Appendix E - 6

The Cost-Effective Emission Reduction Potential of Non-Carbon Dioxide Greenhouse Gases within the United States and Abroad[1]

To date, most of the focus on greenhouse gas emissions reductions in the U.S. has been on energy-related carbon emissions. This is understandable since carbon dioxide (CO_2) emissions currently account for about 82 percent of the total U.S. greenhouse gas emissions weighted by 100-year global warming potentials (EPA, 1999a).[2] However, a number of recent analyses suggest that the non-CO_2 greenhouse gases included in the Kyoto Protocol — methane, nitrous oxide, and the high-GWP (global warming potential) gases (HFCs, PFCs, and SF_6) — can make a significant contribution to cost-effective emissions reductions for the United States. Our current estimate is a reduction in non-CO_2 emissions of 112 MMTCE at $50/ton carbon equivalent in 2010, excluding carbon sinks.

This paper provides a perspective on the current and projected emissions of greenhouse gas (GHG); outlines the potential methods for achieving emissions reductions for various sources; and summarizes several recent studies on the cost of reductions for the U.S. and other countries. Although the paper does not specifically address the potential for reductions of these gases in individual countries outside the U.S. and the European Union, its findings are generally applicable to many countries. Moreover, in many developing countries and some developed countries, e.g., New Zealand, Australia, and Ireland, non-CO_2 sources are a much larger proportion of the total emissions inventory — even exceeding CO_2 in some countries, such as Uruguay.

1. EMISSIONS AND PROJECTIONS

Combining CO_2 emission estimates from this study with our non-CO_2 emission projections, the total U.S. needed GHG reductions — between the Kyoto Protocol targets and baseline projections — for 2010 are 623 MMTCE. For the non-CO_2 gases, updated data developed by EPA show baseline emissions of 296 MMTCE and projections for 2010 of 381 MMTCE (EPA, 1999b; Harvey, 1999).[3] These projections of business as usual do not reflect expected reductions from the voluntary Climate Change Action Programs nor expected reductions from sinks and thus overestimate the likely emissions in the future. These estimates and projections are shown in Exhibit 1 on the following page.

Our preliminary economic analyses forecast U.S. reductions in non-CO_2 emissions of 112 MMTCE at $50/ton carbon equivalent (TCE) for 2010, which is 18 percent of the reductions needed to meet the Kyoto targets.[4] These results suggest that cost-effective non-CO_2 reductions fully offset their implicit share of the overall reduction targets and make a small contribution to the implicit target for CO_2. This shows that the inclusion of non-CO_2 gases in a multi-gas abatement strategy is unquestionably preferable to meeting the targets through reductions solely in CO_2.

Exhibit 1: Projected GHG emissions to 2010
(in MMTCE)

Reference / Emissions	CO_2	non-CO_2	Total
Baseline (1990/1995)	1,346	296	1,642
2010 Projections	1,769	381	2,150
2010 Required reductions	1,252	276	1,527
Difference	(517)	(106)	(623)
Projected reductions at $50/TCE	306 — 332	112	418 - 444
Remaining needed reductions	(185 — 211	6	(179 - 205)

Source: CO_2 data from this report; non-CO_2 data from EPA, 1999b; Harvey, 1999

Data from the CEF Study indicates that to reach the Kyoto targets by 2010, the U.S. would need an estimated 517 MMTCE in energy-related, CO_2 reductions. This study further suggests that 306 to 332 MMTCE of emission reductions could be achieved at $50/TCE through domestic technology investments and the use of low-carbon fuels. This means, in turn, that other strategies such as sequestration, international trading, joint implementation and the clean development mechanism must provide the remaining MMTCE reductions needed for the U.S.

