DOE/EIA-0573(2003)

Emissions of Greenhouse Gases in the United States 2003

December 2004

Energy Information Administration
Office of Integrated Analysis and Forecasting
U.S. Department of Energy
Washington, DC 20585

Contacts

This report, *Emissions of Greenhouse Gases in the United States 2003*, was prepared under the general direction of John Conti, Director of the International Economics and Greenhouse Gases Division, Office of Integrated Analysis and Forecasting, Energy Information Administration. General questions concerning the content of this report may be directed to the National Energy Information Center at 202/586-8800.

Specific technical information concerning the content of the report may be obtained from Perry Lindstrom at 202/586-0934 (e-mail, perry.lindstrom@eia.doe.gov).

Without the assistance of Science Applications International Corporation this report would not have been possible. In particular we would like to thank Nancy Checklick, Christina Davies, Sarah Goldstein, Michael Mondshine, John Sottong, and Robin Taylor.

The authors would also like to express their gratitude to all the people who provided information or comments on this report, and particularly to Mark Schipper of EIA's Office of Energy Markets and End Use, who provided survey data and analysis from the 1998 Manufacturing Energy Consumption Survey.

Specific questions about the report should be referred to the following analysts:

Executive Summary	Paul McArdle	(paul.mcardle@eia.doe.gov,	202/586-4445)
Chapter 1	Paul McArdle	(paul.mcardle@eia.doe.gov,	202/586-4445)
Chapter 2	Perry Lindstrom	(perry.lindstrom@eia.doe.gov,	202/586-0934)
Chapter 3	Perry Lindstrom	(perry.lindstrom@eia.doe.gov,	202/586-0934)
Chapter 4	Stephen Calopedis	(stephen.calopedis@eia.doe.gov,	202/586-1156)
Chapter 5	Stephen Calopedis	(stephen.calopedis@eia.doe.gov,	202/586-1156)
Chapter 6	Paul McArdle	(paul.mcardle@eia.doe.gov,	202/586-4445)

Preface

Title XVI, Section 1605(a) of the Energy Policy Act of 1992 (enacted October 24, 1992) provides:

> *Not later than one year after the date of the enactment of this Act, the Secretary, through the Energy Information Administration, shall develop, based on data available to, and obtained by, the Energy Information Administration, an inventory of the national aggregate emissions of each greenhouse gas for each calendar year of the baseline period of 1987 through 1990. The Administrator of the Energy Information Administration shall annually update and analyze such inventory using available data. This subsection does not provide any new data collection authority.*

The first report in this series, *Emissions of Greenhouse Gases 1985-1990*, was published in September 1993. This report—the twelfth annual report, as required by law—presents the Energy Information Administration's latest estimates of emissions for carbon dioxide, methane, nitrous oxide, and other greenhouse gases. These estimates are based on activity data and applied emissions factors and not on measured or metered emissions monitoring.

For this report, data on coal and natural gas consumption and electricity sales and losses by sector were obtained from the Energy Information Administration's (EIA's) November 2004 *Monthly Energy Review*. Additional detailed information on petroleum consumption was obtained from unpublished material in support of EIA's *Annual Energy Review 2003*. Data on electric power sector emissions were obtained from EIA's *Electric Power Annual*. In keeping with current international practice, this report presents data on greenhouse gas emissions in million metric tons carbon dioxide equivalent. The data can be converted to carbon equivalent units by multiplying times 12/44.

Contents

Appendixes

Special Topics

Tables

Figures

Executive Summary

Overview

U.S. Anthropogenic Emissions of Greenhouse Gases, 1990-2003

	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	6,935.7
Change Compared to 2002 (Million Metric Tons)	44.8
Change from 2002 *(Percent)*	*0.7%*
Change Compared to 1990 (Million Metric Tons)	820.5
Change from 1990 *(Percent)*	*13.4%*
Average Annual Increase, 1990-2003 *(Percent)*	*1.0%*

U.S. emissions of greenhouse gases in 2003 totaled 6,935.7 million metric tons carbon dioxide equivalent, 0.7 percent more than in 2002 (6,890.9 million metric tons carbon dioxide equivalent). Although emissions of carbon dioxide and emissions of methane grew by 0.8 percent and 0.5 percent, respectively, those increases were partially balanced by reductions in emissions of nitrous oxide (-0.9 percent) and hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride (-0.3 percent). U.S. greenhouse gas emissions have averaged 1.0-percent annual growth since 1990.

