evaporate and/or are the product of incomplete combustion, such as in biomass burning.
Nitrogen Oxides (NO$_X$)	Byproduct of combustion of fossil fuels and biomass.
Carbon Monoxide (CO)	Byproduct of combustion of fossil fuels and biomass.
Black Carbon (BC) and Organic Carbon (OC) (Soot and dust)	Incomplete combustion product of fossil and biomass fuels and also dust from fields and highways. Diesel fuel combustion is a major urban source.
Ammonia (NH$_3$)	Nitrogen fertilizer use, manure management, and sewage.

The most important of the non-CO$_2$ anthropogenic gases is methane, whose emissions grew from the expansion of agriculture, particularly the increased production of paddy rice and ruminant livestock. Paddy rice production creates conditions similar to those that exist in natural wetlands, where decomposition

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with limited oxygen favors the production of methane. With greatly expanded livestock production, enteric fermentation by cattle and other ruminant livestock (the process by which these animals digest cellulosic material in their feed) also has become a significant source of methane, well beyond the levels produced by ruminants in the wild or from the relatively small herds kept by pre-industrial humans.

Modern methods of handling waste also have increased methane production. Landfills, used most widely in the United States, create anaerobic conditions where decomposition of biomass material in the waste leads to methane production. Similarly, large-scale manure management systems, where the waste is stored in pits with little mixing, create anaerobic conditions and methane production. Other waste disposal methods, such as incineration, open disposal, or direct spreading of manure on fields, lead to less methane production. Also, modern methods of sewage treatment expose the waste to oxygen during decomposition, so emissions are in the form of CO_2 rather than the more potent methane.

Fossil fuel production is also an important contributor because natural gas is mostly methane,[1] and any leakage during production and distribution contributes to atmospheric concentrations. Natural gas is also associated in varying quantities with oil and coal deposits, and often it is intentionally vented during production. If flared (combusted) to convert the methane to CO_2, it has less effect on the radiative balance. Methane is also a byproduct of incomplete combustion of biomass. Incomplete combustion occurs when the burning process is very inefficient, as is often the case during land clearing, burning of agricultural waste, and heating and cooking in traditional communities.

Human contributions to N_2O emissions are also important. The major sources of anthropogenic N_2O are in agriculture, but energy combustion is also a significant source. The cycling of nitrogen—an essential plant nutrient—through soils inevitably leads to some losses in the form of gaseous N_2O. Modern agriculture has sought ever-higher yields by applying additional nutrients to cropland, particularly nitrogen in the form of synthetic fertilizers. Even the addition of nitrogen to the soil in the form of manure and leguminous (nitrogen-fixing) crops increases the amount of N_2O emitted from soils. The gas is also a minor byproduct of combustion—most importantly of fossil fuels, but also of biomass—and is emitted in certain industrial chemical processes, like nylon production.

Another important warming gas increased by human activities is ozone in the lower atmosphere or troposphere. For the most part, ozone is not produced directly by human activities; as noted above, NO_x, CO, NMVOCs, and methane in the atmosphere lead to its production, and human activities are major sources of these "precursors." We observe the result of these chemical processes most directly in photochemical smog.

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Human activities are also important contributors to aerosols, which are a complex mix of substances, as discussed above; some cause cooling and others contribute to warming. Pure sulfur dioxide and other sulfur oxides produce aerosols that are reflective and have a cooling effect. Sulfur is present in varying forms in fossil fuels, especially in some coals, and their combustion leads to sulfur emissions, although the United States and nearly all other industrial countries regulate these emissions to some degree.

The pure form of heat-absorbing aerosol is "black carbon" (a component of soot). It is the product of incomplete combustion of fossil fuels, the main source being diesel engines. Some amount of soot and ash (i.e., aerosols or, in pollution control circles, "particulate matter") are emitted from all combustion processes. The more inefficient the combustion and the greater the fuel impurities, the higher the emissions. Separating aerosols into their constituent parts makes it possible to consider their pure properties from a scientific perspective, but this separation is somewhat artificial. These absorbing and reflecting aerosols are produced together, or, once in the atmosphere, are combined into the same "particle." All of these factors contribute to uncertainty about their overall radiative effects and make it difficult to track the fate of emissions as they are transported and reconfigured in the atmosphere.

Concern about emissions of ozone precursors and the various aerosols arise first and foremost because they are responsible for urban and regional air pollution problems. Black carbon contributes to lung-related illness. Tropospheric ozone also causes lung problems and damage to crops and natural ecosystems. Emissions of SO_X and NO_X, and the acid aerosols that are produced, are harmful to human health as well as being a source of acid rain. Thus, two areas of policy development, climate change and air pollution, are inextricably intertwined.

Finally, there are the industrial gases or halocarbons, including the CFCs (Table 1). Beginning in the 1930s, chemists developed a set of gases for refrigeration, solvent use, and other applications that would not react during their use or with other molecules in the environment after their release. In this way the manufacturers intended to ensure that they would not directly injure human or other life. Unfortunately, only much later was it found that they destroy the Earth's protective ozone layer, and so they are being rapidly phased out of use under the Montreal Protocol.[2] Hydrofluorocarbons (HFCs) are used in air conditioning, foam blowing, and other applications, and were developed to replace CFCs. HFCs do not deplete stratospheric ozone, have shorter lifetimes, and are less potent warming substances than CFCs. The radiative properties of different gases within the HFC family also differ, and so it is possible to substitute toward those with the lowest warming potential. Nevertheless, their use is expected to

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grow substantially and thus, even with lower warming properties than CFCs, HFCs could contribute sub-stantially to global warming if their release to the atmosphere is not controlled.[3] Perfluorocarbons (PFCs) have their main sources in semiconductor manufacturing and aluminum smelting. Finally, sulfur hexafluo-ride (SF_6) is used mainly in electrical transformers and magnesium smelting. Molecule for molecule, all of these chemicals are much more powerful greenhouse gases than CO_2. Thus, although they are present only in small quantities in the atmosphere today, they can be potent contributors to changes in the radia-tive balance in the long term.

III. The Relative Importance of the Non-CO$_2$ Gases

A. Characteristics of the Gases

The substances that influence the Earth's radiative balance differ from one another in three ways:

- The direction of the radiative effect (warming or cooling);
- The strength of the effect (called "instantaneous radiative forcing"); and
- Their residence time in the atmosphere (the longer their life, the bigger their cumulative effect).

All of these characteristics are important for studies of climate change and thus for the formulation of emissions control policy. Because of these varying characteristics, however, very different analytical difficulties arise depending on whether the focus is on emissions, on atmospheric concentrations and total radiative effect, or on climate change over the next few decades or centuries.

Analysis of the radiative effects of atmospheric concentrations at any point in time is straight-forward conceptually, though technically complex. The total radiative forcing of any mix in the atmosphere is approximately the instantaneous radiative forcing of each substance (its forcing per unit mass multiplied by its mass in the atmosphere) added up over all the materials that have some radiative effect. Figure 1, adapted from the Intergovernmental Panel on Climate Change's Third Assessment Report (IPCC, 2001a) presents such an estimate for the late 1990s, expressed as a difference from pre-industrial times (1750). Using the central estimates for each of these forcings, the net effect is an increase in total radiative forcing of about 1.2 watts per square meter.

Emissions of carbon dioxide from human activities were the biggest single contributor to increased radiative forcing over the period. However, radiative forcing of the other greenhouse gases—tropospheric ozone, methane, nitrous oxide, and the industrial gases—together are of equal importance to that from CO$_2$. The figure also shows the estimated radiative effects of the other climatically important substances, the aerosols. All are subject to considerable uncertainty, as the figure shows, with the weakest understanding attached to mineral dust and the "indirect" effect of aerosols through their possible influence on cloud

Figure 1

Contributions to Increased Radiative Forcing 1750 to late 1990's
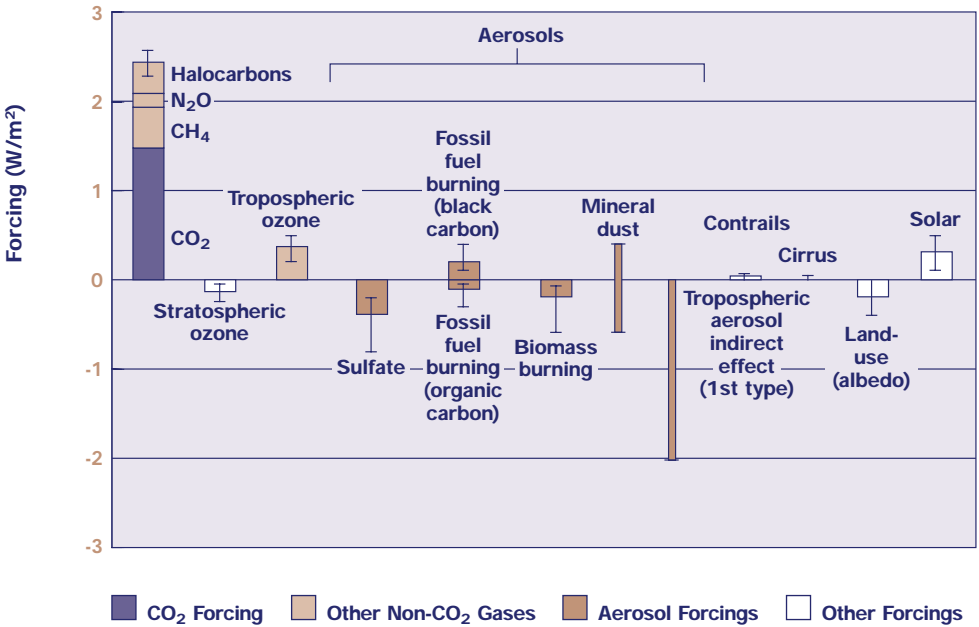
Note: This figure breaks out the contributions, positive and negative, of individual gases and substances to radiative forcing. CO_2 forcing is shown in dark blue. Other non-CO_2 warming gases are shown in light brown, and the various aerosol forcings are shown in dark brown. This color coding facilitates comparison of the relative importance of CO_2, non-CO_2 GHGs, and aerosols. The halocarbons include forcing from CFCs, HFCs, PFCs, and SF_6. Historical contributions are dominated by the CFCs that are now rapidly being phased out, while the other sources, particularly HFCs, are becoming more important. The vertical bars indicate the uncertainty in the effect attributed to each source. Ideally, one would like to express the uncertainty in total net forcing of all these substances, +/- a given amount, but there is no good way to combine the error bars presented in this figure. Taking either all-high or all-low values and adding them together would give a very wide range, almost certainly too wide, because that process would be correct only if the errors were perfectly correlated.

Source: IPCC, 2001a.

formation. Note also that the central estimate of the cooling effect of sulfate aerosols is similar to the warming effect of either tropospheric ozone or methane, but is partly offset by the positive forcing (warming) by black carbon aerosols. Jet aircraft contrails and cirrus clouds contribute a relatively small amount of warming, as shown in Figure 1.