Fig. 1: GHG Marginal Abatement Curves
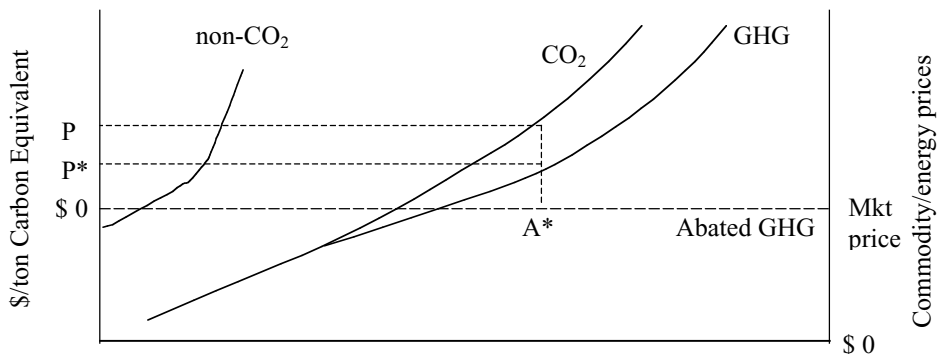
The economic benefit of pursuing a strategy that includes the non-CO_2 GHGs is illustrated above in Figure 1. Marginal abatement curves are presented for non-CO_2, CO_2, and all GHGs (the summation of the first two) showing the additional amounts of abated GHGs per increases in the price of carbon equivalent ($/TCE) — the left vertical axis. The horizontal axis is the amount of abated GHGs and the right vertical axis is the price of a GHG source or the price of a GHG as a supply of energy. This includes, for example, the price of coal for CO_2 emissions, of fertilizer for nitrous oxide emissions, of HFCs as commodities themselves, or of natural gas for methane emissions.

The commodity/energy market prices are aligned to $0/TCE since this is where there are no additional price signals from GHG permits to motivate emissions reductions; all emissions reductions are due to increased energy efficiencies, conservation of production materials, or both. As a value is placed on GHG reductions in terms of $/TCE, these values are added to the commodity/energy market prices and allow for additional emissions to clear the market. The below-the-line amounts, with respect to $/TCE, illustrate this dual price-signal market.

Given an abatement target, A*, for the Kyoto basket of gases, the total cost of achieving those reductions will be less, by including available non-CO_2 reductions, than by attempting to reach that target by CO_2 reductions alone. This is shown by the decrease in \$/TCE price from P to P*. Analyses conducted by researchers at MIT (Reilly, 1999a) and the Univ. of Illinois (Hayhoe, 1999), discussed below, demonstrate that inclusion of non-CO_2 gases and sinks greatly reduces the costs of achieving emissions reductions under the Kyoto Protocol.

2. TECHNOLOGIES FOR NON-CO_2 EMISSIONS REDUCTIONS

There is a wide range of emission reduction technologies available for the non-CO_2 GHG sources, such as gas capture (e.g., reuse of methane for energy), efficiency improvements, end-of-pipe controls (e.g., incineration), leak reduction, and gas substitution. Moreover, some methods aimed at CO_2 reductions (e.g., fuel substitution or efficiency measures for large fuel combustors or automobiles) may also yield matching reductions in methane and nitrous oxide. The specific methods vary depending on the gas and source. This section provides a brief overview of available approaches - more information on the techniques can be found in the references to this paper.

2.1 METHANE

Methane accounts for about 10 percent of all U.S. GHG emissions in 1997 (EPA, 1999a). Among the methane sources in the U.S., the largest sources of emissions are from municipal solid waste landfills, followed by natural gas and oil systems, ruminant animals, coal mines, and animal manure systems. Smaller sources of emissions in the U.S. are wastewater, biomass combustion, rice production, and other miscellaneous sources. EPA has five voluntary methane emissions reduction programs underway as part of the Climate Change Action Plan. They are:

- Landfill Methane Outreach Program
- Natural Gas Star
- Ruminant Livestock Efficiency Program
- Coalbed Methane Outreach Program
- AgStar (livestock manure systems)

Lessons learned by private sector and local government partners in these voluntary programs have led to an understanding of the available technologies and management options for reducing methane emissions. The predominant emissions reduction measure for anthropogenic methane emissions is methane capture and use as energy, since methane is the principal component of natural gas.