The U.S. economy grew by 3.0 percent in 2003, which is equivalent to the average annual growth rate that has prevailed during the 1990-2003 period. Consequently, U.S. greenhouse gas intensity (greenhouse gas emissions per unit of real economic output) was 2.3 percent lower in 2003 than in 2002. From 1990 to 2003, U.S. greenhouse gas intensity has declined by 22.3 percent, or by an average of 1.9 percent per year.

U.S. greenhouse gas emissions in 2003 were 13.4 percent higher than 1990 emissions (6,115.2 million metric tons carbon dioxide equivalent)—an average annual increase of 1.0 percent over the period. Since 1990, U.S. emissions have increased more slowly than the average annual growth in population (1.2 percent), primary energy consumption (1.2 percent), electric power generation (1.9 percent), or gross domestic product (3.0 percent). While the annual growth rate in carbon dioxide emissions since 1990 (1.3 percent) has closely tracked annual growth in population and energy consumption, the average annual rate of growth in total greenhouse gas emissions has been lower (1.0 percent) because of reductions in methane and nitrous oxide emissions since 1990.

Table ES1 shows trends in emissions of the principal greenhouse gases, measured in million metric tons of gas. In Table ES2, the value shown for each gas is weighted by its global warming potential (GWP), which is a measure of marginal radiative efficiency. The GWP concept, developed by the Intergovernmental Panel on Climate Change (IPCC), provides a comparative measure of the impacts of added units of different greenhouse gases on global warming relative to the global warming potential of carbon dioxide.[1]

Table ES1. Summary of Estimated U.S. Emissions of Greenhouse Gases, 1990 and 1995-2003
(Million Metric Tons of Gas)

Gas	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Carbon Dioxide.	4,990.1	5,306.7	5,495.5	5,558.1	5,590.7	5,671.6	5,844.8	5,777.0	5,824.8	5,870.2
Methane	30.8	29.6	28.3	28.2	27.2	26.6	26.7	26.0	26.1	26.2
Nitrous Oxide	1.1	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.1	1.1
HFCs, PFCs, and SF_6 . .	M	M	M	M	M	M	M	M	M	M

M = mixture of gases. These gases cannot be summed in native units. See Table ES2 for estimated totals in carbon dioxide equivalent.
P = preliminary data.
Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003).
Source: Estimates presented in this report.

---

[1] See "Units for Measuring Greenhouse Gases" on page xi, and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990 and 1995-2003
(Million Metric Tons Carbon Dioxide Equivalent)

Gas	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Carbon Dioxide	4,990.1	5,306.7	5,495.5	5,558.1	5,590.7	5,671.6	5,844.8	5,777.0	5,824.8	5,870.2
Methane.	707.8	681.6	650.5	647.7	624.6	612.3	614.7	598.3	599.2	601.9
Nitrous Oxide.	328.7	347.9	346.5	337.0	336.4	335.2	331.2	325.6	323.2	320.2
HFCs, PFCs, and SF_6 . .	88.5	94.7	114.7	122.4	138.0	137.8	142.4	134.2	143.7	143.4
Total	**6,115.2**	**6,430.9**	**6,607.1**	**6,665.1**	**6,689.6**	**6,756.9**	**6,933.0**	**6,835.0**	**6,890.9**	**6,935.7**

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003).