Changes in atmospheric composition are not the only human influence on global climate, as noted earlier. Land use change, caused mainly by expansion of cropland, clearing of forests, urbanization, and other activities, is estimated to have had a cooling effect. A natural change, that of solar intensity due to natural variability of the Sun's energy output, had a warming effect over the past century, as estimated by the IPCC, but there is no reason to expect a consistent direction or magnitude of this forcing in the future.

Because different greenhouse gases have different lifetimes and varying potency, it is difficult to compare their relative importance for potential climate change. To illustrate the problems that arise, consider the emissions of just two gases, CO_2 and methane. To analyze the effects of the release of one ton of each, it is not enough to simply compare their instantaneous radiative forcings because, even though methane is much stronger per ton, the ton of methane will be largely removed from the atmosphere in a couple of decades, whereas much of the CO_2 will remain for a century or so. Nonetheless, some set of exchange rates or relative weightings is needed to allow comparison of emissions of the various gases— for example, in calculating the relative value of reductions of one gas versus another, or in computing the credit to be given for some combination of emissions reductions. Because such a weighting system is used mainly in policy studies of various types, the weights should reflect the relative damage they cause through their impact on human and natural systems.

Unfortunately, we lack broadly acceptable measures of climate damage to serve this function. Some intermediate measure, like the effect of a ton of emissions on global temperature, might serve as a proxy, but such an approach introduces all the uncertainty in the climate system and its response to radiative forcing. As a rough compromise, the effects of emissions of a ton of CO_2 and a ton of some other gas are usually compared by adding up the radiative forcing produced by a ton of each over some arbitrarily chosen time period (the standard has become 100 years as adopted for the Kyoto Protocol) and stating their relative importance in relation to CO_2. The resulting number is called the global warming potential, or GWP, of the gas. The convention of reporting the index relative to CO_2 means that the indices are dimensionless and CO_2 has a GWP of 1.0. As calculated by the IPCC (1996), methane, with a higher instantaneous forcing than CO_2 but a shorter lifetime, has a GWP of 21, whereas SF_6, which is both a strong energy absorber and very long-lived, has a GWP of 23,900. To illustrate that these are hardly firm numbers, the IPCC in its most recent report revised these estimates to 23 for methane and 22,200 for SF_6 (IPPC, 2001a). With such a set of exchange rates, however, emissions of gases with direct radiative effects can be stated in "carbon-equivalent" units.

As convenient as this set of equivalence indices has proven, there are a number of difficulties with this method of comparing emissions of gases. One example is the problem of handling aerosols and tropospheric ozone. The primary purpose of the GWPs is to guide tradeoffs in emissions control among the various contributors to climate change. A GWP for SO_2 would be negative, which might indicate that its emissions should be encouraged. Obviously, one needs to take into account in crafting SO_2 policies the negative effects of these emissions on human health and the environment, but these effects cannot be converted into radiative forcing; to compare the effects

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would require monetizing all of the damages of climate change and sulfur emissions. Similarly, a GWP for tropo-spheric ozone could be estimated, but this would provide a very poor guide to emissions control because the emissions of interest are tropospheric ozone precursors (NO_X, CO, NMVOCs, and methane), and their relationship to tropospheric ozone is highly nonlinear and strongly dependent on the particular urban pollution environment into which they are emitted. Moreover, tropospheric ozone is not well-mixed in the atmosphere and its lifetime is on the order of hours, so any climate effects are principally local to where the tropospheric ozone is produced. A global average GWP for tropospheric ozone or its precursors would have little meaning in comparison to GWPs for globally well-mixed greenhouse gases.

We return to these and other issues as they pertain to climate policy in Section V below. Even with these problems, however, GWPs can provide an approximate measure of the relative importance of some sources of the greenhouse effect, particularly those gases covered in the Kyoto Protocol, which do not introduce the more difficult problems presented by tropospheric ozone and aerosols. For example, Figure 2 shows the relative contribution of the most important human emissions if computed using the 1996 IPCC

Figure 2

Carbon-Equivalent Greenhouse Emissions by Gas, Year 2000

Legend: ■ CO_2 ■ CH_4 ■ N_2O ■ Industrial Gases
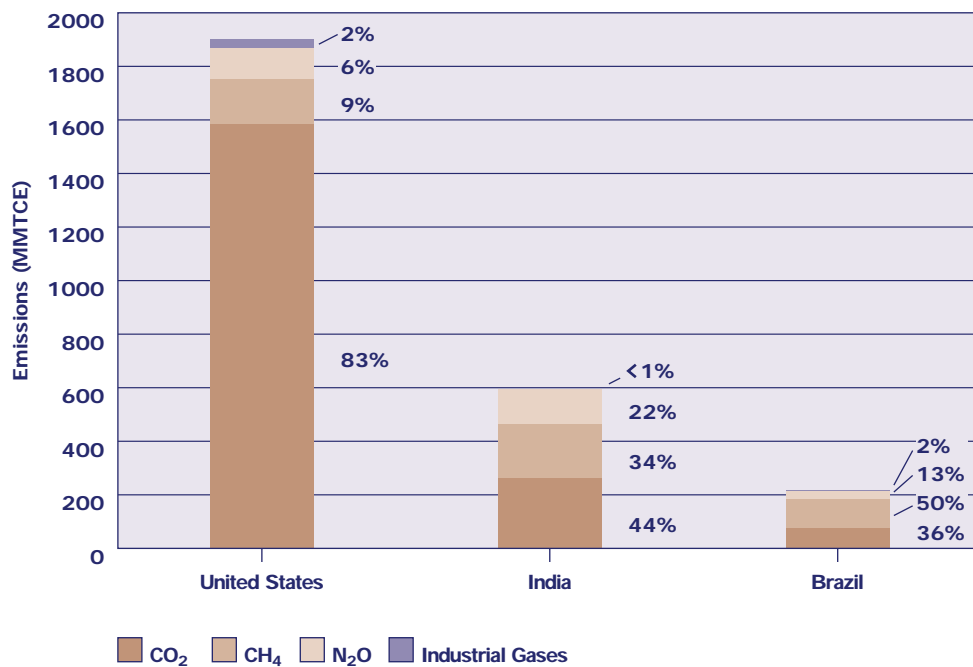
Notes: 1. CO_2 emissions accounted for more than 80% of U.S. GHG emissions in the year 2000 but far less than half of GHG emissions in India and Brazil.
2. Percentages may not add to 100% due to independent rounding.

Sources: United States (U.S. EPA, 2002; U.S. EIA, 2001b), India and Brazil (Mayer et al., 2001).

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GWPs. Emissions in the United States, with its large energy sector, are dominated by CO_2. Countries like India and Brazil currently have GHG emissions more heavily comprised of the non-CO_2 gases.

B. An Illustration Using Alternative Emissions Paths

The relative importance of non-CO_2 GHG emissions for future climate change, and the effects of mitigation, can be illustrated by comparing a set of projections with different patterns of control among the GHGs, aerosol precursors, and other radiatively important emissions. Figure 3 shows such a calculation using the Massachusetts Institute of Technology (MIT) Integrated Global System Model, or IGSM (Prinn et al., 1999; Reilly et al., 1999; Wang et al., 1998; Mayer et al., 2000; Sokolov and Stone, 1998).

The analysis starts with construction of a reference projection of emissions assuming no climate policy, and estimation of the effect of these emissions on future climate. In this reference case the increase in global surface temperature is 1.0ºC in 2050 and 2.3ºC in 2100. Against this reference the effects of various assumptions about the structure of emissions control are compared. The figure shows

Figure 3

Global Mean Temperature Effects of Emissions Reductions
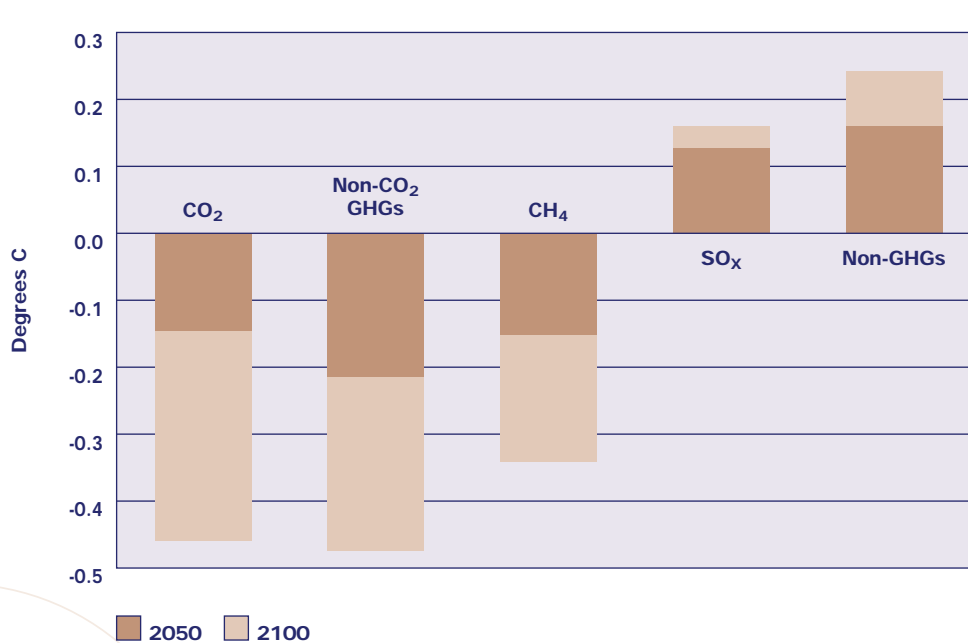
Notes: 1. In the reduction cases, emissions of the gases shown are reduced to 50% below reference between 2000 and 2050, and maintained at that percentage through 2100.
2. Non-CO_2 GHGs include CH_4, N_2O, PFCs, HFCs, and SF_6.
3. Non-GHG substances include NO_X, SO_X, CO, and NMVOCs.

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five such cases, and in each it is assumed that emissions of the selected gases are reduced from 2000 forward so that by 2050 they have been reduced to one-half of the reference level. Emissions of the selected gases are then held at that fraction of the reference levels through 2100. The figure shows the departure from the reference temperature change resulting from the assumed controls. The calculation accounts for the indirect effects of the emissions changes on tropospheric ozone, the lifetime of methane, and other interactions not captured by GWPs.

The first bar shows the reduction in surface temperature when CO_2 emissions are reduced to one-half of their projected reference level. By 2050, the temperature change would be about 0.15ºC below the no-control reference level.[4] By 2100, the estimated reduction in temperature would be 0.47ºC. The relative importance of the non-CO_2 gases (including methane) is shown in the second bar. Reducing these emissions to one-half of their reference level (while now leaving CO_2 at the reference level) results in a one-third greater reduction in surface temperature in 2050, (0.21°C compared to 0.15°C). By 2100, the temperature reduction is about the same (0.48ºC) when the non-CO_2 gases are reduced, as compared with the CO_2 reduction case. The 2050 temperature effect of reducing the non-CO_2 gases is surprising because if one uses GWPs to measure the importance of different gases, CO_2 would appear to be the dominant contributor to the problem. The surprising importance in this shorter time-frame of the non-CO_2 gases is largely due to the role of methane. The third bar shows the temperature result if emissions of only methane are reduced in the assumed manner. By 2050, reducing methane alone has a slightly larger effect on temperature than does reducing CO_2. The effect of putting methane on this reduction path is less effective on the century horizon, however, because of its shorter life. It is for this reason that methane reduction is more attractive if one is interested in slowing climate change in the nearer term, and less so if the focus is on long-term temperature increases. This calculation also illustrates a weakness of the GWP concept: it does not aid our understanding of the timing of the climate effects resulting from different GHG control strategies.

