I. Technical Summary

I.1 Overview

The objective of this report is to provide a comprehensive and consistent data set on global mitigation of noncarbon dioxide (non-CO_2) greenhouse gases to facilitate multigas analysis of climate change issues. Mitigating emissions of non-CO_2 greenhouse gases can be relatively inexpensive compared with mitigating CO_2 emissions. Thus, attention has been focused on incorporating international non-CO_2 greenhouse gas mitigation options into climate economic analyses. This requires a large data collection effort and expert analysis of available technologies and opportunities for greenhouse gas reductions across diverse regions and sectors.

This report builds on a study previously conducted by the U.S. Environmental Protection Agency (USEPA) for the Energy Modeling Forum, Working Group 21 (EMF-21). The Energy Modeling Forum was established by Stanford University to explore energy and environmental issues through the collaboration of diverse modeling teams from around the world. The EMF-21 focused specifically on multigas strategies to address climate change and resulted in the publication of a special issue of the *Energy Journal* (see Weyant and de la Chesnaye [in press]). The specific non-CO_2 mitigation papers in the EMF-21 study include energy- and industry-related methane (CH_4) and nitrous oxide (N_2O) (Delhotal et al., in press), agricultural-related $CH_4$and N_2O (DeAngelo et al., in press), and industry-related fluorinated gases (Ottinger et al., in press). Much of the original work comes from two previous USEPA studies for the United States (USEPA, 2001, 1999) and a study conducted by the European Commission (EC) (2001) that evaluated technologies and costs of CH_4 abatement for EU members from 1990 to 2010.

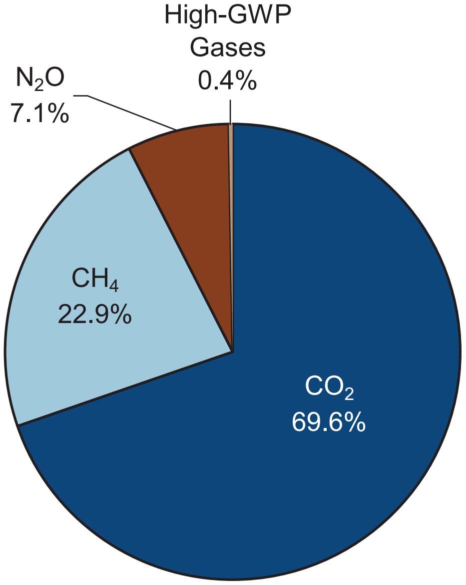
Following the basic methodology of the EMF-21 study with some enhancements (as described in Section I.3.4 of this report), this report contains detailed analyses by economic sector and region for all non-CO_2 greenhouse gases over the period from 2000 to 2020. The end result of this report is a set of marginal abatement curves (MACs) that allow for improved understanding of the mitigation potential for non-CO_2 sources, as well as inclusion of non-CO_2 greenhouse gas mitigation in economic modeling. The MAC data sets can be downloaded in spreadsheet format from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

I.2 Non-CO_2 Greenhouse Gases

Greenhouse gases other than CO_2 play an important role in the effort to understand and address global climate change. The non-CO_2 gases include CH_4, N_2O, and a number of high global warming potential or fluorinated gases. The non-CO_2 greenhouse gases are more potent than CO_2 (per unit weight) at trapping heat within the atmosphere and, once emitted, can remain in the atmosphere for either shorter or longer periods of time than CO_2. Figure 2-1 shows that these non-CO_2 greenhouse gases are responsible for approximately 30 percent of the enhanced, anthropogenic greenhouse effect since preindustrial times.

Table 2-1 shows the global total greenhouse gas emissions for the year 2000, broken down by sector and by greenhouse gas type. The non-CO_2 gases constitute 24 percent of the global total greenhouse gas emissions in 2000.

Figure 2-1: Contribution of Anthropogenic Emissions of Greenhouse Gases to the Enhanced Greenhouse Effect from Preindustrial to Present (measured in watts/meter^2)



Source: IPCC, 2001b. Note that gases regulated under the Montreal Protocol are excluded.

Table 2-1: Global Greenhouse Gas (GHG) Emissions for 2000 ($MtCO_2eq$)

Sectors	CO_2	CH_4	N_2O	High-GWP	Global Total	Percentage of Global Total GHGs
Energy	23,408	1,646	237		25,291	61%
Agriculture	7,631	3,113	2,616		13,360	32%
Industry	829	6	155	380	1,370	3%
Waste		1,255	106		1,361	3%
Global Total	31,868	6,021	3,114	380	41,382	
Percentage of Global Total GHGs	77%	15%	8%	1%		

Source: Adapted from de la Chesnaye et al., in press; USEPA, 2006.

I.2.1 Methane (CH_4)

CH_4 is about 21 times more powerful at warming the atmosphere than CO_2 over a 100-year period.[1] In addition, CH_4's chemical lifetime in the atmosphere is approximately 12 years, compared with approximately 100 years for CO_2. These two factors make CH_4 a candidate for mitigating global warming in the near term (i.e., within the next 25 years or so) or in the time frame during which atmospheric concentrations of CH_4 could respond to mitigation actions.

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[1] Per IPCC (1996) guidelines. The GWP of methane in the IPCC Third Assessment Report (2001a) is 23.

CH_4 is emitted from a variety of manmade sources, including landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes. CH_4 is also a primary constituent of natural gas and an important energy source. As a result, efforts to prevent or capture and use CH_4 emissions can provide significant energy, economic, and environmental benefits.

The historical record, based on analysis of air bubbles trapped in glaciers, indicates that CH_4 is more abundant in the Earth's atmosphere now than at any time during the past 400,000 years (National Research Council [NRC], 2001). Since 1750, global average atmospheric concentrations of CH_4 have increased 150 percent, from approximately 700 to 1,745 parts per billion by volume (ppbv) (Intergovernmental Panel for Climate Change [IPCC], 2001a). Although CH_4 concentrations have continued to increase, the overall rate of CH_4 growth during the past decade has slowed. In the late 1970s, the growth rate was approximately 20 ppbv per year. In the 1980s, growth slowed to 9 to 13 ppbv per year. From 1990 to 1998, CH_4 saw variable growth between 0 and 13 ppbv per year (IPCC, 2001a). A recent study by Dlugokencky et al. (2003) shows that atmospheric CH_4 was at a steady state of 1,751 ppbv between 1999 and 2002.

Once emitted, CH_4 is removed from the atmosphere by a variety of processes, frequently called sinks. The balance between CH_4 emissions and CH_4 removal processes ultimately determines atmospheric CH_4 concentrations and determines the length of time CH_4 emissions remain in the atmosphere. The dominant sink is oxidation within the atmosphere by chemical reaction with hydroxyl radicals (OH). Methane reacts with OH to produce alkyd radicals (CH_3) and water in the tropospheric layer of the atmosphere. Stratospheric oxidation also plays a minor role in removing CH_4 from the atmosphere. Similar to tropospheric oxidation, in stratospheric oxidation, minor amounts of CH_4 are destroyed by reacting with OH in the stratosphere. These two reactions account for almost 90 percent of CH_4 removal (IPCC, 2001c). Other known sinks include microbial uptake of CH_4 in soils and the reaction of CH_4 with chlorine (Cl) atoms in the marine boundary layer. It is estimated that these two sinks contribute 7 percent and less than 2 percent of total CH_4 removal, respectively.

I.2.2 Nitrous Oxide (N_2O)

N_2O is a clear, colorless gas with a slightly sweet odor. Because of its long atmospheric lifetime (approximately 120 years) and heat-trapping effects—about 310 times more powerful than CO_2 on a per-molecule basis—N_2O is an important greenhouse gas.

N_2O has both natural and manmade sources and is removed from the atmosphere mainly by photolysis (i.e., breakdown by sunlight) in the stratosphere. In the United States, the main manmade sources of N_2O are agricultural soil management, livestock waste management, mobile and stationary fossil fuel combustion, adipic acid production, and nitric acid production. N_2O is also produced naturally from a variety of biological sources in soil and water. On a global basis, it is estimated that natural sources account for over 60 percent of total N_2O emissions (IPCC, 2001c).

Global atmospheric concentrations of N_2O have increased from about 270 ppbv in 1750 to 314 ppbv in 1998, which equates to a 16 percent increase. In the last 2 decades, atmospheric concentrations of N_2O continue to increase at a rate of 0.25 percent per year. There has been a significant multiyear variance in observed growth of N_2O concentrations, but the reasons for these trends are not fully understood yet (IPCC, 2001b).

I.2.3 High-GWP Gases

There are three major groups or types of high-GWP gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). These compounds are the most potent greenhouse gases because of their large heat-trapping capacity and, in the cases of SF_6 and the PFCs, their extremely long atmospheric lifetimes. Because some of these gases, once emitted, can remain in the atmosphere for centuries, their accumulation is essentially irreversible. High-GWP gases are emitted from a broad range of industrial sources; most of these gases have few (if any) natural sources.