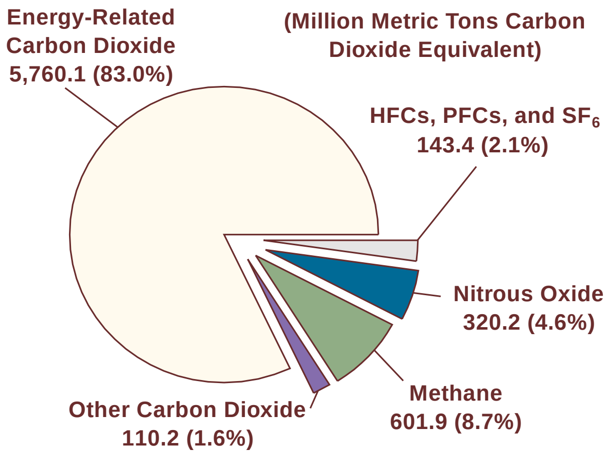
Sources: **Emissions:** Estimates presented in this report. **Global Warming Potentials:** Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 38 and 388-389.

In 2001, the IPCC Working Group I released its Third Assessment Report, *Climate Change 2001: The Scientific Basis*.[2] Among other things, the Third Assessment Report updated a number of the GWP estimates that appeared in the IPCC's Second Assessment Report.[3] The GWPs published in the Third Assessment Report were used for the calculation of carbon dioxide equivalent emissions for this report. Generally, the level of total U.S. carbon dioxide equivalent emissions is 0.6 percent higher when the GWPs from the Third Assessment Report are used; however, the trends in growth of greenhouse gas emissions are similar for both sets of GWP values.

During 2003, 83.0 percent of total U.S. greenhouse gas emissions consisted of carbon dioxide from the combustion of fossil fuels such as coal, petroleum, and natural gas (after adjustments for U.S. territories and international bunker fuels). U.S. emissions trends are driven largely by trends in fossil energy consumption. In recent years, national energy consumption, like emissions, has grown relatively slowly, with year-to-year deviations from trend growth caused by weather-related phenomena, fluctuations in business cycles, changes in the fuel mix for electric power generation, and developments in domestic and international energy markets.

Other 2003 U.S. greenhouse gas emissions include carbon dioxide from non-combustion sources (1.6 percent of total U.S. greenhouse gas emissions), methane (8.7 percent), nitrous oxide (4.6 percent), and other gases (2.1 percent) (Figure ES1). Methane and nitrous oxide emissions are caused by the biological decomposition of various waste streams and fertilizer; fugitive emissions from chemical processes; fossil fuel production, transmission, and combustion; and many smaller sources. The other gases include hydrofluorocarbons (HFCs), used primarily as refrigerants; perfluorocarbons (PFCs), released as fugitive emissions from aluminum smelting and also used in semiconductor manufacture; and sulfur hexafluoride (SF_6), used as an insulator in utility-scale electrical equipment.

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 2003



Source: Table ES2 and Table 5 in this report.

This report, required by Section 1605(a) of the Energy Policy Act of 1992, provides estimates of U.S. emissions of greenhouse gases. The estimates are based on activity data and applied emissions factors, not on measured or metered emissions monitoring.

Carbon Dioxide

The preliminary estimate of U.S. carbon dioxide emissions from both energy consumption and industrial processes in 2003 is 5,870.2 million metric tons, which is 0.8 percent higher than in 2002 (5,824.8 million metric tons) and accounts for 84.6 percent of total U.S. greenhouse gas emissions. U.S. carbon dioxide emissions have grown by an average of 1.3 percent annually since 1990.

---

[2] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

[3] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

Units for Measuring Greenhouse Gases

Emissions data are reported here in metric units, as favored by the international scientific community. Metric tons are relatively intuitive for users of English units, because 1 metric ton is only about 10 percent heavier than 1 English short ton.

Emissions of most greenhouse gases are reported here in terms of the full molecular weight of the gas (as in Table ES1). In Table ES2, however, and subsequently throughout the report, carbon dioxide and other greenhouse gases are reported in carbon dioxide equivalents. In the case of carbon dioxide, emissions denominated in the molecular weight of the gas or in carbon dioxide equivalents are the same. Carbon dioxide equivalent data can be converted to carbon equivalents by multiplying by 12/44.