Control of SO_x emissions, to limit direct health and ecosystem effects unrelated to climate, also has a strong effect, though in the opposite direction. If SO_x emissions were reduced along the assumed control path, while the other non-CO_2 gases remained at reference levels, the loss of the cooling aerosols to which they contribute is enough to counteract the equivalent CO_2 reduction, at least out to 2050 (see the fourth bar in Figure 3). On the longer time scale to 2100, the effect relative to CO_2 reduction is smaller,

again because the effects of CO_2 reduction last many decades into the future, while the aerosols, and hence their climate effects, remain in the atmosphere only about a week or so.

Depending on the particular change in the mix of other non-GHG emissions, including NO_X, NMVOCs, and CO, the effect on climate can be a net cooling or warming. The particular scenario examined here and shown in the fifth bar of Figure 3, labeled Non-GHGs, results in a small additional net cooling beyond that where only SO_2 was reduced. Like SO_X, these pollutants are already subject to control, at least in the richer countries, because of air quality concerns, and continued reduction in emissions rates are included in the reference forecast. Of course, even tighter controls on these emissions might well be warranted by air pollution concerns. By lowering these gases and SO_X, their total cooling is reduced so that global temperatures are above reference by about 0.15°C in 2050, and as much as 0.22°C in 2100. (These calculations do not include the effects of black carbon.) The further increase is a complex result of partly offsetting effects. The pollutants controlled in this case are tropospheric ozone precursors, so with fewer of them there is less tropospheric ozone, which alone would mean cooling. But, this reduction also diminishes concentrations of the OH radical, extending the life of methane and thereby leading to higher concentrations of it, which alone would mean warming. Whether the net effect is warming or cooling depends crucially on just how emissions are reduced and where, so one must be cautious about generalizing from the result in the far-right column of Figure 3.

There are also uncertainties in these emissions estimates and their potential climatic effects. As shown in Table 2, even current global emissions are estimated with an error of +/- 50 percent for most of these substances. Inevitably these uncertainties percolate through to forecasts of emissions (Box 3) and into

Table 2

Annual Global Total Emissions Estimates Circa 1995, and Error Ranges

	Natural	Anthropogenic	Total
CH_4 [Tg CH_4]	160 (110 – 210)	375 (300 – 450)	535 (410 – 600)
N_2O [Tg N]	9 (4.3 – 14.7)	7.2 (2.1 – 19.7)	16.2 (6.4 – 34.4)
NO_X [Tg N]	19.3 (6 – 35)	31.1 (16 – 46)	50.4 (22 – 81)
SO_X [Tg S]	32 (25 – 40)	70 (69 – 76)	102 (95 – 116)
CO [Tg CO]	370 (280 – 960)	925 (600 – 1250)	1295 (880 – 2210)
BC [Tg C]		6.5 (1.8 – 13) fossil	13.7 (3.8 – 26)
		7.2 (2 – 13) biomass	
OC [Tg]	7.8 (??)-very uncertain	7.5 (0.75 – 15) fossil	59.3 (5.2 – 95)
		44 (4.4 – 80) biomass	

Note: These compounds and their sources are defined in Table 1.

Source: Webster et al., 2001a, as summarized from Olivier et al., 1995; Seinfeld and Pandis, 1998; and Mosier and Kroeze, 1998.

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results such as those shown in Figure 3 (Webster et al., 2001b). A low forecast of future CO_2 emissions will make the non-CO_2 gases appear relatively more important and, similarly, a low reference forecast of any of the other gases will mean it will have a smaller effect, with less scope for further control.

Large uncertainties and lack of data also plague our ability to understand the potential future influence of black carbon and the other aerosols. For example, black carbon is only one of several carbon-containing aerosols produced during combustion of fossil fuels and biomass. Some of these aerosols are energy absorbers like black carbon, while others, such as wildfire soot, are reflective. Also, while black carbon absorbs sunlight and warms the air around it, it also cools the surface below by shielding the sunlight. These uncertainties explain why in Figure 1 the direction of the effect (whether warming or cooling) of black carbon is uncertain and the IPCC offered only a range, and no "central" estimate as they did for other substances.

Even with these uncertainties, it is nonetheless clear that the interactions between air pollution and climate change deserve more attention in the formulation of climate policy. One proposal that has gained considerable attention is that, through 2050 at least, it might be possible to cap the increase in radiative forcing by controlling only methane, N_2O, and black carbon (Hansen et al., 2000), gaining double benefits in reduced air pollution and its health and ecological consequences. There are other unique aspects of this scenario. The authors hypothesized very low growth in CO_2, even without controls, that they believed possible because of low- or zero-cost conservation measures. We have already noted the complexity of the methane-ozone relationship and the uncertainty regarding the radiative role of carbon aerosols, and this alternative scenario picks, as any single scenario must, one set of assumptions about these relationships.
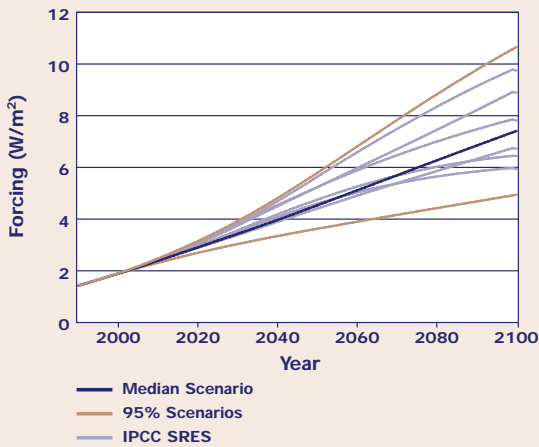
An important point is made by these proposals, however. There can be considerable leverage in controlling the "other" GHGs. They rival CO_2 in importance as a target for mitigating the threat of climate change and, to the degree that the pace of temperature change in the early decades is at issue, methane is particularly important. By the same token, even though local air pollution problems will drive policies to control these other pollutants, any policy affecting the non-GHG gases should at least be cognizant of the potential climate effects. Moreover, policies directed toward pollutants like carbon aerosols should not remain outside the international climate policy framework. Of course, the extent to which control of the non-CO_2 gases is part of a sensible strategy depends on the costs of their control, which is the focus of the next section.

Box 3

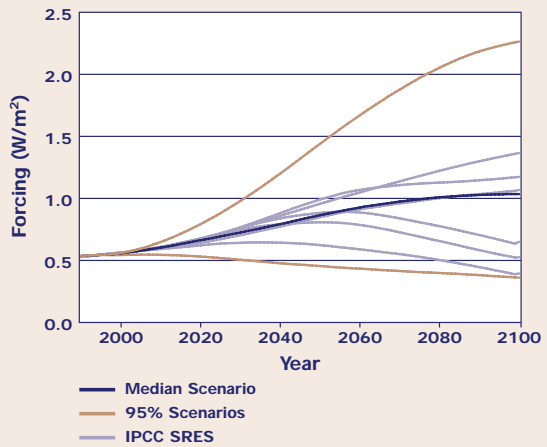## Uncertainty in Future Radiative Effects of Greenhouse Gases

The figures below show the uncertainty in human-induced emissions of CO_2, methane, nitrous oxide, and sulfate aerosols. The analysis was conducted using the MIT Integrated Global System Model, or IGSM (Webster et al., 2001a). The brown lines are the 95 percent confidence limits, indicating that the likelihood of falling outside this range is just 5 percent. The dark blue line is the median estimate, indicating that there is a 50 percent chance of the result being either higher or lower than this scenario. The emissions scenarios developed in the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović and

Swart, 2000) were also simulated through the IGSM, and are shown as light blue lines. Both the formal uncertainty analysis of Webster et al. (2001a) and the IPCC SRES scenarios show a wide range of possible future outcomes in the absence of climate policies, although the SRES scenarios show a smaller range of emissions for methane and sulfates. These differences may reflect alternative views about the chance of high sulfate and methane emissions, or the fact that the SRES constructed no high emissions scenarios for these pollutants.

CO₂ Forcing

- Median Scenario
- 95% Scenarios
- IPCC SRES

CH₄ Forcing

- Median Scenario
- 95% Scenarios
- IPCC SRES

N₂O Forcing

- Median Scenario
- 95% Scenarios
- IPCC SRES
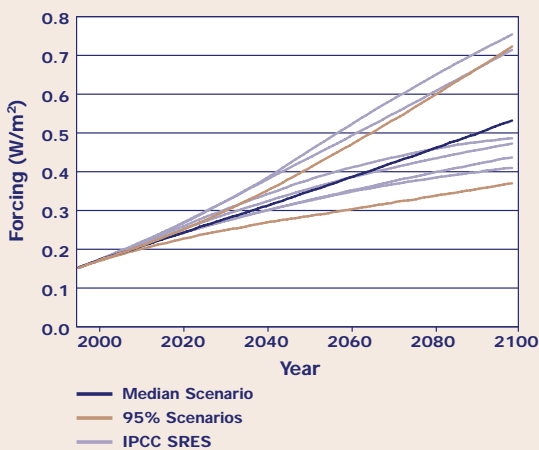
Sulfate Aerosol Forcing

- Median Scenario
- 95% Scenarios
- IPCC SRES

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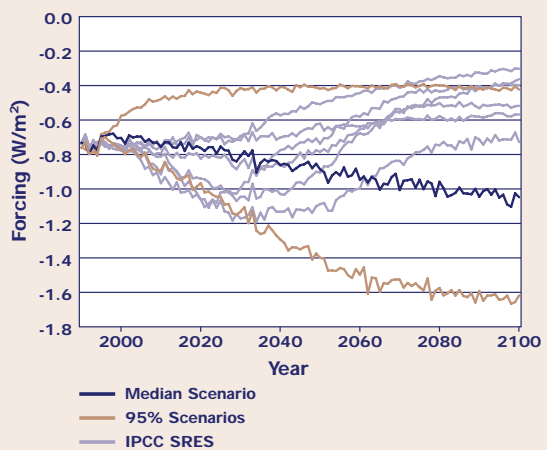
IV. Costs of Multiple-Gas Climate Policies

The cost implications of a multi-gas approach to climate policy can be explored using the gases covered under the Kyoto Protocol: carbon dioxide, methane, nitrous oxide, and the industrial gases (hydrofluorocarbons, per-fluorocarbons, and sulfur hexafluoride.) Also, for such an assessment, we can use the set of global warming potentials (GWPs) that have been adopted by the Parties to the Climate Convention (IPCC, 1996). Although the United States has declared that it will not proceed with ratification of the Kyoto Protocol, and has proposed an alternative domestic approach, the Protocol can still provide a useful case for studying the relative cost implications of multi-gas emissions control. However, it is worth noting that, given the decision of the United States to proceed under a different course and less ambitious reduction target, actual costs of a domestic control program are likely to be lower than those used in this analysis. We look first at the two main factors that influence the costs of control of the various gases, the baseline forecast and the abatement cost function. We then review some estimates that illustrate how careful treatment of this basket of gases can substantially reduce the cost of achieving any reduction target.