I.2.3.1 HFCs

HFCs are manmade chemicals, many of which have been developed as alternatives to ozone-depleting substances (ODSs) for industrial, commercial, and consumer products. The GWPs of HFCs range from 140 (HFC-152a) to 11,700 (HFC-23). The atmospheric lifetime for HFCs varies from just over a year (HFC-152a) to 260 years (HFC-23). Most of the commercially used HFCs have atmospheric lifetimes of less than 15 years (for example, HFC-134a, which is used in automobile air-conditioning and refrigeration, has an atmospheric lifetime of 14 years).

The HFCs with the largest measured atmospheric abundances are (in order) HFC-23 (CHF_3), HFC-134a (CF_3CH_2F), and HFC-152a (CH_3CHF_2). The only significant emissions of HFCs before 1990 were from HFC-23, which is generated as a by-product during the production of HCFC-22. Between 1978 and 1995, HFC-23 concentrations increased from 3 to 10 parts per trillion (ppt), and these concentrations continue to rise. In 1990, HFCs other than HFC-23 were almost undetectable; today, global average concentrations of HFC-134a have risen significantly to almost 10 ppt. HFC-134a has an atmospheric lifetime of about 14 years and its abundance is expected to continue to rise in line with its increasing use as a refrigerant around the world. HFC-152a has increased steadily to about 0.3 ppt in 2000; however, its relatively short lifetime (1.4 years) has kept its atmospheric concentration below 1 ppt (IPCC, 2001a).

I.2.3.2 PFCs

Primary aluminum production and semiconductor manufacture are the largest known manmade sources of tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). PFCs are also relatively minor substitutes for ODSs. Over a 100-year period, CF_4 and C_2F_6 are, respectively, 6,500 and 9,200 times more effective than CO_2 at trapping heat in the atmosphere.

PFCs have extremely stable molecular structures and are largely immune to the chemical processes in the lower atmosphere that break down most atmospheric pollutants. Not until the PFCs reach the mesosphere, about 60 kilometers above Earth, are they destroyed by very high-energy ultraviolet rays from the sun. This removal mechanism is extremely slow; as a result, PFCs accumulate in the atmosphere and remain there for several thousand years. The estimated atmospheric lifetimes for CF_4 and C_2F_6 emissions are 50,000 and 10,000 years, respectively. Measurements in 2000 estimated CF_4 global concentrations in the stratosphere at over 70 ppt. Recent relative rates of concentration increase for these two important PFCs are 1.3 percent per year for CF_4 and 3.2 percent per year for C_2F_6 (IPCC, 2001a).

I.2.3.3 Sulfur Hexaflouride (SF_6)

The GWP of SF_6 is 23,900, making it the most potent greenhouse gas evaluated by IPCC. SF_6 is a colorless, odorless, nontoxic, nonflammable gas with excellent dielectric properties. It is used (1) for insulation and current interruption in electric power transmission and distribution equipment; (2) to protect molten magnesium from oxidation and potentially violent burning in the magnesium industry; (3) to create circuitry patterns and to clean vapor deposition chambers during manufacture of semiconductors and flat panel displays; and (4) for a variety of smaller uses, including uses as a tracer gas and as a filler for sound-insulated windows.

Like the PFCs, SF_6 is very long lived, so all manmade sources contribute directly to its accumulation in the atmosphere. Measurements of SF_6 show that its global average concentration increased by about 7 percent per year during the 1980s and 1990s, from less than 1 ppt in 1980 to almost 4 ppt in the late 1990s (IPCC, 2001a).

I.2.4 Use of GWPs in this Report

The GWP compares the relative ability of each greenhouse gas to trap heat in the atmosphere during a certain time frame. Per IPCC (1996) guidelines, CO_2 is the reference gas and thus has a GWP of 1. Based on a time frame of 100 years, the GWP of CH_4 is 21 and the GWP of N_2O is 310. Table 2-2 lists all GWPs used in this report to convert the non-CO_2 emissions into CO_2-equivalent units. This report uses GWPs from the 1996 IPCC Second Assessment Report (rather than the 2001 Third Assessment Report) because these are the values specified by greenhouse gas reporting guidelines under the United Nations Framework Convention on Climate Change.

Table 2-2: Global Warming Potentials

Gas	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous oxide (N_2O)	310
HFC-23	11,700
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF_4	6,500
C_2F_6	9,200
C_4F_{10}	7,000
C_6F_{14}	7,400
SF_6	23,900

I.3 Methodology

This section describes the basic methodology used in this report to analyze potential emissions and abatement of non-CO_2 greenhouse gases. In this analysis we construct MAC curves for each region and sector by estimating the carbon price at which the present value benefits and costs for each mitigation option equilibrates. The methodology produces a stepwise curve, where each point reflects the average price and reduction potential if a mitigation technology were applied across the sector within a given region. This section describes the components of our methodology. First, we establish the baseline emissions for each sector in Section I.3.1. Then we describe the methodology used to evaluate mitigation options in Section I.3.2, which involves calculating the abatement potential and the breakeven price for each option. Lastly, we describe the construction of the MACs in Section I.3.3. Some sectors deviate from this methodology depending on specific circumstances, which are briefly mentioned here and described in more detail in the sector-specific chapters.

The results of the analysis are presented as MACs by region and by sector and generally focus on or within the 2000 to 2020 time frame. In some cases, sensitivities to the MACs are presented where the discount rate, tax rate, and energy prices vary. Emissions abatement in the MACs is shown as both absolute emissions reductions and as percentage reductions from the baseline. Non-CO_2 emissions sources analyzed in this report are coal mining; natural gas production, processing, transmission, and distribution; oil production; solid waste management; wastewater; specialized industrial processes; and agriculture.

I.3.1 Baseline Emissions for Non-CO_2 Greenhouse Gases

Current and projected (through 2020) emissions estimates are based primarily on emissions projections from the USEPA's *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020* (USEPA, 2006). The methods used to estimate and project non-CO_2 emissions in USEPA (2006) are briefly summarized here. In some cases, particularly for the fluorinated gas emissions and agricultural emissions, it was necessary to develop separate baselines from which to assess the mitigation analyses. These deviations are also explained in this report.

For Annex I countries,[2] baseline (i.e., reference) projections are based largely on publicly available reports produced by the countries themselves. The preferred sources for these reports are the *National Communications* for the United Nations Framework Convention on Climate Change,[3] which contain current emissions rates and emissions projections through 2020. Estimates from the various countries should be comparable because they rely on the same (or similar) IPCC methodologies and country-specific activity data.

Estimates of historical and projected emissions for developing countries were based on national and international reports. These emissions rates also reflect the most recent results of the USEPA study *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020* (USEPA, 2006). The preferred approach to estimate emissions from developing countries is to use the latest published information for each country. Some developing countries reported emissions estimates from 1990 or later in the latest *National Communications,* in *Asia Least-Cost Greenhouse Gas Abatement Strategy* (ALGAS) (Asian Development Bank, 1998), or in a country-specific report. Preference is given to the latest published estimates from the *National Communications* and ALGAS reports, including both historical and projected estimates.

When the emissions data from these references did not cover the entire historical or projected period from 1990 to 2020, or in cases where no emissions data were reported, estimated emissions were obtained using the following approaches:

1. For countries reporting estimates from 1990 to 2010 in 10-year intervals, a linear interpolation was used to estimate values in 5-year increments.

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[2] Annex I countries are countries that are listed in Annex I to the United Nations Framework Convention on Climate Change. A complete list of the Annex I countries is available at <http://unfccc.int/essential_background/convention/background/items/1346.php>.

[3] The *National Communications* are available at <http://www.unfccc.org>.

2. For countries not reporting emissions through 2000, emissions growth rates were estimated based on IPCC Tier 1[4] estimates for the country for 1990 through 2000. The growth rates were applied to reported inventories since 1990 and used to estimate the remaining years through 2000. Projections to 2020 are based on growth-rate projections applied to source-specific drivers for each country, using the estimate for 2000 as the base year.
3. When no emissions data were available or when the data were insufficient, the USEPA developed emissions estimates, projections, or both, using the default methodology presented in the *1996 Revised IPCC Guidelines* (IPCC, 1997) and the *IPCC Good Practice Guidance* (IPCC, 2000).

Baseline projections represent business-as-usual scenarios, where currently achieved reductions are incorporated, but future mitigation actions are only included if either a well-established program or an international sector agreement is in place. Thus, projections do not include planned climate change source-level mitigation efforts, although they do include voluntary and nonclimate-based policies that indirectly reduce greenhouse gases. For consistency, if a country's reported projections include planned climate mitigation efforts, the reductions from those efforts were added back into the emissions projections, where identified. If planned climate policy reductions could not be identified, a country's emissions projections were estimated by continuing trends from previous years, as reported in historical inventories.

Source-by-source and country-by-country explanations of how the projections were developed can be found in the appendix to USEPA (2006).