For landfills, coal mines, and manure systems, methane gas can be captured through a collection system, cleansed of impurities (water, other gases), and then used as an on-site fuel, used to generate electricity, or sold to an energy end-user, such as a factory or municipal building in need of a constant supply of fuel. Methane can also be sold into the natural gas system, which is the dominant approach for methane from coal mines. Use of this renewable energy source thus avoids combustion of non-renewable energy sources. Alternatively, methane can be flared rather than emitted to the atmosphere if it is not used as an energy source.

For natural gas and oil systems, a number of leak reduction measures can be taken at various stages of production, transmission, and distribution. For ruminant livestock, increases in meat and milk production efficiency, through improved grazing practices and animal management, result in reductions in methane emissions per unit of product. There are also potentially cost-effective reduction approaches for some of

the smaller methane emissions sources in the U.S., such as modifications to rice paddy flooding regimes. These have not been analyzed, however, due to their smaller contributions to total emissions.

2.2 NITROUS OXIDE

Nitrous oxide emissions make up about six percent of all U.S. GHG emissions in 1997 (EPA, 1999a). The main sources of nitrous oxide emissions, in order of magnitude, are agriculture, mobile sources, and the industrial production of adipic and nitric acid.

Under the Climate Change Action Plan, the U.S. Department of Agriculture and EPA have examined the potential for emissions reductions of nitrous oxide resulting from fertilizer application to agricultural soils. More efficient farming practices in general, such as no till practices, improved soil conservation, and substitution of organic fertilizers for synthetic fertilizers, are all measures that may lead to reductions in nitrous oxide, as well as other co-benefits, such as reduced soil erosion.

Nitrous oxide emissions from mobile sources result from increased use of catalytic converters in cars and trucks. A wide range of practices in this sector could result in nitrous oxide emissions reductions —as well as correlated reductions in CO_2 and methane from fuel combustion. These practices include measures to affect vehicle miles traveled (such as mass transit improvements), technological changes to catalytic converters, and fuel substitution (e.g., increasing use of hybrid, electric, ethanol, and natural gas vehicles).

In the industrial sector, nitrous oxide emissions are a by-product in the production of adipic and nitric acid. Ninety percent of all adipic acid manufactured in the U.S. is used in the production of nylon 6,6 (EPA, 1998a). However, substantial measures have already been taken voluntarily by U.S. chemical companies to largely reduce emissions of nitrous oxide from U.S. adipic acid production (i.e., installation of end-of-pipe thermal oxidation technologies). Nitric acid is used primarily to make synthetic commercial fertilizer and is also a major component in the production of adipic acid and explosives (EPA, 1998a). For nitric acid production, similar end-of-pipe technologies could potentially result in substantial reductions at low costs.

2.3 HFCS, PFCS, AND SF$_6$

The high-GWP gases account for about two percent of all U.S. GHG emissions in 1997 (EPA, 1999a). These gases fall into two broad categories: first, they are substitutes for the ozone-depleting gases being phased out under the Montreal Protocol (CFCs and HCFCs) and thus are used in a variety of applications, including air conditioning, refrigeration, foams, fire fighting, solvents, and aerosols. Second, these gases are used or emitted in a range of industrial applications. For example, PFCs are generated and emitted in the production of aluminum whereas HFC-23 is a by-product of HCFC-22 production. Other applications for these gases include semiconductor manufacture, use of SF_6 in magnesium casting, and as an insulating gas in electrical systems. Measures that already have been taken or could be taken to reduce emissions from these sources include gas substitution, leak reduction programs, incineration, and gas recycling. For example, HCFC-22 manufacturers are using a combination of process optimization, equipment modification, and thermal oxidation to reduce emissions of HFC-23 during production.

Under the Clean Air Act, the EPA has authority to regulate use of these gases as substitutes for ozone depleting substances and thus ensures that they are used responsibly in low emission applications. In addition, EPA has established specific voluntary programs in partnership with industry to encourage voluntary reductions in these gases, such as programs for PFC emissions from aluminum production and SF_6 emissions from electrical systems. Other industries, such as the world semiconductor industry, already have made significant commitments to reduce emissions from 1995 levels.