A. Factors Influencing Multi-Gas Cost Estimates

Widely different cost estimates, among regions or among studies for the same region, often can be traced to different reference emissions projections. For example, even for U.S. CO_2 emissions, which are relatively well-studied, the U.S. Energy Information Administration (U.S. EIA, 2001a) forecasts a range of emissions in 2010 that differs by 5 percent for the high and low economic growth cases. While this is a small difference, with a Kyoto-type reduction target (7 percent below 1990 for the United States), this difference in reference emissions yields a required reduction below baseline forecast that is 17 percent greater in the high emissions case than in the low. Because of the rising marginal cost of abatement, the costs in the two cases can easily differ by still more.

Compared to CO_2, relatively little effort has been devoted to study of the growth of non-CO_2 gases. Table 3 shows recent assessments and forecasts by U.S. government agencies, covering the period from 1990 to 2010. Two aspects are particularly worth noting. The growth rate in emissions varies widely among

the various gases, and as a group they are expected to grow more slowly than CO_2 (26 percent, as compared to 35 percent). These trends have two implications for climate policy. First, similar but separately targeted reductions across the gases would almost certainly be economically unsound. For example, if emissions of each gas were independently targeted to be a certain percentage below the base year, the reduction from the reference path would differ substantially among them. Second, because there is slower growth in the non-CO_2 gases, including them as a group reduces the percentage reduction in CO_2 required to meet a specified all-gas target. In other words, fewer cuts have to be made in CO_2 if other gases are reduced simultaneously.

Table 3

Estimated **Emissions of Non-CO$_2$** (Anthropogenic) Greenhouse Gases in the United States (MMTCE)

	1990	1995	2000	2005	2010	% Growth 1990-2010
CH$_4$	177	180	168	176	178	1
N$_2$O	106	115	116	122	127	20
HFCs & CFC Replacements	10	14	25	42	54	440
PFCs	6	4	4	10	17	180
SF$_6$	10	10	5	9	13	30
Total Non-CO$_2$ GHGs	309	323	318	360	388	26
Fossil Fuel CO$_2$	1345	1424	1583	1690	1809	35
TOTAL GHGs	**1654**	**1747**	**1901**	**2050**	**2197**	**33**

Note: 1. Converted to millions of tons of carbon equivalent (MMTCE) using 100-year global warming potentials. Reported data for 1990, 1995. Projections and estimates for 2000-2010.
2. Non-CO_2 gas numbers may not sum due to independent rounding.

Sources: 1990, 1995, and 2000 Non-CO_2 greenhouse gas data are U.S. EPA estimates (U.S. EPA, 2002). Methane forecasts are from U.S. EPA (2001d); nitrous oxide forecasts are from U.S. EPA (2001e), and forecasts of other non-CO_2 gases are from U.S. EPA (2001b). Carbon dioxide emissions (U.S. EIA, 2001a, b) exclude non-fossil fuel sources and sinks.

Exploration of the factors underlying the different growth forecasts is informative. Gases with agricultural sources (methane and N$_2$O) are generally projected to grow more slowly than CO_2 because the number of livestock (and the manure they produce), cropping area, and fertilizer use are not growing as rapidly as other parts of the economy. In addition, methane growth is being slowed by the Landfill Rule that is now part of the U.S. Clean Air Act.[5] Landfill gas must be collected and either flared or used at all landfills that have a design capacity greater than 2.5 million metric tons (MMT) of waste and emit at least 50 metric tons (MT) per year of NMVOCs. Although not a control directly on methane emissions (the focus is on NMVOC emissions because they contribute to tropospheric ozone), the methane is mixed in with the NMVOCs and is combusted along with them. Controls on SF$_6$ emissions are also being spurred by forces unrelated to the climate issue. Cost increases have led utilities to introduce programs of leak prevention and recycling. But these significant forecasted reductions in SF$_6$ emissions from utilities are offset by increases in magnesium production as forecasted by the U.S. EPA.

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The estimates for PFCs, HFCs, and other replacements for ozone-depleting substances raise still another set of forecasting issues. Historically, aluminum smelting has been the major source of PFCs, but the rapid growth forecast for PFCs originates in the computer chip industry. The manufacturers have pledged to reduce emissions to 10 percent below 1995 levels, but the U.S. EPA forecasts do not take these pledged reductions into consideration because a true "business-as-usual" scenario would not see the climate-related reductions (U.S. EPA, 2001a). The difference in forecasts with and without the industry pledge is striking. The EPA estimates that only 1.35 million metric tons of carbon equivalent (MMTCE) of PFCs were emitted by the industry in 1995, so a 10 percent reduction would lead to 2010 emissions of just over 1.2 MMTCE. The EPA forecast, which ignores the industry pledge and makes the conservative assumption of no change in emissions per unit of production, is that emissions will be 17.5 MMTCE. Clearly, the computer chip industry, while subject to varying rates of growth, has the potential to grow far faster than agriculture or waste delivered to landfills, and so if voluntary reduction agreements are not realized and emissions per unit of production do not fall dramatically, growth in PFCs could be many times the growth in methane or N_2O.

HFCs and other replacements for ozone-depleting substances raise similar issues. Some analysts point to the fact that there has been rapid innovation and replacement of the ozone-depleting substances when measured either in terms of the ozone depletion potential or in terms of their GWP (McFarland, 2000). This is because the replacements have less warming potential than the CFCs. They thus envision continued substitution toward and development of substances that have even less warming potential. Such progress might slow the growth in the replacement substances far below the high rates of growth forecast by the EPA and by others (McCulloch, 2000; Harnisch et al., 2000). Producers and users of these CFC replacement gases might limit growth and seek alternatives, particularly if they anticipate future regulatory constraints under a climate policy. As we move closer to a time when actual policies are likely to be in place, this anticipatory behavior makes it difficult to distinguish between a reference projection that assumes no policy and one that is in effect a climate policy scenario.

The second major factor determining costs is the shape of the marginal abatement curves for the various gases. Even considering the inescapable uncertainty, the non-CO_2 gases are estimated to have substantial abatement opportunities at low cost compared with CO_2 (see Reilly et al., 1999). As shown in Figure 4, an estimated 20 to 40 percent of these gases can be abated at less than $35 per ton of carbon equivalent, whereas less than 10 percent of CO_2 can be abated at that carbon price. In part, of course, this cost difference may reflect the different methods used to prepare these estimates. The non-CO_2

Figure 4

Marginal Abatement Curves for CO_2, CH_4, N_2O, and the High-GWP

Industrial Gases (HFCs, PFCs, SF_6)
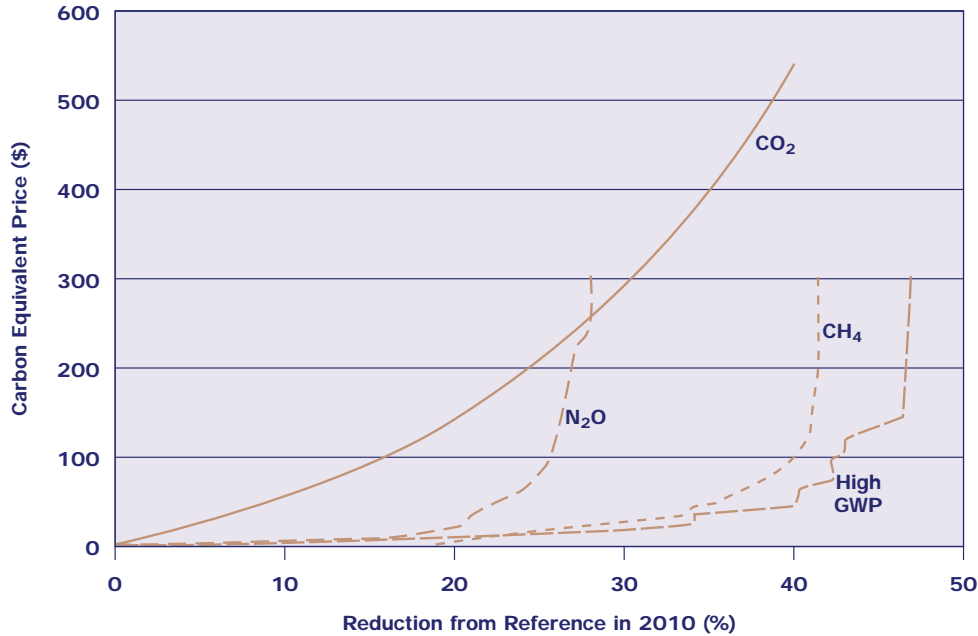
Sources: Methane: U.S. EPA, 1999; High-GWP Industrial gases: U.S. EPA, 2001b; Nitrous oxide: Jochen Harnisch, 2001, private communication and authors' own calculations; CO_2: Authors' own calculations based on EPPA model simulations.

abatement opportunities are from engineering-economic studies, whereas the CO_2 abatement curve is generated from simulations of MIT's computable general equilibrium model of the economy (Babiker et al., 2001). Where engineering-economic studies have been conducted for CO_2 abatement for the U.S. economy (e.g., those of the Office of Technology Assessment or the National Academy of Sciences as reviewed in Brown et al., 1998), they typically have produced marginal abatement curves showing substantial reductions at low cost, or even with a positive benefit.

There are, however, differences in the nature of reductions of CO_2 from fossil fuel, in contrast to the non-CO_2 gases, that suggest that their cost curves reflect more than methodological differences. First, there is no low-cost way to burn fossil fuels while preventing CO_2 emissions. Engineering systems to capture and sequester CO_2 from power plants or other large point sources are available, but they are estimated to cost $150 per ton of carbon and upwards (Herzog, 2000). The lowest-cost CO_2 reductions involve fuel switching, energy efficiency, and conservation measures. In contrast, for the other gases there are opportunities to

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prevent emissions cheaply with little change in the basic operations that produce them. Also, consumers and firms have extensive experience with fuel switching, efficiency, and conservation. Thus the prices paid at the point of use provide indirect evidence regarding the ability to reduce carbon emissions. Consumers of energy have pushed themselves up the marginal abatement curve for CO_2 through reductions in energy use by the very fact that they have to pay money for the energy. For other GHGs however, like N_2O, some sources of methane, and byproduct releases of HFCs, PFCs, and SF_6, there are no comparable price signals. As a result, the opportunities for reduction of emissions remain largely unexplored. As their role in climate change becomes more widely known, many companies and communities are now finding low-cost ways to reduce these emissions, but the flat part of the abatement curve has not been exhausted as it has for energy (Box 4).

Box 4

Companies and Communities Are Reducing Non-CO$_2$ Greenhouse Gases

As concern about climate change has grown and the evidence of its dangers have accumulated, companies and communities have taken actions to reduce GHGs that they would not otherwise have taken. It is often seen as an economic paradox that companies, under fierce competitive pressures, would take on such activities that might add to their production costs or divert management attention from other areas. The motivations are varied and range from deep-felt concern for environmental stewardship to a recognition that sooner or later some type of mandatory control system will be required, and acting early will leave their company better prepared for that eventuality. Many of the actions taken to date are very low-cost, or even economically profitable, because the abatement technology collects and uses or recycles the gas that would otherwise be emitted, thereby producing revenue or saving the purchase price of the substance. Many companies have established corporate-wide targets for GHG emissions reductions (Margolick and Russell, 2001).