I.3.1.1 Baseline Emissions for Agriculture

For the agricultural mitigation analysis, separate baseline emissions for croplands and rice cultivation were developed and used, even though USEPA (2006) includes estimates for these sources. Process-based models—DAYCENT for croplands and DeNitrofication–DeComposition (DNDC) for rice cultivation—were used for both the baseline emissions estimates and the greenhouse gas implications of mitigation options, thus allowing for a clear identification of baseline management conditions and consistent estimates of changes to those conditions through mitigation activities. For emissions associated with livestock, the mitigation analysis in this report relies on USEPA (2006) baseline estimates. Further details about the emissions baselines estimated by the DAYCENT and DNDC models, and their relationship to USEPA (2006) estimates, are provided in Section V Agriculture of this report.

I.3.1.2 Baseline Emissions for Fluorinated Gases

Baselines for the fluorinated gases are also based on *Global Anthropogenic Non-CO$_2$ Greenhouse Gas Emissions: 1990–2020* (USEPA, 2006). The 2006 USEPA analysis builds on the 2001 USEPA analysis to develop country-by-country and industry-by-industry projections of emissions using projections of activity data, emissions factors, or other data related to emissions. For the industrial sources, activity data were multiplied by emissions factors to obtain emissions projections. For the substitutes for ODSs, estimates of country-specific ODS consumption as reported under the Montreal Protocol were used in conjunction with output from the USEPA's Vintaging Model to project emissions. Activity data and activity growth projections were obtained from a variety of sources, including international industry trade organizations and databases, U.S. government agencies, and international organizations. For all industries, country-specific estimates of activity (or a factor related to activity) were available. Information on emissions rates was generally less precise but was often available on a regional, if not country-specific, basis.

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[4] Tier 1 refers to the emissions factor estimation methodology in the IPCC guidelines with the highest level of implied accuracy in emissions estimation in a hierarchy of methodology tiers.

For industrial sources of fluorinated gases, this report presents international baselines and MACs for five industrial sources of HFCs, PFCs, and SF_6, including the production of aluminum, magnesium, semiconductors, and HCFC-22, and the use of electrical equipment in electric power systems. For all five of these sources, two sets of baselines and MACs are presented: the technology-adoption baseline, based on the assumption that the industries will achieve their announced global emissions reduction goals for the year, and the no-action baseline, based on the assumption that the industries' emissions rates will remain constant. Detailed discussions of the methodology used to develop the baselines for each source can be found in USEPA (2006).

In addition to the industrial sectors, this report also includes estimates of fluorinated gases that are used as substitutes for ODSs. The USEPA's Vintaging Model and industry data were used to simulate the aggregate impacts of the ODS phaseout on the use and emissions of various fluorocarbons and their substitutes in the United States. Emissions estimates for non-U.S. countries incorporate estimates of the consumption of ODSs by country, as provided by the United Nations Environment Programme (UNEP) (1999). The estimates for the European Union (EU) were provided in aggregate, and each country's gross domestic product (GDP) was used as a proxy to divide the consumption of the individual member nation by the EU total. Estimates of country-specific ODS consumption, as reported under the Montreal Protocol, were then used in conjunction with Vintaging Model output for each ODS-consuming sector. In the absence of country-level data, preliminary estimates of emissions were calculated by assuming that the transition from ODSs to HFCs and other substitutes follows the same general substitution patterns internationally as observed in the United States. From this preliminary assumption, emissions estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences in economic growth, rates of ODS phaseout, and the distribution of ODS use across end-uses in each region or country, as explained in Section IV Industrial Processes in this report.

I.3.2 Mitigation Option Analysis Methodology

Although non-CO_2 emissions from each sector are estimated according to the available data and issues important to that sector, the mitigation option analysis throughout this report was conducted using a common methodology. This section outlines the basic methodology. The sector-specific chapters describe the mitigation estimation methods in greater detail, including any necessary deviations from the basic methodology. Mitigation options represented in the MACs of this report are applied to the baselines described in Section I.3.1.

The abatement analysis for all non-CO_2 gases for agriculture, coal mines, natural gas systems, oil systems, landfills, wastewater treatment, and nitric and adipic acid production are based on and improve upon DeAngelo et al. (in press), Delhotal et al. (in press), and Ottinger et al. (in press); two previous USEPA studies for the United States (USEPA, 2001, 1999); and a study conducted by the European Commission (EC) (2001) that evaluated technologies and costs of CH_4 abatement for EU members from 1990 to 2010. These studies provided estimates of potential CH_4 and N_2O emissions reductions from major emitting sectors and quantified costs and benefits of these reductions.

The EC study evaluates the abatement potential and cost options at representative facilities or point sources of emissions, such as waste digesters, and then extrapolates the results to a country and to the EU level. Given the more detailed data available for U.S. estimates, the USEPA's U.S. analysis also uses representative facility estimates but then applies the estimates to a highly disaggregated and detailed set of emissions sources for all the major sectors and subsectors. For example, the USEPA analysis of the natural gas sector is based on more than 100 emissions sources in that industry, including gas well equipment, pipeline compressors and equipment, and system upsets. Thus, the EC analysis provides more of a sector-average cost for individual abatement options at the country or EU level, while the USEPA analysis provides more detail at the sector and subsector levels.

For this report, average U.S. abatement costs and benefits are estimated for each abatement option to build a set of regional options and estimates comparable to that for the EU. Together, this new combined set of abatement options is applied to all defined regions in the study, both the United States and the EU, as well as to regions where data and detailed analyses are unavailable. The advantage of using the "average" approach over the more detailed analyses for the United States and the EU is that the approach incorporates the latest emissions estimated and compiled in USEPA (2006) and provides for a consistent methodology throughout the analysis for all regions. It should be noted that mitigation estimates from this "average" approach are more conservative than those reported in the USEPA and EC reports.

For the high-GWP abatement analysis, it is assumed that some mitigation technologies are adopted to meet industry reduction targets. Therefore, some mitigation options are accounted for in the baseline emissions. If an option is assumed to be adopted in the baseline, it is not included when generating the MAC. In addition, expert judgment determines market penetration rates of mitigation technologies competing for the same set of fluorinated gas emissions.

The agricultural sector's emissions abatement analysis improves upon a previous study supported by the USEPA (DeAngelo et al., in press) that generated MACs by major world region for cropland N_2O, livestock enteric CH_4, manure CH_4, and rice CH_4 for the year 2010. The most significant change in this report is the use of biophysical, process-based models (i.e., DAYCENT and DNDC) to better capture the net greenhouse gas and yield effects and to capture the spatial and temporal variability of those effects for the cropland and rice emissions baseline and mitigation scenarios. Use of these process-based models is intended to show broad spatial and temporal baseline trends and broad changes when mitigation scenarios are introduced, rather than to show definitive absolute emissions numbers for specific locations. Additional mitigation options are now assessed (e.g., slow-release fertilizers, nitrogen (N)-inhibitors, and no-till), and more detailed, less aggregated results are provided for individual crop types under both irrigated and rainfed conditions. Improved agriculture MACs are generated for 2000, 2010, and 2020.

I.3.2.1 Technical Characteristics of Abatement Options

The non-CO_2 abatement options evaluated in this report are compiled from the studies mentioned above, as well as from the literature relevant for each sector. For each region, either the entire set of sector-specific options or the subset of options determined to be applicable is applied. Options are omitted from individual regions on a case-by-case basis, using either expert knowledge of the region or technical and physical factors (e.g., appropriate climate conditions). In addition, the rate or extent of penetration of an option into the market within different regions may vary based on these conditions. The selective omission of options represents a static view of the region's socioeconomic conditions. Ideally, more detailed information on country-specific conditions, technologies, and experiences will be available in the future, which will enable more rigorous analyses of abatement option availability over time in each region. The average technical lifetime of an option (in years) is also determined using expert knowledge of the technology or recent literature, as referenced in each section of this report.

Table 3-1 summarizes how the abatement potential is calculated for each of the available abatement options. The total abatement potential of an option for each region is equal to an option's technical applicability multiplied by its implied adoption rate multiplied by its reduction efficiency. Total baseline emissions are summed from each of the emissions sources within each sector and each region. Each

Table 3-1: Abatement Potential Calculation for Mitigation Options

Technical applicability (%)	X	Implied adoption rate (%)	X	Reduction efficiency (%)	=	Abatement potential (%)
Percentage of total baseline emissions from a particular emissions source to which a given option can be potentially applied.		Percentage of technically applicable baseline emissions to which a given option is applied; avoids double counting among overlapping options and fixes penetration rate of options relative to each other.[a]		Percentage of technically achievable emissions abatement for an option after it is applied to a given emissions stream.		Percentage of baseline emissions that can be reduced at the national or regional level by a given option. Product of technical applicability, implied adoption rate, and reduction efficiency of the option.

[a] Implied adoption rate for nonoverlapping options (i.e., applicable to different emissions streams) is assumed to add to 100 percent of technically applicable baseline emissions.

mitigation option reduces baseline emissions by the reduction efficiency percentage of the relevant portion of the total baseline emissions, as defined by the technical applicability and implied adoption rate.