3. SURVEY OF RELEVANT STUDIES

Until recently, few comprehensive studies had been conducted examining the potential for cost-effective reductions in the non-CO_2 gases or among all GHGs. Where studies did try to incorporate non-CO_2 gases, they tended either to assume that non-CO_2 emissions reductions would cost the same as CO_2, would be infinitely costly, or were free — necessary simplifications in the absence of data.

In the past few years, however, a number of studies have emerged from the U.S., Europe, and Australia that provide useful cost estimates for larger studies that evaluate the cost of meeting GHG reduction targets. This section provides a quick survey of some of these studies. The following list notes the authors, scope of gases, and geographic scope:

- MIT - multi-gas reductions among Annex B countries
- Univ. of Illinois - CO_2 and CH_4 reductions in the U.S.
- CEA - multi-gas reductions for U.S. and Annex B countries
- ABARE - CO_2, CH_4, N_2O reductions among Annex B countries
- U.S. EPA - methane reductions in the U.S.
- ECOFYS - multi-gas reductions in Europe
- ECN - multi-gas reductions in Europe
- March Consulting - High-GWP reductions in UK and Europe

Although other studies have included estimates of non-CO_2 reductions, these particular studies are highlighted either because they tend to provide new information on the costs of specific non-CO_2 gas reductions or they incorporate multi-gas approaches to analyze the reductions in costs occasioned by moving from a CO_2-only approach to a multi-gas approach.

3.1 MIT

A group of researchers affiliated with the Massachusetts Institute of Technology's (MIT's) Joint Program on the Science and Policy of Global Change (i.e., John Reilly, Ronald G. Prinn, Jochen Harnisch, Jean Fitzmaurice, Henry D. Jacoby, David Kicklighter, Peter H. Stone, Andrei P. Sokolov, and Chien Wang) published an article in *Nature* (Reilly, 1999a) showing that "inclusion of sinks and abatement opportunities from gases other than CO_2 could reduce the cost of meeting the Kyoto Protocol by 60%. A similar study in January 1999 (Reilly, 1999b), which also examined the implications of reductions in multi-gases on atmospheric composition, climate, and ecosystem impacts, found that "omitting other trace gases leads to an overestimate of the carbon price ... from about 8% in the EET [Central and Eastern Europe] to 153% in the OOE [OECD countries other than the U.S., Japan, and Europe]."

It notes that the U.S., Europe, and the other OECD countries "stand to benefit substantially by inclusion of sinks and other gases," noting that "for Annex B as a whole, the error of leaving out other trace gases is about a $38 billion/year [converted to 1999 US$] overestimate of costs in 2010." For the U.S. alone, the benefit of a multi-gas approach would be about $25 billion annually (in 1999 US$), a 40 percent reduction in costs from a CO_2 only control approach. Their analysis was based on all six greenhouse gases and sinks. Methane cost estimates in this analysis were based on EPA's 1998 preliminary methane cost analysis (EPA, 1998b).

3.2 Univ. of Illinois

A study presented in the journal *Science* (Hayhoe, 1999), showed increases in control options and a decrease in the costs of meeting international agreements to reduce GHGs by following a multi-gas approach. Based on the latest abatement costs, the study estimated that for short-term targets, CH_4 can offset CO_2 reductions and reduce U.S. costs by more than 25% relative to strategies involving CO_2 alone. The study was prepared by a team of atmospheric scientists, economists, and policy analysts at the University of Illinois, the U.S. Department of Energy s Pacific Northwest Laboratory, the U.S. Environmental Protection Agency, and ICF Consulting.

3.3 CEA

In July 1998, the U.S. Council of Economic Advisors analyzed the cost of the Kyoto Protocol for the U.S. (CEA, 1998). The analysis incorporated preliminary estimates for the U.S. for reductions in the non-CO_2 gases, developed by EPA. While the larger analysis suggested that costs in 2010 would range between $14/TCE to $23/TCE, the data produced for this analysis examined potential reductions in methane, nitrous oxide, and the high-GWP gases up to a maximum price of $70/TCE.