The U.S. EPA (2001f) estimates that in 2000 alone emissions of 17 million metric tons carbon equivalent (MMTCE) of non-CO$_2$ GHGs were avoided as a result of voluntary partnership programs they have established. Measures have been taken by small and large companies for all of the major GHGs, and in all areas of the United States. One example is a Pennsylvania partnership between Waste Management, Inc. and the county of Northampton, whereby Waste Management collected landfill gas and, instead of flaring it, allowed the community to utilize the methane, with revenues from the sale going to local

economic development projects. Companies that account for a large share of U.S. natural gas production, transmission, distribution, marketing, and processing participate in a program that helps companies minimize natural gas leaks and losses. These companies include, for example, gas producers such as BP-Amoco, ExxonMobil, Shell, and Texaco, and many interstate transmission and distribution companies, including Keyspan, Wisconsin Public Service, and Pacific Gas and Electric. In addition, virtually all underground coal mines in the United States have worked with EPA's voluntary program to reduce methane emissions from mining.

With regard to industrial gases, a voluntary aluminum partnership involving most U.S. smelters had achieved by 2000 a 45% reduction from 1990 levels in PFC emissions on a per unit product basis, and the U.S. semiconductor industry has agreed to reduce its PFC emissions to 10% below 1995 levels by 2010. Electric power producers representing 45% of U.S. generating capacity are part of a partnership to reduce SF_6 emissions, and U.S. producers are partners in a search for best management practices to reduce such emissions from magnesium production. Companies involved in the production of HFCs and in the manufacture and servicing of air conditioning units in vehicles are also working to minimize emissions of this GHG. The main refrigerant, HFC134a, has a global warming effect that is six times lower than that of CFC-12, which it replaces, although, even at this lower level, forecasts of growth in refrigerant use could be a significant contributor to global warming in the absence of efforts to limit emissions (MacFarland, 2000).

Even when a purchase price has provided some incentive for avoiding release to the atmosphere, another difference from CO_2 comes into play. The GWP indices determine the relative value of controlling a ton of carbon as compared with, for example, a ton of methane, N_2O, or SF_6. Because of their radiative potency, as represented by their GWPs, a carbon price having only a small effect on fuel prices can lead to very large penalties on the release of non-CO_2 gases. The relative value comparison would be a simple task of multiplying the dollar price of carbon times the GWP, except for the peculiarity that the GWPs have been estimated relative to CO_2, while most of the analyses of mitigation costs are described in cost per ton of carbon. To state the GWP in these terms, it must be corrected by the ratio of the molecular weights of CO_2 and carbon, a factor of 44/12, or 3.67. Making this adjustment (dividing the GWP by this constant), one can then simply multiply the carbon price in dollars per ton to get the price per ton of another gas. Consider the methane that is vented from a coal mine but that could be captured and sold to a natural gas pipeline, say at a price of $3 per thousand cubic feet (MCF). In the absence of any charge on emissions, the $3 price would be the firm's incentive to abate the methane. Now, assume an emissions penalty of $100 per ton of carbon is put in place. If the mine owner is charged only for the CO_2 that will be released when the methane is ultimately burned, the incentive to abate rises by about $1.40 per MCF, for a total incentive of $4.40. If, however, the methane is penalized for its carbon-equivalent radiative effect, as defined by its GWP, the total incentive rises to around $12.40 per MCF. At such levels, capture technologies that seemed prohibitive given historical ranges of natural gas prices might well be worth considering and developing.

The incentives for controlling emissions of the industrial gases and N_2O are still stronger, because their radiative potency is so much greater than that of either methane or CO_2. For example, SF_6 sells for around $10 per pound, but with a GWP of roughly 23,900, a carbon-equivalent price of $100 per ton would translate into a penalty of $300 per pound for emitting the gas. The carbon-equivalent charge avoided by recycling would be more than 30 times the current sales price.

Another characteristic of the marginal abatement curves (MACs) for the non-CO_2 gases is that they are much more sharply nonlinear than the usual abatement curves for CO_2 as seen in Figure 4. While the first increments of abatement are very inexpensive for the non-CO_2 gases, above a price of $35 to $50 per ton of carbon-equivalent most of the abatement opportunities are exhausted, even though 50 to 70 percent of the emissions remain unabated. This aspect of the cost curves reflects the fact that estimates are based on the relatively conservative assumption that only existing abatement technologies are applied,

and that some emissions simply cannot be abated. For example, the U.S. EPA excluded small landfills from its abatement cost estimates, concluding that it would be impractical to collect the methane. Of the emissions from livestock, they considered abatement only from manure pits at relatively large and concentrated feedlots. As discussed in the paragraph above, if carbon prices indeed rose to $100 or more per ton and these penalties were actually charged on unabated emissions, a strong incentive would be created to find new ways to reduce emissions, even from relatively small sources. In the extreme, these small sources may simply become non-competitive, and instead activities that lead to emissions would be concentrated at larger point sources that could be more cost-effectively controlled.

For the industrial gases, as has been the case with CFCs, significant financial incentives to reduce emissions could lead to replacements not yet foreseen. Or, high penalties on their emissions would create an incentive to collect and recycle the substances except where there were uncontrollable accidental releases. The HFCs used in automobile air conditioners provide a good example. If the penalty for their release was hundreds of dollars per car, a strong incentive would be given to salvage and recycle, particularly if substitutes were not available.

For the reasons noted above, the sharp bend in their marginal abatement curves (Figure 4) probably provides an overly pessimistic picture of the ability to reduce emissions of the non-CO_2 gases if, in fact, carbon-equivalent prices rose to $50 or $100 per ton. The same inability to see technological innovations in alternative fuels and energy efficiency may affect estimated abatement curves for CO_2, but, at similar carbon prices, the resulting energy prices are not nearly as far outside the bounds of historical experience with energy prices.

B. Estimates of Multi-Gas Control Costs

Most studies of the climate issue have approximated a Kyoto-type target by using CO_2 emissions to establish the base-year quantity, and then applying the negotiated percentage reductions to that amount (e.g., Weyant and Hill, 1999; Hourcade and Shukla, 2001). They thus ignore reductions that might be achievable from the non-CO_2 gases, and overlook the growth in their emissions in calculating the required reduction. Leaving out both the abatement opportunities offered by the other gases and the increased reduction required to meet an all-gas reduction target has opposite effects on the marginal cost, and most analysts believed that these two effects might just about balance if one were able to include the other gases. Given this approach, and absent direct consideration of non-CO_2 Kyoto emissions, one cannot conclude

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whether cost estimates in these previous studies were too high or too low (Box 5).[6] Thus, it was surprising that the early studies found that even when a multi-gas target required a greater reduction in total emissions, the marginal and total costs were lower than for a CO_2-only policy (Hayhoe et al., 1999; Manne and Richels, 2000; 2001; Reilly et al., 1999; 2000; 2002).

At the time most of these early studies were done, abatement opportunities for the non-CO_2 gases had not been fully incorporated within the models.[7] Instead, exogenous MAC curves for these gases were combined with economic model results for fossil carbon emissions (Reilly et al., 1999; 2002; Hayhoe et al., 1999). One of the main disadvantages of this approach is the inability to capture many of the interactions that would result from a GHG constraint, such as effects on exports and imports of energy and other goods, on wage rates, investment and depletion of fossil fuel resources, and on levels of consumption and production of the various goods in the economy. Also, it is not possible to consider the spillover effects of control of one gas onto another. Gases such as methane, N_2O, and SF_6 will be affected by a carbon restriction because some of their emissions sources are closely tied to energy production and use. Methane is emitted from energy production activities, as noted earlier, and N_2O is produced in fossil fuel combustion. Reduced electricity production would reduce SF_6 emissions because of its use in electrical switchgear.

A general equilibrium model is designed to capture many of these effects. To this end, the MIT Emissions Prediction and Policy Assessment (EPPA) model (Babiker et al., 2001) has been extended to include all of the greenhouse-relevant human emissions, with their various interactions and feedbacks. Partial equilibrium studies of control costs can be used as a basis for estimating cost relationships that are imposed within the general equilibrium structure of the model. There are significant advantages in including the forecasting and cost analysis of all gases within a single model in this way. Internal consistency is maintained as economic growth and other assumptions change, sectoral interactions and the effects on abatement of all greenhouse gases are considered automatically, and the cost of abatement can be estimated in terms of carbon equivalent price, impact on gross domestic product (GDP), or economic welfare loss. Hyman (2001) describes the approach in detail and demonstrates its application to methane. In work by Mayer et al. (2001) and Babiker et al. (2001), a set of internationally consistent inventories and reference projections has been developed that differ somewhat from the most recent U.S. inventories (U.S. EPA, 2001c). The major conclusions of the earlier studies remain, however: inclusion of these gases substantially reduces the cost of meeting a given percentage reduction target.

Box 5

The Cost Implications of Including Non-CO$_2$ Greenhouse Gases

Several things change as a result of inclusion of the non-CO$_2$ greenhouse gases when targets are set as a percentage of a historic base year, as they are in the Kyoto Protocol. First, non-CO$_2$ greenhouse gases are added to the base year emissions. A larger base means the required reduction, in tons, is larger. By itself, that would increase the cost of the policy, even though the policy might be achieving greater climate benefits. Second, reference emissions of each gas are growing at different rates, and emissions of some gases may even fall. Adding a rapidly growing gas to the control policy would cause total reference emissions to grow faster, requiring a greater reduction from the reference level in order to meet the target, again increasing costs. On the other hand, if the trend of emissions for a gas is downward, adding it into the policy would reduce the reduction required, thereby reducing costs. Third, abatement opportunities differ among gases and this can either increase or decrease costs.

Some of these effects are shown in the graph below where the abatement opportunities for carbon dioxide are represented by the marginal abatement cost curve labeled "CO$_2$ MAC." A CO$_2$ reduction from reference emissions results in the marginal cost labeled "MC$_0$" found by drawing a vertical line to the CO$_2$ MAC and then a horizontal line to the vertical axis of the graph. A "CH$_4$ MAC," similarly representing abatement opportunities for methane, can be summed horizontally with the CO$_2$ MAC to show the abatement opportunities for both gases together, and shown as a "Two-Gas MAC." We show a case (labeled "Two-Gas Target S") where methane emissions grow slowly in the reference so the required reduction from introducing methane does not increase much. This leads to an overall lower marginal abatement cost (MC$_S$) than the CO$_2$-only policy. But, if those emissions of methane that were relatively hard to abate were to grow fast, as represented by "Two-Gas Target F," then the marginal cost increases to MC$_F$, which is higher than MC$_0$. Different abatement opportunities, represented by different shaped MACs (i.e., steeper or flatter in different regions), combined with a higher target (or potentially lower target if the emissions trends for the gas are downward), lead to vastly different cost implications of including another gas. If the target does not change, then, of course, the consideration of additional abatement opportunities always reduces the marginal and total cost of the policy.