Technical applicability accounts for the portion of emissions from a facility or region that a mitigation option could feasibly reduce based on its application. For example, if an option applies only to the underground portion of emissions from coal mining, then the technical applicability for the option would be the percentage of emissions from underground mining relative to total emissions from coal mining.

The implied adoption rate of an option is a mathematical adjustment for other qualitative factors that may influence the effectiveness of a mitigation option. For the energy, waste, and agriculture sectors, it was outside the scope of this analysis to account for adoption feasibility, such as social acceptance and alternative permutations in the sequencing of adoption. The implied adoption rate of each of the n overlapping options is equal to $1/n$, which avoids cumulative reductions of greater than 100 percent across options. Given the lack of region-specific data for determining the relative level of diffusion among options that could compete for the same emissions stream, we applied this conservative adjustment. When nonoverlapping options are applied, they affect 100 percent of baseline emissions from the relevant source. Examples of two nonoverlapping options in the natural gas system are inspection and maintenance of compressors and replacement of distribution pipes. These options are applied independently to different parts of the sector and do not compete for the same emissions stream. An example of overlapping options is the sequencing of cropland mitigation options, where the adoption of one option (e.g., conversion to no tillage) affects the effectiveness of subsequent options (e.g., reduced fertilizer applications). While this describes the basic application of the implied adoption rate in the energy, waste, and agriculture sectors, this factor is informed by expert insight into the potential market penetration over time in the industrial processes sector.

The reduction efficiency of a mitigation option is the percentage reduction achieved with adoption. The reduction efficiency is applied to the relevant baseline emissions as defined by technical applicability and adoption effectiveness. Most abatement options, when adopted, reduce an emissions stream less than 100 percent.

Once the total abatement potential of an option is calculated as described above, the abatement potential is multiplied by the baseline emissions for each sector and region to calculate the absolute amount of emissions reduced by employing the option. The absolute amount of baseline emissions reduced by an option in a given year is expressed in million metric tons of CO_2 equivalent ($MtCO_2eq$).[5]

If the options are assumed to be technically feasible in a given region, the options are assumed to be implemented immediately, Furthermore, once options are adopted, they are assumed to remain in place for the duration of the analysis, and an option's parameters are not changed over its lifetime.

I.3.2.2 Economic Characteristics of Abatement Options

Each abatement option is characterized in terms of its costs and benefits per an abated unit of gas (tCO_2eq or tons of emitted gas [e.g., tCH_4]).

For each mitigation option, the carbon price (*P*) at which that option becomes economically viable can be calculated (i.e., where the present value of the benefits of the option equals the present value of the costs of implementing the option). A present value analysis of each option is used to determine breakeven abatement costs in a given region. Breakeven calculations are independent of the year the mitigation option is implemented but are contingent on the life expectancy of the option. However, in the energy and waste sectors, sensitivities are conducted to examine the implication of time. The net present value calculation solves for breakeven price *P*, by equating the present value of the benefits with the present value of the costs of the mitigation option. More specifically,

$$\underbrace{\sum_{t=1}^{T}\left[\frac{(1-TR)(P\cdot ER+R)+TB}{(1+DR)^{t}}\right]}_{\textit{Net Present Value Benefits}} = \underbrace{CC+\sum_{t=1}^{T}\left[\frac{(1-TR)RC}{(1+DR)^{t}}\right]}_{\textit{Net Present Value Costs}} \qquad (3.1)$$

where

P = the breakeven price of the option ($/$tCO_2eq$);

ER = the emissions reduction achieved by the technology ($MtCO_2eq$);

R = the revenue generated from energy production (scaled based on regional energy prices) or sales of by-products of abatement (e.g., compost) or change in agricultural commodity prices ($);

T = the option lifetime (years);

DR = the selected discount rate (%);

CC = the one-time capital cost of the option ($);

RC = the recurring (O&M) cost of the option (portions of which may be scaled based on regional labor costs) ($/year);

TR = the tax rate (%); and

TB = the tax break equal to the capital cost divided by the option lifetime, multiplied by the tax rate ($).

Assuming that the emissions reduction *ER*, the recurring costs *RC*, and the revenue generated *R* do not change on an annual basis, then we can rearrange this equation to solve for the breakeven price *P* of the option for a given year:

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[5] One $MtCO_2eq$ equals 1 teragram of CO_2 equivalent ($TgCO_2eq$): 1 metric ton = 1,000 kg = 1.102 short tons = 2,205 lbs.

$$P = \frac{CC}{(1-TR)ER\sum_{t=1}^{T}\frac{1}{(1+DR)^t}} + \frac{RC}{ER} - \frac{R}{ER} - \frac{CC}{ER \cdot T} \cdot \frac{TR}{(1-TR)} \quad (3.2)$$

Costs include capital or one-time costs and operation and maintenance (O&M) or recurring costs. Additionally, some one-time costs (where data are available) are subdivided into labor and equipment components. Recurring costs may also be subdivided into labor costs, fertilizer costs, and other cost components. Benefits or revenues from employing an abatement option can include (1) the intrinsic value of the recovered gas (e.g., the value of CH_4 either as natural gas or as electricity/heat, the value of HFC-134a as a refrigerant), (2) nongreenhouse gas benefits of abatement options (e.g., compost or digestate for waste diversion options, increases in crop yields), and (3) the value of abating the gas given a greenhouse gas price in terms of dollars per tCO_2eq ($\$/tCO_2eq$) or dollars per metric ton of gas (e.g., $\$/tCH_4$, \$/tHFC-134a). In most cases, there are two price signals for the abatement of CH_4: one price based on CH_4's value as energy (because natural gas is 95 percent CH_4) and one price based on CH_4's value as a greenhouse gas. All cost and benefit values are expressed in constant year 2000 U.S. dollars.

Costs and benefits of abatement options are adjusted based on energy and labor costs in corresponding regions. If not otherwise available, the equipment component of fixed costs is not adjusted and stays the same for all regions. Most of the agricultural sector options, such as changes in management practice, do not have applicable capital costs, with the exception of anaerobic digesters for manure management. In general, labor costs comprise the majority of O&M costs. Given this fact, we have used labor costs as a proxy to adjust O&M costs across regions, as well as the labor component of the one-time cost. Specifically, O&M costs for each region are estimated based on a ratio between the average regional labor cost in manufacturing in that region and in the United States for U.S.-based options or the EU for EU-based options. Regional labor costs in manufacturing are taken from World Bank data (2000). For the agricultural sector, labor costs are calculated labor shares of agricultural production costs from the Global Trade Analysis Project (GTAP) and agricultural wage data from the International Food Policy Research Institute (IFPRI).

Breakeven price calculations for this analysis do not include transaction costs, because there are no explicit assumptions in this report about policies that would encourage and facilitate adoption of the mitigation options. Refer to Section I.5 for a more complete discussion of the limitations of this analysis.

In regions where there is a lack of detailed revenue data, revenues are scaled based on the ratio between average prices of natural gas (when CH_4 is abated and sold as natural gas) or of electricity (when CH_4 is used to generate electricity or heat) in a given region and in the United States or EU. Similarly, revenues from non-CH_4 benefits of abatement options are scaled based on the ratio between the GDPs per capita in a given region and in the United States or EU. In the agricultural sector, changes in revenue occur as a change in either crop yield or livestock productivity. Data on changes in crop yield or livestock productivity are combined with data on regional producer prices for the relevant agricultural commodity to calculate revenue changes.

This analysis is conducted using a 10 percent discount rate and a 40 percent tax rate. In some sectors, sensitivities on alternative discount and tax rates illustrate different social and industry perspectives. Sensitivities with a social perspective use lower discount rates and a zero percent tax rate, while sensitivities with an industry perspective assume higher discount rates and greater than zero tax rates. For quick reference, Table 3-2 lists the basic financial assumptions used throughout this report. In addition, because of the high sensitivity to energy prices, the analysis tests the MAC sensitivity to

Table 3-2: Financial Assumptions in Breakeven Price Calculations for Abatement Options