The data suggested that, in 2010, at $50/TCE about 78 MMTCE of non-CO_2 gases (largely high-GWP gases and methane) could be reduced and at $70/TCE about 82 MMTCE could be reduced. EPA has updated some of the analyses for these gases (see section 3.4 below and footnote 3, in which we discuss our updated estimates for methane, nitrous oxide, and high-GWP gases). The CEA analysis forecasted non-CO_2 emissions projections for other countries but used the simplifying assumption that the cost of non-CO_2 emissions reductions in those countries would be the same as CO_2.

3.4 ABARE

The Australian Bureau of Agricultural and Resource Economics (ABARE) published an analysis in May 1999, conducted by Stephen Brown, Darren Kennedy, and others, that modeled the economic impacts of the Kyoto Protocol on Annex B and non-Annex B regions, examining the combined effect of emissions trading among CO_2, methane, and nitrous oxide. The analysis confirmed the hypothesis that inclusion of additional gases allows Annex B regions to utilize a greater number of emission abatement options. The authors note that "it can be readily shown that under a given abatement target the total abatement cost with extra gases will always be less than, or equal to, the abatement cost of carbon dioxide only."

The study found that, for 2010, the estimated Annex B regions cost, in carbon equivalent terms ($/TCE), fell by roughly 20 percent when assuming the targets were met by emissions trading among the three gases in the analysis versus CO_2 only. Methane cost estimates in this analysis were based on EPA's 1998 preliminary methane cost report (EPA, 1998b).

3.5 U.S. EPA

EPA's Methane Branch published a report, in September 1999, of methane emissions and the cost of reducing those emissions in the U.S. (EPA, 1999b). Emission estimates are given for 1990 through 1997 with projections for 2000 to 2020. The cost analysis for reductions is for 2000, 2010, and 2020. The report presents cost (marginal abatement) curves estimating that, at $50/TCE, about 70 MMTCE of methane reductions would be available in 2010. These reductions were based on analyzing four major sources of methane in the U.S., i.e., landfills, coal mines, natural gas systems, and manure systems.

EPA is also conducting related analyses for nitrous oxide and the high-GWP gases in order to obtain better estimates of the total reduction potential from the non-CO_2 sources (Harvey, 1999). For the purposes of this paper, based on work to date, a total of 112 MMTCE of reductions are assumed to be available at \$50/TCE from the non-CO_2 gases in the United States, of which 70 MMTCE are from methane, 37 MMTCE are from the high-GWP gases, and 5 MMTCE are from nitrous oxide.

3.6 ECOFYS

In 1998, de Jager, Hendriks, Heijnes, and Blok of ECOFYS Energy and Environment, based in the Netherlands, conducted a study for the European Union analyzing emissions reductions potential and cost for non-CO_2 greenhouse gases among the 15 EU countries. They concluded that "in the year 2010 about 40% of the required emission reduction for the EU-15 can be realised by these gases at relative low specific costs." This amounts to 217 million metric tons of CO_2 equivalent in 2010 reduced at costs below 50 Euro per ton CO_2 equiv. (This is approximately 59 MMTCE reduced at costs below \$193/TCE[5].)

The choice of 50 Euro as the illustrative price of carbon was assumed, rather than derived through modeling. Finally, the authors note that "control options for methane would be responsible for about 40% of this amount, for nitrous oxide this figure is 10% and for the halogenated gases (mostly the HFCs) 50%."

3.7 ECN

In September 1998, Dolf Gielen and Tom Kram of ECN in the Netherlands published a preliminary analysis that suggested that the non-CO_2 greenhouse gases could contribute about 27 percent to the total emission reduction in 2010 from the EU 15 countries at below 25 Euro/ton CO_2 equivalent (\$96/TCE), even though these gases represent about 21 percent of total EU emissions. Major emissions reductions were projected for methane from landfills, nitrous oxide from the chemical industry, and substitutes for the HFCs. Although total EU non-CO_2 emissions are expected to decrease to 18 percent in the baseline (due in part to coal mine closures and waste policies), some sources were projected to increase over the same time, such as HFC emissions from cooling and air conditioning equipment.