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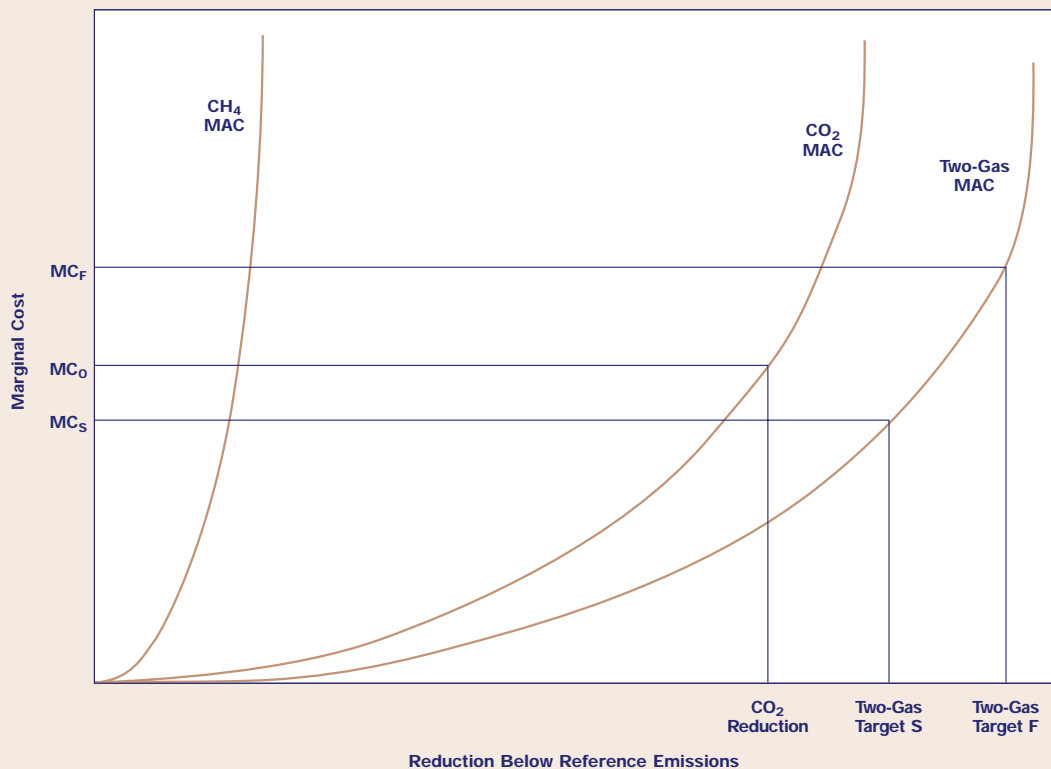
We evaluate two sets of policy scenarios to show this effect. One set considers the cost to the United States of meeting its Kyoto Target, i.e., returning to an emissions level 7 percent below 1990 emissions. The other assumes that the United States does not join the Kyoto Protocol, but instead adopts its own less-stringent target of holding combined emissions to year 2000 levels. To show the cost advantage of including other gases, we consider two variants of the above policy cases. In a CO_2-only case we assume that a CO_2 target is met without emissions trading among the gases. In the all-gas case, we control all of the GHGs and allow emissions trading so that the most cost-effective mix of control strategies among the gases is achieved. This assumes that these gases can be effectively incorporated into an emissions management system—perhaps an optimistic assumption, as we discuss later. On the other hand, while we do not exclude any of the GHGs from the management system, note that the data behind Figure 4—the primary basis for our abatement curves—excludes 50 to 70 percent of these emissions from consideration for abatement. The inability to develop emissions management systems for these sources, or to imagine new technologies, are reasons for the exclusion—but this may be overly pessimistic, as explained above.

The results are shown in Table 4. The first two columns report the MIT EPPA reference emissions projections for 2010,[8] and the growth in emissions from 1990 to the year 2010 that is used to represent the 2008-2012 first Kyoto commitment period. The two sets of policies, with the CO_2-only and all-gas policy variants, and the resulting 2010 emissions, carbon price, and welfare cost are shown in the third and fourth columns. These scenarios are for the U.S. meeting the specified target without international emissions trading and without consideration of any carbon sink potential. Thus, the reported carbon equivalent prices are much higher than is often reported for the U.S. cost of meeting the Kyoto target. Babiker et al. (2002) estimate an international trading price of less than $50/TCE (tons carbon equivalent) for a case where the United States remained in the Protocol with agreed use of sinks, compared to the figure here of $370/TCE without trading and sinks. Most of this difference is due to the effect on the market price of carbon of the extra emissions allocation to Russia, the Ukraine, and other European transition economies beyond what their emissions are expected to be. This extra allocation is often referred to as hot air. We do not consider trading and sinks here because it introduces another set of uncertainties, making it more difficult to study the contribution of the non-CO_2 gases themselves.

The comparison of the CO_2-only and all-gas cases reveal cost savings from including the non-CO_2 gases that are similar to those given in earlier studies. In the Kyoto case, shown in the middle columns of

Table 4

U.S. Abatement Costs of Meeting Emissions Targets

	2010 Ref. Emissions	Ref. Growth, % 1990-2010	Kyoto		Ref. Growth, % 2000-2010	Year 2000 Stabilization	
			CO₂ Only	All Gas		CO₂ Only	All Gas
CO_2 (MTC)	1904	41	1269	1376	19	1542	1735
CH_4 (MTCE)	232	31	201	95	15	220	120
N_2O (MTCE)	111	35	101	63	17	107	72
PFC (MTCE)	5	–16	5	0	–21	5	0
HFC (MTCE)	32	220	32	3	83	32	4
SF_6 (MTCE)	15	31	12	0	21	14	0
Total (MTCE)	2230		1620	1536		1920	1930
Price ($/TCE)			370	250		142	50
% Welfare loss			–0.9	–0.6		–0.1	<–0.1

Note: Carbon dioxide emissions are expressed as millions of tons of carbon (MTC). Non-CO_2 emissions are expressed in millions of tons carbon equivalent (MTCE) using 100-year global warming potentials. These scenarios are for the U.S. meeting the specified target without international emissions trading and without consideration of any carbon sink potential. Thus, the reported carbon equivalent prices are much higher than is often reported for the U.S. cost of meeting the Kyoto target. Babiker et al. (2002) estimate an international trading price of less than $50/TCE for a case where the U.S. remained a party to the Kyoto Protocol, and that includes carbon sinks as agreed to in the Protocol, compared to the figure here of $370/TCE without trading and sinks.

Table 4, the carbon price falls by about one-third, from $370 to $250 per ton,[9] with a similar one-third drop in the welfare loss. The lost economic welfare in the CO_2-only case works out to about $1,000 per U.S. household per year, dropping to just over $600 when the other GHGs are included (Babiker et al., 2002). (Again, actual costs of meeting this target would be lower for the United States if it were to participate in the Kyoto Protocol and were able to take full advantage of the flexibility mechanisms contained in the Protocol, including access to Russian hot air.) In addition to these economic savings, inclusion of the non-CO_2 gases also reduces total carbon-equivalent GHG emissions by an additional 5 percent below the CO_2-only case—a win-win situation.

Table 4 also shows that—even with a CO_2-only policy—methane, N_2O, and SF_6 emissions are incidentally reduced as a result of changes in energy production and use. When the other GHGs are brought under control, on the other hand, their emissions all fall by more than one-half. Reductions in the industrial gases are particularly large, with emissions of SF_6 and PFCs falling to near zero. Of course, the availability of low-cost abatement options for the non-CO_2 gases means that less stringent controls are required for CO_2 emissions. Emissions of CO_2 are cut by 28 percent, instead of the 33 percent reduction under a CO_2-only approach.

Table 4 also shows hypothetical targets for the United States that are less stringent than under the Kyoto Protocol and where GWP-weighted emissions are held constant to 2010 at their 2000 levels. Including the non-CO_2 gases still reduces the costs substantially. The shift away from CO_2 emissions control and toward the other gases is even more pronounced than in the more stringent Kyoto case.

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This result is hardly surprising. A $50 per ton carbon price would increase prices for fuels like gasoline and natural gas by 5 to 15 percent,[10] a relatively small incentive for conservation and efficiency improvements. On the other hand, the penalty for emitting rather than collecting or otherwise avoiding methane, even at $50 per ton, is equivalent to increasing the price of natural gas by more than 2 1/2 times. The penalty for emitting SF_6 is equivalent to multiplying the normal price of the gas by a factor of over 15.

We have noted the many uncertainties in the underlying estimates of emissions growth and in the evaluation of abatement opportunities. There are also uncertainties in GWPs, discussed below, although even revisions of 30 percent or more would not change the basic result. Also, as discussed next, there may be great difficulty in including some of the non-CO_2 gases in a coherent system. Still, while providing a relatively small incentive to reduce energy use, a relatively low carbon price extended to a carbon equivalent price for non-CO_2 gases would create very great incentives to reduce emissions of them. As a result, they represent an easy first step toward limiting climate change, and for smaller percent reductions from reference, such as the case where emissions are held at 2000 levels through 2010, the EPPA model suggests nearly all of the cost-effective reductions would come from the non-CO_2 gases. Of course, they cannot be the whole answer. Once the non-CO_2 gases are largely controlled, we are still left with CO_2 emissions from growing energy use and land-use change and these alone would contribute to a large change in the Earth's radiative balance. The shape of the abatement curves for non-CO_2 gases indicate that abatement opportunities are quickly exhausted after a few years of a climate policy, and then most of the further reductions would need to come from CO_2 abatement.

V. Incorporating Non-CO$_2$ Gases Within a Control Regime

To realize the low-cost abatement opportunities that are to be found among the non-CO$_2$ greenhouse gases, they must be fit into the broad architecture of climate policy, as embodied in the Kyoto Protocol (UNFCCC, 1997) or other proposals. To gain these cost-savings, climate policy faces two challenges: (1) accurate measurement of reductions, and (2) accurate relative weighting of the gases. As we discuss below, however, some sources of these gases could be or already are easily measured, while others present real problems. So, the debate should really not be about whether or not to include non-CO$_2$ gases in early climate policies, but rather which sources of what gases can easily be included. Measurement issues are not unique to the non-CO$_2$ gases; policymakers have had little problem recognizing that emissions of CO$_2$ from fossil fuel combustion can be measured and monitored relatively easily, whereas it would be harder to measure and enforce limits on emissions of CO$_2$ from soils that result from various cropping practices. The question is where to start along the line that runs from the immediately practical to the conceptually ideal. While one might argue about the correct global warming potential within a range of 10 or 20 percent, applying the GWPs we have is better than ignoring these gases altogether while we await some ideal index.

A. Measurement, Monitoring, and Compliance

The major difficulty in including the non-CO$_2$ gases in a control regime is the limited ability to measure and monitor some of these emissions so that, whatever set of policies are in place, compliance can be assured. The various sources summarized in Table 1 can be divided into two rough categories on this score. For some, emissions can be measured directly or inferred in a simple and accurate manner from some activity or practice. For the others, direct measurement is difficult to impossible, and inference from observation of practices or activities is problematic.