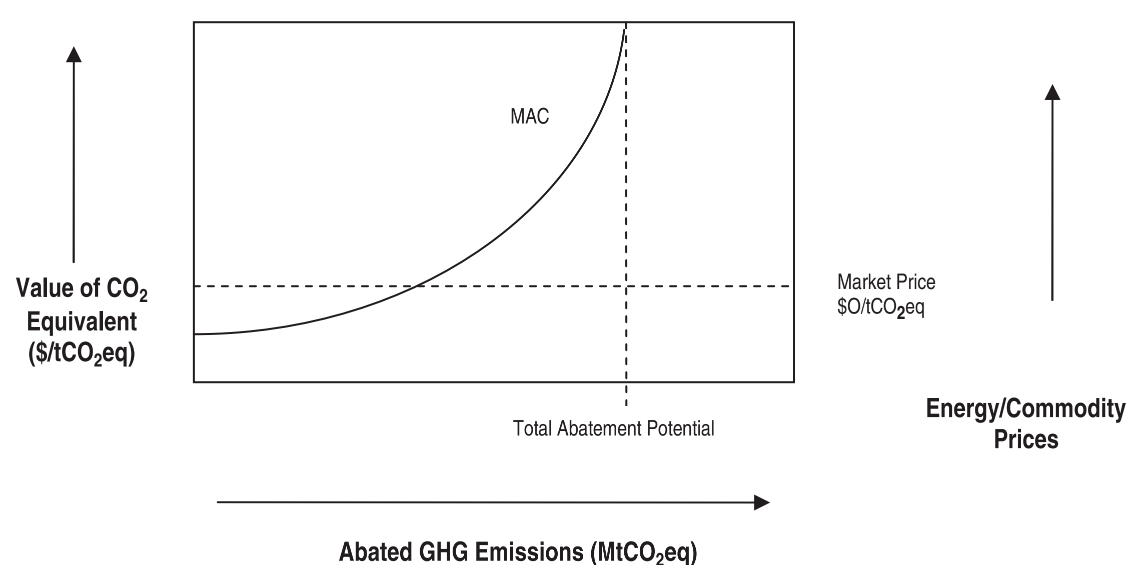
Variable	Assumption
Discount rate	10%
Tax rate	40%
Year dollars	2000$

changes in base energy price (from –50 percent to 200 percent) for both electricity and natural gas, where this sensitivity test is relevant to the sector. The energy price assumptions are also included in the TechTables.xls file in the appendices to the *International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21* on the USEPA's Web site <http://www.epa.gov/nonco2/econ-inv/international.html> (USEPA, 2005).

I.3.3 Marginal Abatement Curves

MACs are used to show the amount of emissions reduction potential at varying price levels. In theory, a MAC illustrates the cost of abating each additional ton of emissions. Figure 3-1 shows an illustrative MAC. The x-axis shows the amount of emissions abatement in $MtCO_2eq$, and the y-axis shows the breakeven price in $\$/tCO_2eq$ required to achieve the level of abatement. Therefore, moving along the curve, the lowest cost abatement options are adopted first. The curve becomes vertical at the point of maximum total abatement potential, which is the sum of abatement across all options in a sector or region.

Figure 3-1: Illustrative Non-CO_2 Marginal Abatement Curve



In Figure 3-1, the commodity/energy market price is aligned to $\$0/tCO_2eq$ since this price represents the point at which no additional price signals exist from GHG credits 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 $\$/tCO_2eq$, these values are added to the commodity/energy market prices and allow for additional emissions reductions to clear the market. The points on the MAC that appear at or below the zero cost line ($0/tCO$_2$eq) illustrate this dual price-signal market. These "below-the-line" amounts represent mitigation options that are already cost-effective given the costs and benefits considered (and are sometimes referred to as "no-regret" options) yet have not been implemented because of the existence of nonmonetary barriers.

The MACs in this report are constructed from bottom-up average breakeven price calculations. The average breakeven price is calculated for the estimated abatement potential for each mitigation option (see Section I.3.2.2). The options are then ordered in ascending order of breakeven price (cost) and plotted against abatement potential. The resulting MAC is a stepwise function, rather than a smooth curve, as seen in the illustrative MAC (Figure 3-1), because each point on the curve represents the breakeven price point for a discrete mitigation option (or defined bundle of mitigation strategies). Conceptually, marginal costs are the incremental costs of an additional unit of abatement. However, the abatement cost curves developed here reflect the incremental costs of adopting the next cost-effective mitigation option. We estimated the costs and benefits associated with all or nothing adoption of each well-defined mitigation practice. We did not estimate the marginal costs of incremental changes within each practice (e.g., the net cost associated with an incremental change in paddy rice irrigation). Instead, the MACs developed in this report reflect the average net cost of each option for the achieved reduction (*ER* in Equations 3.1 and 3.2). When data were not available to clearly identify marginal abatement roles for mitigation technologies because of either (a) the potential for abatement of the same share of baseline emissions, or (b) sensitivities to the order of adoption, we employed the implied adoption rate (Table 3-1).

In the energy and waste sectors, representative facilities facing varied mitigation costs employ mitigation technologies based on the lowest average breakeven option price. In calculating the abatement potential, options are evaluated according to whether they are complements or substitutes. If a group of options are complements (or independent of one another), the implied adoption rates are all equal to one. If options are substitutes for each other, the lowest price option is selected for each representative facility; in this way, the implied adoption rate for each technology is estimated.

In the industrial processes sector, mitigation options are applied to one representative facility, in order of lowest average breakeven price to highest average breakeven price. Each option is applied to a portion of the baseline emissions based on the implied adoption rate (the *1/n* factor, as described in Section I.3.2.1), which, in the industrial sector, is informed by expert insight into potential adoption rates of various mitigation technologies.

In the agriculture sector, mitigation options are applied to representative farms of each region based on the lowest average breakeven price. The implied adoption rate is based purely on the number of available migration options (*1/n*), where each option is applied to an equal portion of the cropland base or livestock population and, thus regional baseline emissions, for each region over time. Given the existence of nonprice and implementation factors that influence market share and the lack of accurate and detailed information regarding these qualitative characteristics, we assume an even distribution of options across the baseline for the agriculture sector. This approach allows options to share a portion of market penetration, regardless of their cost-effectiveness, rather than allowing only the least-cost option to completely dominate the market. Our methodology is more conservative than if we had assumed only price factors exist, thus allowing the least-cost option to penetrate the sector by 100 percent.

The MACs represent the average economic potential of mitigation technologies in that sector, because it is assumed that if a mitigation technology is technically feasible in a given region, then it is implemented according to the relevant economic conditions. Therefore, the MACs do not represent the market potential or the social acceptance of a technology. The models used in the analysis are static (i.e., they do not represent adoption of mitigation technologies over time). This analysis assumes partial equilibrium conditions that do not represent economic feedbacks from the input or output markets. This analysis makes no assumptions regarding a policy environment that might encourage the implementation of mitigation options. Additional discussion of some key limitations of the methodology is provided in Section I.5.

The end result of this analysis is a tabular data set for the MACs by sector, gas, and region, which are presented in Appendix A.[6] Sectoral MACs are aggregated by gas and by region to create global MACs, which are presented in Section I.4.

I.3.4 Methodological Enhancements from Energy Modeling Forum Study

This report builds on a study previously conducted by the USEPA for Stanford's EMF-21. The EMF-21 focused specifically on multigas strategies and the incorporation of non-CO_2 greenhouse gas data sets into economic models. Although this analysis is built largely on the previous USEPA analysis for the EMF-21, we have made several key enhancements.

In the energy and waste sectors, new sensitivity cases illustrate the effect of technical change over time. Introducing technical change by incorporating the rate of change of technical applicability can potentially shift the MAC down and to the right on the graph, as abatement potential increases and net costs decrease at a given carbon price.

For industrial sources of fluorinated gases, the emissions baselines have been updated since the EMF-21 analysis. The analysis included one set of baseline emissions for industrial sources, while this report presents two sets of baselines for aluminum, magnesium, and semiconductor manufacturing. One baseline set assumes industry agreements establishing emissions reduction targets will be upheld, while the other baseline set assumes that the industry agreement has no effect on the baseline emissions. In addition, the MACs for aluminum manufacturing and electrical power systems have been enhanced with additional data.

The emissions baselines in the ODS substitute sector have also been enhanced. The EMF-21 ODS substitute baseline was an average between baselines derived by the USEPA and ECOFYS. For this report, the USEPA has generated an updated baseline. Assumptions in the ODS substitute sector, such as the market penetration potential of various mitigation options, have been updated from the EMF-21 analysis based on the input of industry experts.

In the agricultural sector, the previous methodology is improved on for this analysis by using the biophysical, process-based models DAYCENT and DNDC. These models capture the net greenhouse gas effects of the cropland and rice baseline emissions and mitigation options, and they reflect the heterogeneous emissions and yield effects of adopting mitigation practices. In addition, new agricultural mitigation options are now assessed, and more detailed results are provided for individual crop types. Finally, the agricultural commodity market effects are explored with a global agricultural trade model (IMPACT of the IFPRI).

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[6] Tables are presented that provide the percentage abatement for a series of breakeven prices. The MAC data are presented as tables so that exact values can be determined for use in modeling activities.

I.4 Aggregate Results

Worldwide, 2005 total non-CO_2 anthropogenic greenhouse gas baseline emissions are estimated to be 10,278 $MtCO_2eq$ and are projected to increase by 27 percent to 13,013 $MtCO_2eq$ by 2020. These gases are emitted from four major emitting sectors: the energy, waste management, industrial processes, and agricultural industries. China, India, the United States, Brazil, and the European Union are the world's five largest emitters and account for approximately 76 percent of total non-CO_2 emissions.

This section presents the forecasted baseline emissions and provides a global overview of the results from the MAC analysis by sector and for the five largest emitting regions. The data represented in this chapter are aggregated and provide a summary of all sources and non-CO_2 greenhouse gases. The individual chapters are organized by source and present the full details of these analyses. For a complete data set of mitigation potential by sector, gas, and region, refer to Appendix A.