3.8 March Consulting

In 1998 and 1999, March Consulting in the United Kingdom conducted studies for the European Union and the U.K. Department of the Environment, Transport and the Regions (DETR) that analyzed technologies and costs of emissions reductions for the high-GWP sources of HFCs, PFCs, and SF_6. These analyses provide substantial technical detail for the specific sources and market sub-segments for these gases, along with an assessment of the relative cost-effectiveness of emissions reductions among the high-GWP sources. The authors found that an EU-wide 15 percent emissions reduction below the 1995 baseline for these gases could be achieved, assuming that actions that cost less than 20 to 30 Euro/ton CO_2 equivalent (about \$77/TCE to \$116/TCE) were implemented.

4. CONCLUSIONS

The studies highlighted above demonstrate that the non-CO_2 GHG included in the Kyoto Protocol — methane, nitrous oxide, and the high-GWP gases (HFCs, PFCs, and SF_6) — can make a significant contribution to cost-effective emissions reductions for the U.S. Although there are few complete data sources, the initial analyses in the U.S., Europe and Australia suggest that emissions reductions from

these gases could reduce costs substantially (around 15 to 40 percent) in meeting the Kyoto Protocol emissions targets, depending on the country. Further elaboration on potential reductions from the non-CO_2 gases would provide an important contribution to the overall effort to assess the potential range of costs for meeting the Kyoto Protocol.

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6. ENDNOTES

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[2] As noted in EPA 1999a, the concept of global warming potential (GWP) has been developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas over a given period of time. Carbon dioxide is the reference gas, consistent with guidelines developed by the Intergovernmental Panel on Climate

Change (IPCC). U.S. estimates of greenhouse gas emissions are typically presented in units of million metric tons of carbon equivalents (MMTCE). Carbon comprises 12/44ths of carbon dioxide by weight. In order to convert emissions reported in teragrams (Tg) of greenhouse gas to MMTCE, the following equation was used:

MMTCE = (Tg of gas) x (GWP) x (12/44)

For example, a source emitting 1 Tg of methane (GWP = 21) would be emitting 5.73 MMTCE, as follows:

(1 Tg) x (21) x (12/44) = 5.73 MMTCE

While any time period may be selected, the 100—year GWPs recommended by the IPCC, and employed by the United States for policy making and reporting purposes, were used in this report (IPCC, 1996). The effect of selecting alternative time periods depends on the atmospheric lifetime of the gas in relation to the atmospheric lifetime of the reference gas (carbon dioxide). Thus, since methane s lifetime is about 12 years, its 20 year GWP is 56 and its 500 year GWP is 6.5. In contrast, the lifetime of sulfur hexafluoride is 3,200 years and thus its GWP increases from 16,300 over 20 years, 23,900 over 100 years, and 34,900 over 500 years.

[3] EPA annually develops emissions projections for the non-CO_2 sources. The numbers presented here represent business-as-usual emissions without subtracting expected reductions from implementation of the voluntary Climate Change Action Programs or other voluntary reduction efforts planned by industry. The Kyoto Protocol provides that the baseline year for methane and nitrous oxide is 1990 and, for the high-GWP gases, countries have the option of choosing 1990 or 1995. For this analysis, 1995 is used as the baseline for the high-GWP gases.

[4] Of the 112 MMTCE, we estimate that about 70 MMTCE would come from methane sources and, based on preliminary results from our work to date, the balance would come from the high-GWP gases (assumed to be about 37 MMTCE) and nitrous oxide (about 5 MMTCE). These rough estimates are likely to change as we finalize our baseline projections and cost analyses. We do not include any reductions from sinks in this estimate.

[5] To convert from Euro to $US, we assumed a conversion rate of 1.05. To convert from CO_2 to carbon equivalent, we used the ratio of 12/44ths (i.e., 12 Carbon to 44 CO_2). Thus, 1 Tg of CO_2 is equal to 0.273 MMTCE.