In this regard, climate-related emissions are not different from other environmental problems where it has been found far easier to measure and monitor emissions from large point sources, such

as electric power plants, than from widely dispersed non-point sources, such as automobile and truck tailpipes or farmers' fields. As a result, attempts to regulate pollution have taken very different forms depending on the circumstances. An example is the national cap-and-trade program now used to control SO_X emissions from U.S. electric power plants. Permits are distributed to utilities based on historical emissions, and these permits can be bought or sold to cover actual emissions, which are measured directly at the power plant stack. At the same time, however, SO_X emissions from transportation fuels and a number of industrial sources remain outside this system and are controlled by a web of regulatory standards. There are no provisions for these non-utility sources to trade among themselves or with the utilities, and no explicit attempts by regulators to assure equalization of the marginal cost of the various reductions. If even in this relatively simple case environmental control was not extended to all sources of emissions, it is probably not reasonable to expect a uniform, economically efficient system to be possible for all the human emissions that contribute to climate change.

The Easy Cases

No one proposes the direct measurement of all fossil energy CO_2 emissions; there are simply too many dispersed sources. However, emissions can be easily and accurately measured by monitoring the sale of fossil fuels with various levels of carbon content. Monitoring fuel use (or production or sale) could be an important element of a number of different approaches to controlling CO_2, such as carbon taxation, cap-and-trade systems, or direct regulation.

Similar options exist for most of the industrial gases. Because they are produced and sold, buyers and sellers have an interest in accurately measuring their amounts. While in some cases there are many end users, making monitoring of direct releases difficult, these industrial gases are produced by a few relatively large firms. Requiring permits to produce the gases, or imposing an environmental tax, would create an incentive to switch to other substances or recycle. Methane emissions from large landfills are already monitored and, as previously discussed, are being controlled. Emissions of N_2O from industrial sources (adipic and nitric acid production) present somewhat different problems, because they are byproducts that in many cases are vented to the atmosphere. But, again, these are relatively concentrated point sources so that it should not be difficult to identify and monitor releases. Thus, there is no reason not to include these in early climate policies, and no reason not to consider including them within a uniform system like cap-and-trade.

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The Difficult Cases

Agricultural sources of methane and N_2O, on the other hand, present significantly greater problems for measuring and monitoring. Van Amstel et al. (2000) report that national estimates of agricultural sources of methane and N_2O are especially uncertain, citing accuracy levels of ± 30 percent. Indeed, countries have revised estimates of their 1990 emissions of these gases by 70 percent or more in some cases (Berdowski and Oonk, 2000). Because emissions are so difficult to measure directly, inventories are developed on the basis of standard emissions coefficients applied to broad measures of activity levels, such as areas of rice paddies, number of livestock, and amount of nitrogen fertilizer applied. As improvements are made through further disaggregation of activities considered, inclusion of more activities, or improvements in measurement and monitoring technologies, large changes in the estimates may occur.

Control measures similarly would likely need to focus on the monitoring of industrial and agricultural practices and technology use as a proxy for direct measurement of emissions. Difficulties can arise with such use of proxy activities as the basis for a monitoring and enforcement system. These problems can also occur with a CO_2 system if care in design is not taken. As proposed earlier, CO_2 emissions can easily be estimated by monitoring fuel sales, a proxy for actual emissions. But, if CO_2 sequestration from power plants were to occur, actual emissions could no longer be calculated by multiplying a carbon coefficient times the quantity of fuel sales. A pure fuel sales approach to monitoring would need to be adjusted to give credit when the CO_2 in the fuel is sequestered instead of being released to the atmosphere. Separate measurement of sequestration would be needed to estimate the amount of credits for this activity or to adjust estimates of emissions one would make on the basis of fuel sales. Fortunately, one can add direct monitoring of carbon sequestration as envisioned at power plants relatively easily as these are large point sources, and so this does not present a major obstacle in carbon control. But, where small changes in agricultural practices affect emissions of methane, N_2O, or CO_2 from soils, each of these changes needs to be identified, their effect on emissions quantified, and their application regularly monitored to get the incentives for control just right. If one does not target control carefully, the policy is said to "use a blunt control instrument." Use of a blunt instrument may reduce emissions, but not nearly as cheaply or effectively as one honed to go after the cheapest and most effective reductions. In the CO_2 example, failing to hone the control instrument would mean that firms would have no incentive to use carbon sequestration, no matter what the carbon price, because reductions of emissions through sequestration would never be recognized and credited.

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This point seems so obvious for the sequestration example so as to hardly need mention; but for other agricultural practices that might vary in their emissions implications in hundreds of ways, it is far more difficult to design a well-honed policy instrument if one lacks direct measurement.

The policy design problems of managing non-point sources of pollution, including nitrogen fertilizer applications, a source of N_2O emissions, have been extensively studied because of concerns about nitrate contamination of groundwater and run-off into surface waters. These analyses confirm the difficulties and tradeoffs in policy design solutions (Ribaudo et al., 1999). Combinations of soil testing, more carefully crediting applications of manure or nitrogen fixation from crops (either alone or combined with a modest tax on nitrogen) have shown success in reducing nitrogen use. But the overall conclusion of these efforts is that effectively reducing use is not as simple as applying a nitrogen tax (Fuglie and Bosch, 1995). Similar problems affect many other agricultural sources of GHGs, with the one possible exception of methane emissions from manure produced by large livestock operations. These are large point sources, and their emissions can be measured fairly directly.

Given some of these problems, practice-based programs have been widely used in U.S. attempts to control agricultural pollution, but with mixed success. Thus, it seems likely that even with their limitations, these programs will be explored for controlling agricultural sources of GHGs.

Another solution for these more difficult cases is to offer credits that can be sold as offsets in a cap-and-trade system, or to offer other incentive payments when reductions can be verified to the satisfaction of regulators. Under such a credit system, the problem of measuring and monitoring does not extend to all the known and unknown sources in the uncapped sectors, but only to those sources for which the emitters seek payment for reductions they claim.

The problem, of course, is leakage. In a system with an overall cap, a firm that shut down its operations might transfer the credits thus created to others, while other firms might expand their production and emissions. The result would be credits without real reductions. Rules could no doubt be written to avoid the more obvious cases of leakage, but in any such voluntary system it is very difficult to estimate the extent that reductions by participants might be offset by increases of non-participants.

A final issue that arises in agricultural cases is that a change in a single practice may affect emissions of N_2O, methane, and CO_2 (see, e.g., Robertson et al., 2000), increasing some emissions while

decreasing others; just how much depends on the type of soil, the weather, and what one considers the reference system that is the point of comparison. Is the reference system the soils in their natural condition before any disturbance, or is it an average for all cropland? Or, would one need to establish a separate reference for each specific farmer's current practice? The danger in this situation is that a practice-based approach focused just on CO_2, or methane, or N_2O could reduce emissions of the target gas but increase emissions of others so that the net effect of adoption of the practice would be to increase rather than decrease total GHG emissions. These types of situations clearly require much care in the design of measuring and monitoring systems. A poorly designed system is not just a matter of cost-effectiveness, but a potential case of the policy working in the opposite direction and increasing emissions rather than decreasing emissions as intended.

B. Equivalency Among Emissions of Different Substances

Warming Indices and Their Limits

Any multi-gas policy requires some way to compare the relative advantages of reductions of one gas versus another. The GWPs now used for this purpose are calculated by assuming a pulse of one gas or another and then following its direct radiative effects over some time period. This method assumes that the surrounding atmospheric conditions remain constant. Unfortunately, this method does not fully take into account interactions among the gases and with other factors, and some of these interactions have indirect effects on the Earth's radiative balance (See Box 7). As a result, the relative weights are not independent either of the background atmospheric changes or of the emissions control policy.

Taken together, these various interactions can lead to miscalculation of the likely effect of different patterns of control policy, and the error in them can be tested if one uses a model with an explicit representation of the different processes that contribute to emissions, affect gas lifetimes, and determine instantaneous radiative forcing. GWPs are a simplified index based on one unchanging set of assumptions about these processes. The MIT Integrated Global System Model (Prinn et al., 1999) includes these processes explicitly. Using this model, Reilly et al. (1999) constructed an experiment using two control regimes—one reducing all gases, and the other limiting CO_2 only—and simulated the climate effects of these two control regimes. The two scenarios were designed so that if the IPCC GWPs were correct, the climate effects would be the same under either control regime. When simulated with the MIT IGSM, however, substantial differences in the amount of climate change resulted under the two cases (Reilly et al., 1999). The implication was that GWPs significantly underestimate the role of

methane. In part, this is due to omitted interactions (such as the role of methane in tropospheric ozone formation). This was just one examination using one set of reference scenarios, but it points out the need for continuing efforts to improve this weighting system.

Box 7

Limits of Global Warming Potentials

Global warming potentials (GWPs) capture some of the most obvious differences among greenhouse gases and so can offer a general guide to policy in the short term, but the current method has some serious flaws. Over the course of 100 years and where stabilizing temperature change is a goal, the current set of GWPs can lead one astray, particularly when large reductions of non-CO_2 gas emissions are envisaged. Methane and nitrous oxide exhibit some of the more complex interaction effects that cannot be considered by these simple equivalence indices. One is the overlap in the wavelengths in which these gases trap radiated heat. As concentrations of either gas rises, the atmosphere becomes saturated in these particular wavelength bands and the radiative effect of the other gas is reduced. Two other interactions, both easily illustrated in the case of methane, also can be important. First, its rate of destruction in the atmosphere is not constant, as assumed in the GWP calculation, but depends on many factors. The fate of methane depends on the prevalence of the hydroxyl radical (OH), a short-lived chemical in the atmosphere that breaks methane down into CO_2 and water. Rapid increases in methane emissions could outpace the production of OH, in which case the destruction of methane would be slowed, and on average methane would remain in the atmosphere longer. Conversely, because atmospheric OH production is related to the levels of other pollutants such as tropospheric nitrogen oxides and ozone, a change in levels of nitrogen oxides and ozone can indirectly affect the lifetime of methane. Finally, particular focus is needed on just how to include the broader array of substances and their environmental effects such as tropospheric ozone and its precursors, sulfur dioxide, and carbonaceous particles. It may never make sense to extend GWP-type indices to all of these substances, but some examination of the interactions are needed to inform climate and pollution control policy.

Still another area of criticism of the current GWP formulation is its lack of an economic basis (Eckaus, 1992; Reilly and Richards, 1993; Schmalensee, 1993; Kandlikar, 1995, 1996; Hammit et al., 1996; Tol, 1999; Manne and Richels, 2001; Reilly et al., 2001). In proposed economic-based indices, the comparisons go beyond just the effect on radiative forcing to consider the actual implications of these gases for climate change and, in most cases, the economic damages estimated to result from it. An economic discount rate is used to evaluate the fact that damages from different substances are spread over different time periods because of the varying lifetimes of the gases. Discounting and tracking damages as they vary over time with rising atmospheric concentrations of gases allows these approaches to take into account the timing of climate benefits resulting from control strategies, something the current GWPs cannot do. The economic formulation provides, therefore, a better rationale for comparing shorter-lived gases like methane and HFCs with the longer-lived gases like SF_6 or PFCs.