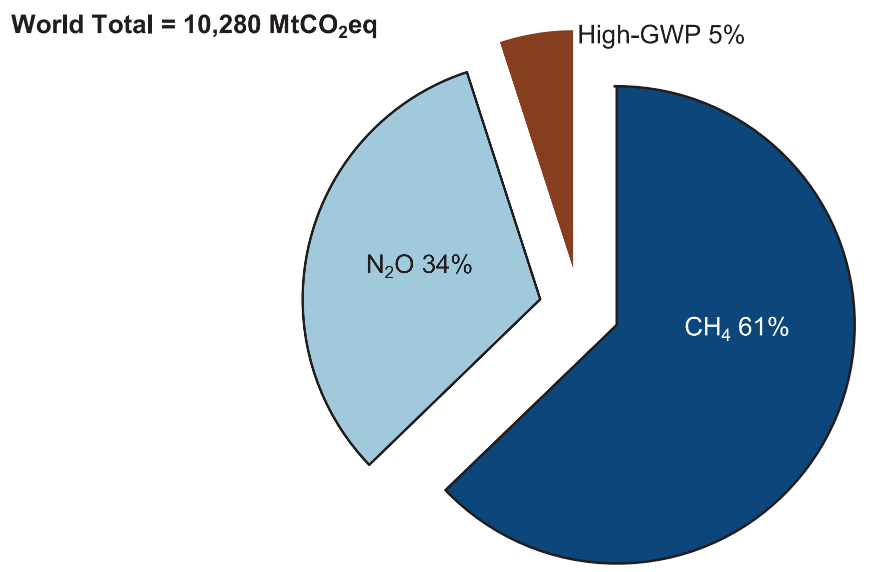
For the purposes of aggregation, the results from the "technology adoption" baseline were used from industrial process subsectors with dual baselines. In the agriculture sector, the MAC data from the "constant area" scenarios were used, while the baselines from *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990−2020* (USEPA, 2006) were used for consistency across the sectors in aggregation.

I.4.1 Baselines

I.4.1.1 By Non-CO_2 Greenhouse Gas

Figure 4-1 provides information on the relative share of each greenhouse gas that comprises the global non-CO_2 greenhouse gas baseline emissions total. CH_4 represents the largest share of emissions worldwide, accounting for approximately 61 percent of the total non-CO_2 emissions in 2005, while N_2O and high-GWP gases accounted for 34 percent and 5 percent, respectively.

Figure 4-1: Percentage Share of Global Non-CO_2 Emissions[a] by Type of Gas in 2005

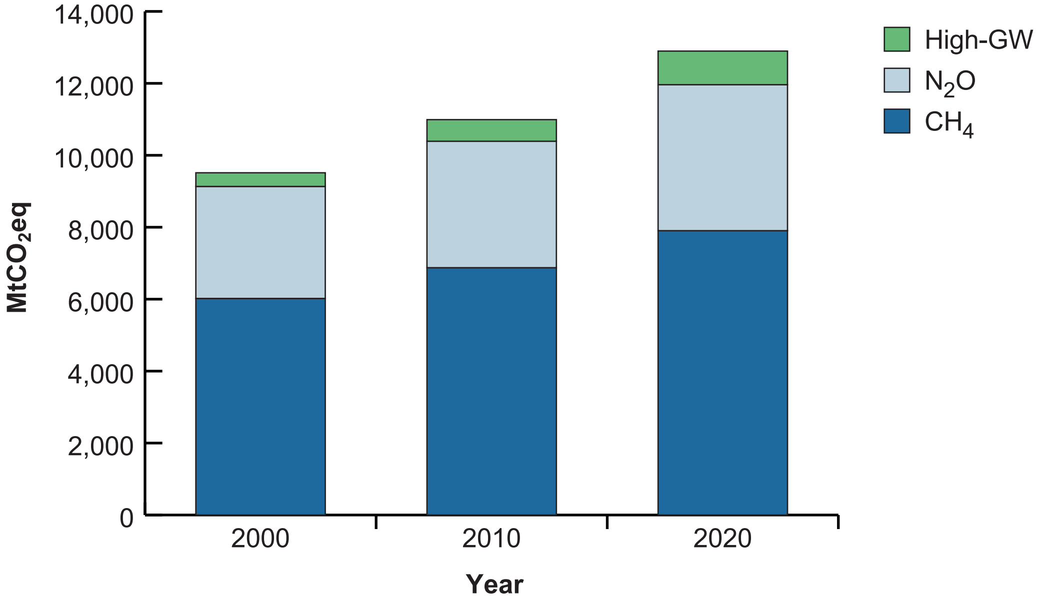


Source: USEPA, 2006.

[a] CO_2 equivalency based on 100-year GWP.

Figure 4-2 presents the projected baseline emissions by greenhouse gas for 2000, 2010, and 2020. The distribution of non-CO_2 greenhouse gases is forecasted to remain relatively unchanged through 2020. The most significant change is represented by a projected increase in the relative share of high-GWP gases with respect to CH_4 and N_2O, growing from 5 percent to more than 7 percent of global non-CO_2 emissions between 2005 and 2020.

Figure 4-2: Non-CO_2 Global Emissions Forecast to 2020 by Greenhouse Gas



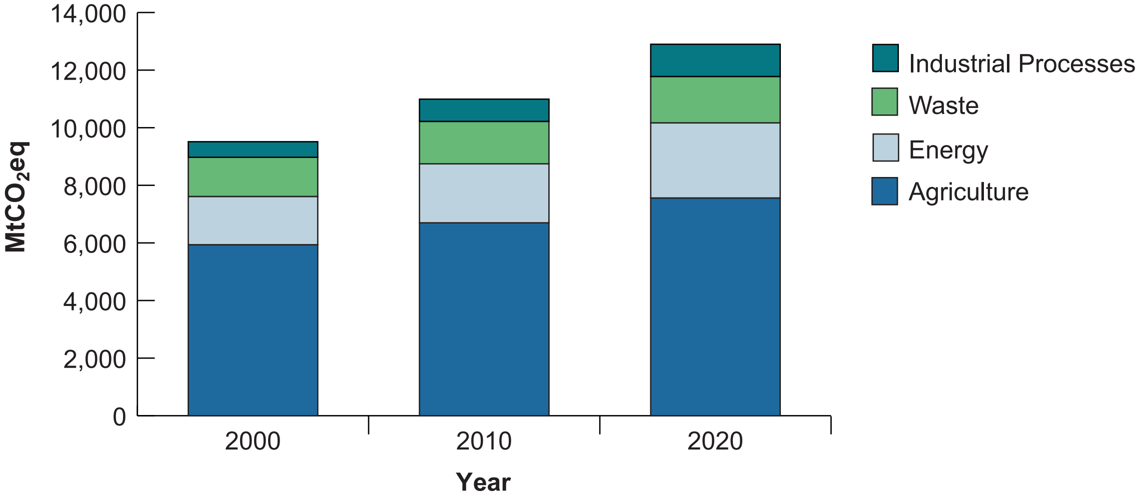
Source: USEPA, 2006.

I.4.1.2 By Major Emitting Sectors and Countries

The sources of non-CO_2 emissions are categorized into four major emissions sectors: energy, waste, industrial processes, and agriculture. Figures 4-3 and 4-4 provide the projected global emissions baseline for 2000, 2010, and 2020, by major emissions sector and by major emitting region, respectively. The agriculture sector includes soil and manure management, rice cultivation, enteric fermentation, and other nonindustrial sources such as biomass burning. Emissions sources categorized in the energy sector include coal mining activities, natural gas transmission and distribution, and gas and oil production. The waste sector includes municipal solid waste management, as well as human sewage and other types of wastewater treatment. The industrial processes sector includes a wide range of activities, such as semiconductor manufacturing, primary aluminum production, and electricity transmission and distribution.

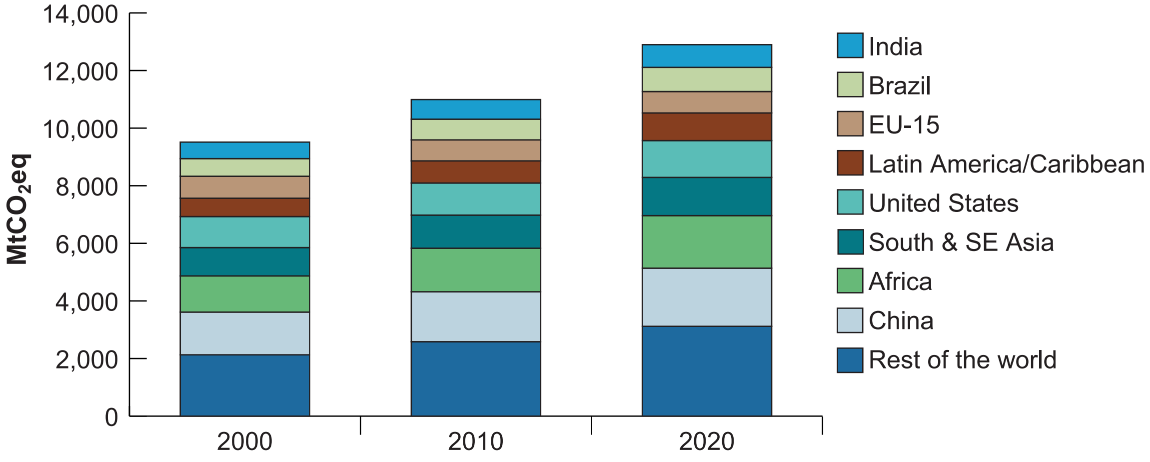
Agriculture is the primary source of non-CO_2 emissions, accounting for 60 percent of the total 2010 baseline. Energy is the second largest emissions producer, representing 20 percent of the total baseline. The waste sector represents 14 percent of the total baseline, and the industrial processes sector represents 7 percent.

Figure 4-3: Global Emissions by Major Sector for All Non-CO_2 Greenhouse Gases



Source: USEPA, 2006. Note that this mitigation analysis uses baseline emissions projections for croplands and rice (within agriculture) that differ from USEPA (2006)

Figure 4-4: Projected World Emissions Baselines for Non-CO_2 Greenhouse Gases, Including the Top Emitting Regions



Source: USEPA, 2006.
EU-15 = European Union.

Figure 4-4 shows the projected emissions baselines for the world, as well as the largest emitting countries. The largest non-CO_2 emitting countries are typically characterized as mature, highly industrialized countries or countries with significant agricultural sectors. In 2005, the top five emitting countries—China, the United States, EU-15, Brazil, and India—account for 44 percent of the world's total non-CO_2 emissions, and their relative contribution to the world baseline is projected to remain the same during the next 15 years.

I.4.2 Global MACs

The MAC analysis methodology outlined in Section I.3 of this report develops bottom-up projections of potential reductions in non-CO_2 emissions in terms of the breakeven price ($/t$CO_2$eq). The emissions reduction potential is constrained by technology limitations, as well as by regional and geographical applicability. In this report, MACs are developed for each major source by sector and country. The resulting series of MACs are aggregated up across sectors, gases, and regions. The MACs indicate the potential reduction in non-CO_2 gas emissions for a given breakeven price. Figure 4-5 presents the results from the MAC analysis for 2020 by major economic sector. Figure 4-6 presents aggregate MACs by greenhouse gas type for 2020. Figure 4-7 presents the 2020 MACs for the world's largest non-CO_2 greenhouse gas emitting regions.

Figure 4-5: Global 2020 MACs for Non-CO_2 Greenhouse Gases by Major Sector

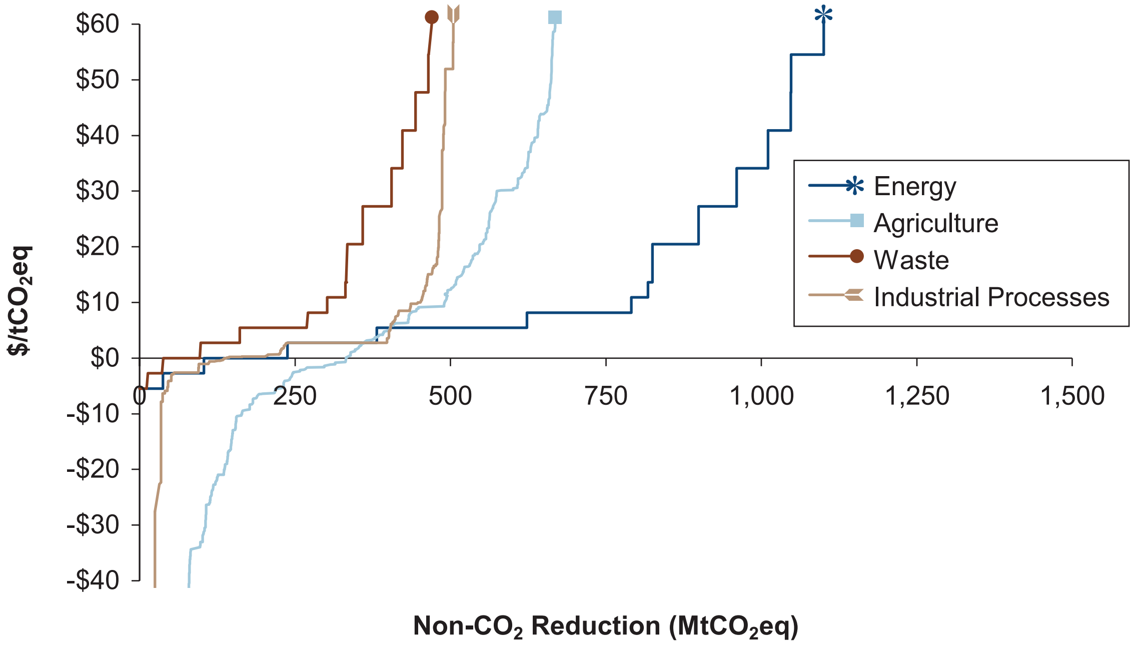


Figure 4-6: Global 2020 MACs by Non-CO_2 Greenhouse Gas Type

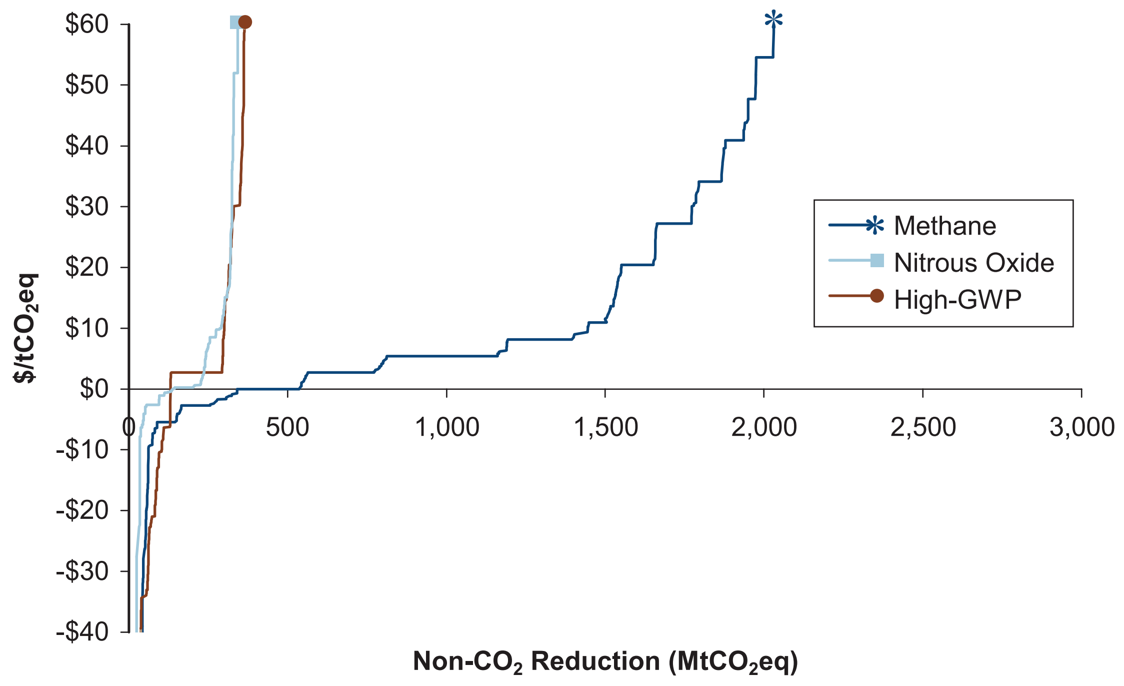
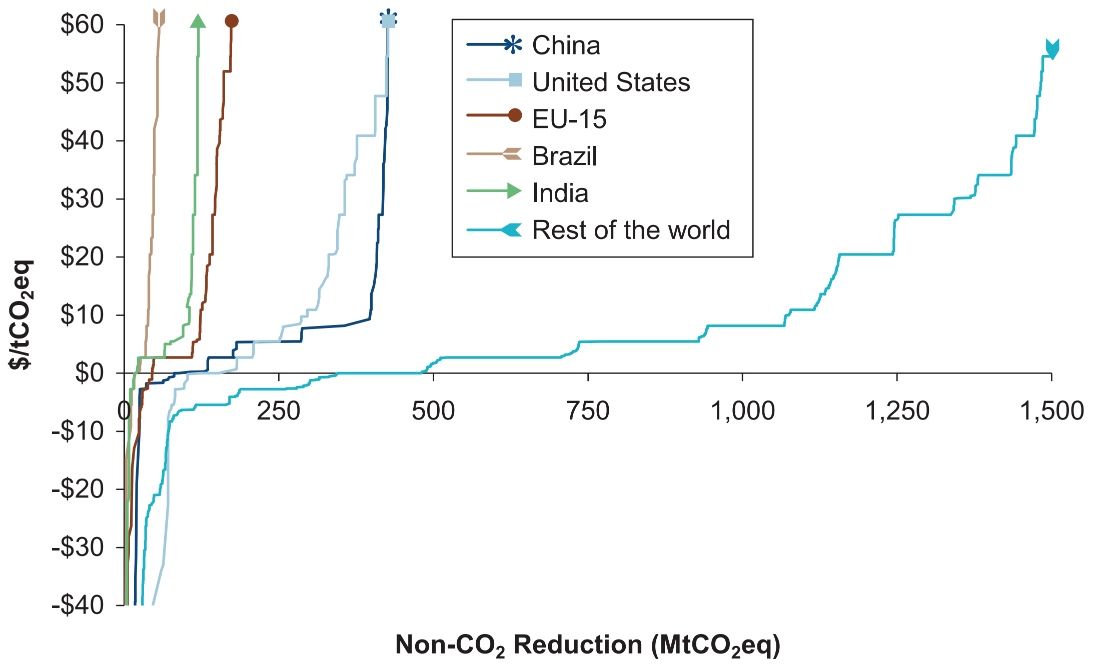