Unfortunately, the economic-based indices that have been estimated show little agreement on how index values would change from the current GWPs. In fact, in several of these economic formulations the researchers, by varying assumptions about the discount rate or the formulation of damages, calculated index values that varied widely, and the range usually contained the current 100-year GWPs (e.g., Reilly et al, 2001, Manne and Richels, 2001). While these approaches formulate the economic aspects of the problem well, they treat the atmospheric chemistry and climate interactions very simply. So there is not yet the ability to effectively combine the best science modeling and the best economic modeling to provide a set of indices that could replace GWPs.

Integration with Pollution Concerns

The advantage of the economic formulations of GWPs is that, because they would turn all of the climate damages into the common metric of dollars, they could, in principle at least, include widely disparate effects of greenhouse gases (i.e., beyond their climate effects). They also offer a method to extend the GWPs to other pollutants that affect climate but also have other local and regional air pollution effects (see Box 8). Although it is conceptually appealing, a primary drawback of this approach is that it requires good estimates of all of these effects in dollar terms. There is little belief, even among the narrow group of economists who have studied climate damages, that the dollar value estimates for damages associated with climate change have a compelling basis.

Box 8

Ancillary Benefits and Pollution Control Incentives

The IPCC (2001b) reported that a significant advance in its efforts to assess mitigation of climate change compared with its earlier assesssments was its expansion to consider mitigation actions in the context of sustainable development, defined to include economic development, ecological integrity, and social justice. A specific example of this broader concern was the increased attention the IPCC placed on the ancillary bene-fits of climate change mitigation. Ancillary benefits, as defined by the IPCC, are other benefits that might result from climate mitigation policies such as reductions in local and regional air pollution, effects on transportation, agriculture, land use, and waste management, and extending to other issues such as employment or energy security. Policies centered around the current global warming potential indices, based just on radiative forcing and GHG lifetimes, do not take these broader issues into account. It remains an open issue of just how far one might go in broadening the basis of GWPs to include such considerations and, failing that, how to assure that climate mitigation efforts are consistent with these broader goals.

The complications that arise in trying to extend equivalency indices to other pollutants go well beyond the problems of monetary estimation of damages. Indices might need to be specific to the gas, source, abatement strategy, and location. Since methane is relatively well-mixed in the atmosphere, its direct effect on climate is about the same no matter where it is emitted. But the strategy used in abating methane emissions could have varying environmental effects. For example, simply abating methane by flaring it or inhibiting its formation by methane bacteria may have limited effects on the emissions of other pollutants, but collecting methane and using it to offset fossil energy use would entail a broader and different set of benefits, possibly leading to the reduction of black carbon or nitrogen oxides from other, more polluting energy sources. And then, pollution benefits would depend on what fuels were offset and whether the offset occurred in a heavily or lightly polluted area.

These issues have risen to more than a scientific curiosity. Citing a National Research Council report (NRC, 2001), the Bush Administration (U.S. Administration, 2001) noted in particular the need to better understand methane and aerosols, which includes SO_2 and carbonaceous particles. The NRC (2001) report dealt with both the climate and other environmental effects of tropospheric ozone, aerosols, and methane. While science can make significant advances in understanding the role of these substances over the next few years, there is no broad consensus as to when the science is adequate to move forward with specific policies. As in any case of policy formation under uncertainty, there is a need to balance the chance that more refined policies could lower the cost of control measures with the risks of delaying action while one waits for improved science.

VI. Conclusions

Of the various GHGs emitted by human activities, CO_2 is the largest contributor to climate change. With its relative role expected to increase in the future, a continuing emphasis on reducing CO_2 emissions is therefore justified. However, to effectively limit climate change, and to do so in a cost-effective manner, climate policies must also take into account the importance of non-CO_2 greenhouse gases. Improvements in our ability to measure and assess the non-CO_2 gases in recent years have made it clear that their control is an essential part of a cost-effective climate policy. Efforts to engage developing countries in climate mitigation will need to give even greater attention to the non-CO_2 greenhouse gases since these gases typically account for a higher percentage of their overall emissions. Non-CO_2 gases currently account for well over one-half of the GHG emissions in Brazil and India, for example, as compared to 20 percent in the United States.

The non-CO_2 greenhouse gases that human activities emit directly include methane (CH_4), nitrous oxide (N_2O), and a group of industrial gases that include perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6). In addition to these, several other substances play a role in retarding or enhancing the greenhouse effect, but are not included in existing climate policy agreements. These include carbon monoxide (CO), nitrogen oxides (NO_X), sulfur oxides (SO_X), aerosols, non-methane volatile organic compounds (NMVOCs), and ammonia. These gases and aerosols are related to one another by their common generation in industry and agriculture as well as by their interaction in the chemistry of urban areas, the lower atmosphere, and the stratosphere.

Modeling studies indicate that a cost-effective abatement strategy would focus heavily on the non-CO_2 gases in the early years. The relative value of controlling non-CO_2 gases, as indicated by the indices or weights known as global warming potentials, is one key reason that inclusion of the non-CO_2 gases in policies to address climate change can be so effective in lowering implementation costs, especially in the short term. Another reason is that, historically, economic instruments (i.e., prices, taxes, and fees) have not been used to discourage or reduce emissions of non-CO_2 gases, even though price signals via energy costs exist to curb fossil fuel emissions. Given the high carbon-equivalent values of the non-CO_2

gases, even a small carbon-equivalent price on these gases could create a huge incentive to reduce emissions. For smaller percent reductions, such as a case where total GHG emissions in the United States are held at year 2000 levels through 2010, nearly all of the cost-effective cuts would come from the non-CO_2 gases. Including the abatement options available for these gases would reduce the carbon-equivalent price of the policy by two-thirds from that needed if the same level of abatement were achieved only through reductions in CO_2 emissions from fossil fuels.

Designing an effective approach to controlling these multiple substances requires that a number of issues be resolved. A major issue is the challenge of finding a more accurate way of accounting for the independent effects of each gas on climate and of comparing their relative reductions. The GWP indices are currently used for doing so, but analysis has shown that the current GWPs significantly underestimate the role of methane. This is due in part to omitted interactions such as the role of methane in tropospheric ozone formation. GWPs also fail to adequately portray the timing of the climate effects of abatement efforts. Economic formulations of the GWP indices have been proposed that would address these concerns, but calculations using these economic-based formulae are bedeviled by a variety of deeper uncertainties, such as how to monetize the damages associated with climate change.

A still more difficult issue is whether and how to compare efforts to control other substances that affect the radiative balance of the atmosphere, such as tropospheric ozone precursors, black carbon, and cooling aerosols. These pollutants have immediate effects on human health, crop productivity, and ecosystems. Further, their climatic effects are mainly regional or even local, which creates difficulties in using a single index to represent the effects of emissions across the globe. It is essential to consider these substances as part of a climate policy, but more research and analysis is needed to quantitatively establish their climate influence and to design policies that take into account their local and regional pollution effects.

Another major concern in including non-CO_2 gases in a control regime is whether their emissions can be measured and monitored accurately so that, whatever set of policies are in place, compliance can be assured. The ability to monitor and measure has less to do with the type of GHG than with the nature of the GHG source—i.e., it is far easier to measure and monitor emissions from large point sources, such as electric power plants, than from widely dispersed non-point sources, such as automobile and truck tailpipes or farmers' fields. Resolving this difficulty may require different regulatory approaches for different sources, at least initially.

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There remain large uncertainties in scientific estimates of the relative climate-changing properties of the various greenhouse gases and aerosols. But these uncertainties do not change the basic conclusion that control of non-CO$_2$ greenhouse gases is a critical component of a cost-effective climate policy, particularly in the near term, and a key complement to carbon dioxide control efforts.

Endnotes

1. Natural gas also contains other gases, including other hydrocarbons, CO_2, and nitrogen.

2. The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in 1987 as an international treaty to eliminate the production and consumption of chlorofluorocarbons (CFCs) and other substances that deplete stratospheric ozone. The Protocol came into force on January 1st, 1989, when 29 countries and the European Economic Community (EEC), representing approximately 82 percent of world consumption, had ratified it. Production of the most damaging ozone-depleting substances was eliminated in developed countries by 1996, even before the Protocol went into effect, except for a few critical uses. Under the Protocol, remaining uses must be eliminated by 2010 in developing countries. As a result, the total concentration of chlorine in the lower atmosphere that can be carried to the stratosphere has peaked already. The concentrations in the stratosphere will likely peak by the end of this decade and then will start to decrease slowly as natural processes remove the ozone-depleting substances. All other things being equal, and with adherence to the international agreements, the ozone layer is expected to recover over the next 50 years or so.

3. Some of the HFC foam products are used as insulation, where they save energy use and therefore reduce CO_2 emissions. HFCs are also relatively efficient refrigerants and so replacing them with less efficient alternatives could increase the energy used in air conditioning. Reduction or elimination of HFC use would therefore need to consider these potential tradeoffs.

4. The gases in Figure 3 are treated one-by-one in order to isolate their effects on climate. In practice, the control policies that would limit CO_2 would also have an effect on other GHGs and substances that are relevant to radiative forcing, such as SO_X and NO_X.

5. Clean Air Act Amendments of 1990 (Public Law 101-549), Section 111.

6. Of course, if one must meet the same total reduction, the marginal cost of abatement would always be lower if one considered abatement opportunities of the non-CO_2 gases.

7. Manne and Richels (2000) did introduce abatement costs as an endogenous component of their model, but did not consider the industrial gases (HFCs, PFCs, and SF_6).

8. The EPPA projected emissions differ from those shown in Table 3 in several ways. The PFC estimate does not include rapid growth in emissions from computer chip manufacturers, as discussed in the preceding section, and the model forecasts less rapid growth for HFCs than EPA following the midrange estimates of Harnisch et al. (2000). On the other hand, the forecasts for methane and nitrous oxide are more in line with growth in underlying forecasts of activity levels (Mayer et al., 2001), whereas the forecasts in Table 3 factor in a variety of efforts designed to reduce emissions, such as those identified in the U.S. Climate Change Action Plan (Clinton and Gore, 1993).

9. Consideration of international emissions permit trading is omitted here to avoid confounding this effect with that of multi-gas policies. In particular, in trading cases the excess permits allocated to Russia, the Ukraine, and some other central European countries (so-called hot air) greatly reduce costs, but also mean less emissions reductions. In scenarios with Annex B trading, the carbon-equivalent prices in the multi-gas case drops to around $40/TCE.

10. For example, $50/TC equals $0.17/gallon of gasoline given the carbon in a gallon of gasoline. At a price of $1.50 per gallon, this is an 11% increase.

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+ **Multi-gas** contributors to global climate change

This report analyzes the important role of non-CO_2 greenhouse gases for cost-effective mitigation of global climate change. The Pew Center was established with a grant from the Pew Charitable Trusts and has been charged with bringing a new cooperative approach to the debate on global climate change. The Pew Center continues to inform the debate by publishing reports in the areas of policy (domestic and international), economics, environment, and solutions.