Figure 4-7: Global 2020 MACs for Non-CO_2 Greenhouse Gases by Major Emitting Regions



In the aggregate MACs by gas for the agriculture sector, the net greenhouse gas effects are represented in the aggregate MACs by gas for both CH_4 and N_2O. While mitigating in the livestock and rice sectors affects both N_2O and CH_4 emissions, the dominant effect is on CH_4. Thus, for this analysis, the net effect on CO_2 equivalents is represented in the CH_4 global aggregate MAC. Likewise, cropland soil mitigation affects both N_2O and CH_4 emissions, but the net greenhouse gas effect is represented in the global aggregate N_2O MAC, because N_2O is the dominant mitigation effect.

The 2020 global MACs by major sector (Figure 4-5) illustrate the breakeven mitigation potential for each of the economic sectors. The greatest potential for cost-effective mitigation (i.e. employing mitigation options that are economically feasible in the absence of a carbon price signal), is in the energy and agriculture sectors. In the energy sector, it is estimated that a reduction of approximately 250 $MtCO_2eq$ is possible at a zero-dollar breakeven price. The MACs also show that at higher emissions prices, such as \$20 or \$30 per tCO_2eq, the energy and agriculture sectors show the greatest potential for emissions reduction. The industrial processes and waste sectors also show increased mitigation potential at higher prices, but to a lesser degree. The more vertical slope of the MAC for the industrial sector shows that an increase in the emissions price may not result in any further mitigation beyond a certain point.

Across all non-CO_2 greenhouse gases, methane has the greatest mitigation potential, as shown in the 2020 MACs by greenhouse gas type (Figure 4-6). In the absence of a carbon price signal, methane emissions could be reduced by nearly 500 $MtCO_2eq$. Nitrous oxide and high-GWP gases also exhibit significant cost-effective mitigation potential, although to a lesser extent than that of methane. As breakeven prices rise, methane potential continues to grow, approaching a reduction potential of 1,800 $MtCO_2eq$ at a breakeven price of \$30/tCO_2eq.

The MACs by major emitting regions (Figure 4-7) exhibit China's large mitigation potential in 2020 at higher breakeven prices. At \$30/tCO_2eq, China could potentially reduce non-CO_2 emissions by up to nearly 450 $MtCO_2eq$, approximately three times the mitigation potential for the European Union. Both China and the United States exhibit the largest potential for mitigation at higher breakeven prices. India and Brazil also fall in the largest five emitting regions for non-CO_2 greenhouse gases.

The aggregate MACs by economic sector, greenhouse gas type, and region highlight the potential for including non-CO_2 greenhouse gases in multigas strategy analysis. The MACs illustrate that a significant portion of this mitigation potential can be realized at a zero cost and at low carbon prices. This report examines the mitigation potential in each sector in greater detail. Sensitivity analysis on factors such as discount rates, the rate of technical change, and the ratio of domestic to foreign inputs can be found in the sector-specific chapters of this report.

I.5 Limitations and Applications of MACs

While this global mitigation report has important implications for researchers and modelers, it is important to understand not only the limitations of this analysis, but also the potential for misapplication of the data in other analyses.

I.5.1 Limitations and Uncertainties

The results of this analysis cover the major emitting regions, emissions sources, and abatement options; we discuss a few limitations of this analysis briefly below.

I.5.1.1 Exclusion of Transaction Costs

Future work in the area of mitigation costs will focus on including transactions costs. Current work still in draft by Lawrence Berkeley National Laboratory (LBNL), *Transaction Costs of GHG Emissions Reduction Projects: Preliminary Results* (2003), estimates that transactions costs will add approximately $1 per ton of carbon to a project. However, the LBNL study is not comprehensive, because it considered only two non-CO_2 projects. Transaction costs are likely to vary significantly, contingent on the size of the project, the applicable mitigation technology, and other factors. Given the lack of comprehensive data, this analysis does not include transaction costs.

I.5.1.2 Static Approach to Abatement Assessment

This analysis does not account for the technological change in such option characteristics as availability, reduction efficiency, applicability, and costs. For example, the same sets of options are applied in 2010 and 2020 and an option's parameters are not changed over its lifetime. This current limitation likely underestimates abatement potential because technologies generally improve over time and costs fall. The introduction of a dynamic approach to assessing regional abatement potentials requires additional assumptions about rates of technological progress and better baseline projections, that, once incorporated into this analysis, will yield a better representation of how MACs change over space and time.

I.5.1.3 Limited Use of Regional Data

The analytic framework used in this study is flexible enough to incorporate regional differences in all the characteristics of abatement options. However, a lack of country-specific data led to a reliance on expert judgment, as noted in the sector-specific chapters. This expert judgment was obtained from source-level technical experts in government and industry with knowledge of project-level technologies, costs, and specific regional conditions. Applicability of abatement options, for example, is reliant on expert judgment, because the makeup of the current infrastructure in a given country in a given sector is uncertain. A much greater use of data originating from local experts and organizations is recommended for the follow-up research of CH_4 abatement in countries outside the United States and EU. Incorporating more regional data could also enhance the range of emissions sources and mitigation options addressed in this analysis.

I.5.1.4 Exclusion of Indirect Emissions Reductions

This analysis does not account for indirect emissions reductions, which can result from either the substitution of electricity from the grid, with electricity produced on-site from recovered CH_4, or from the substitution of natural gas in pipelines with recovered CH_4. Calculation of such indirect reductions requires additional assumptions about the carbon intensity of electricity in different regions. In the U.S. landfill sector, indirect reductions generally augment emissions reductions by about 15 percent. In the agricultural sector, although some mitigation options primarily target a single gas, implementation of the mitigation options will have multiple greenhouse gas effects, most of which are reflected in the agricultural results.

I.5.2 Practical Applications of MACs in Economic Models

MAC data are presented in both percentage reduction and absolute reduction terms relative to the baseline emissions. These data can also be downloaded in spreadsheet format from our Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

The MAC data are an important input into the economic modeling of global climate change. The MACs can be applied in a variety of economic models to represent the potential emissions abatement of non-CO_2 greenhouse gases in each sector at a given carbon price.

While the results presented in this report can inform economic models, caution should be taken not to apply the MAC data directly as offset curves. Offset curves are a supply curve of emissions permits that could potentially be available in the market at a given carbon-price environment. However, a price signal alone is not likely to bring about all of the mitigation opportunities available along the MACs presented in this report. Other nonprice factors, such as social acceptance, tend to inhibit mitigation option installation in many sectors. Because of the lack of quantitative data on nonprice factors determining market penetration, we have represented the implied adoption rate of mitigation technologies in our analysis with a mathematical distribution of technologies across the baseline emissions of a sector. Thus, the MACs in our analyses do not represent a supply curve of emissions permits that would be available for purchase, but rather the technical mitigation potential at a given carbon price.

In addition, caution should be taken when applying MACs for sectors that are dependent on energy supply, because of the potential sensitivity of the MACs for these sectors to carbon prices. For example, a positive carbon-price environment may result in reduction in coal use, which may reduce CH_4 emissions. This potential reduction in emissions would have occurred because of a decrease in use of the facility, rather than the installation of a mitigation option in the facility.

This analysis focuses only on the mitigation of non-CO_2, without considering the impacts of CO_2 mitigation. It should be noted that the mitigation potential of non-CO_2 greenhouse gas emissions generated in the energy sector (e.g., coal mining) is inherently tied to the mitigation potential of CO_2 emissions from the same sector. Any modeling of greenhouse gas mitigation in the energy sector should consider the coeffects of any change in energy consumption in both non-CO_2 and CO_2 mitigation potential.

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Section I: Technical Summary Appendixes

Appendixes for this section are available for download from the USEPA's Web site at http://www.epa.gov/nonco2/econ-inv/international.html.