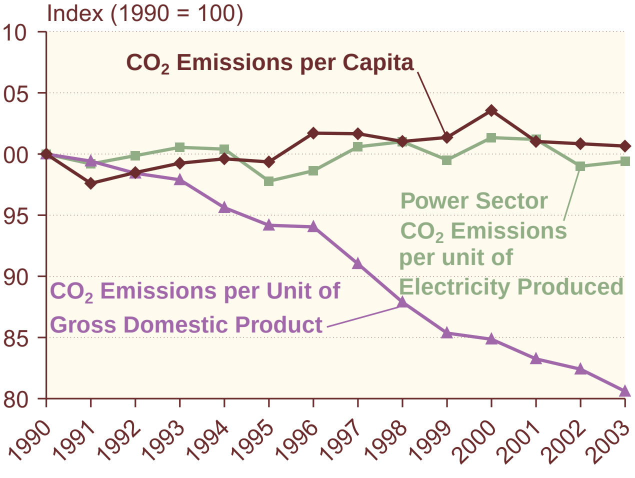
Emissions of other greenhouse gases (such as methane) can also be measured in "carbon dioxide equivalent" units by multiplying their emissions (in metric tons) by their global warming potentials (GWPs). Carbon dioxide equivalents are the amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas.

Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured (for example, methane) by its estimated GWP (which is 23 for methane). GWPs are discussed in Chapter 1 and summarized in Table 4 on page 13.

Although short-term changes in carbon dioxide emissions can result from temporary variations in weather, power generation fuel mixes, and the economy, growth in carbon dioxide emissions in the longer term results largely from population- and income-driven increases in energy use, as well as consumer choices of energy-using equipment. The "carbon intensity" of energy use (carbon dioxide emissions per unit of energy consumed) can also influence trend growth in energy-related carbon dioxide emissions.

Figure ES2 shows recent trends in some common indexes used to measure the carbon intensity of the U.S. economy. Carbon dioxide emissions per unit of gross domestic product (GDP) have continued to fall relative to 1990; by 2003, this measure was 19.4 percent lower than in 1990. Carbon dioxide emissions per capita, however, were 0.6 percent above 1990 levels in 2003. Population growth and other factors resulted in increased aggregate carbon dioxide emissions per year from 1990 through 2003 (a total increase of 17.6 percent). Carbon dioxide emissions per unit of net electricity generation in 2003 were 0.4 percent higher than in 2002.

Figure ES2. Carbon Dioxide Emissions Intensity of U.S. Gross Domestic Product, Population, and Electricity Production, 1990-2003



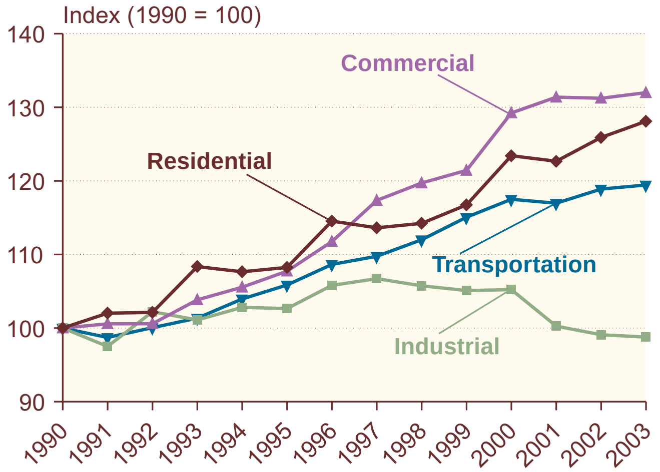
Sources: Estimates presented in this report.

EIA divides energy consumption into four general end-use categories: residential, commercial, industrial, and transportation. Emissions from electricity generators, which provide electricity to the end-use sectors, are allocated in proportion to the electricity consumed in, and losses allocated to, each sector. Figure ES3 illustrates trends in carbon dioxide emissions by energy consumption sector. Average annual growth rates in carbon dioxide emissions by sector during the 1990-2003 period were 2.2 percent for the commercial sector, 1.9 percent for the residential sector, and 1.4 percent for the transportation sector. Industrial sector carbon dioxide emissions, after peaking in 1997, are now below their 1990 level.

In the residential sector, total carbon dioxide emissions were up by 1.7 percent, from 1,193.9 million metric tons in 2002 to 1,214.8 million metric tons in 2003. The increase is attributed mainly to a 4.1-percent increase in residential natural gas consumption due largely to colder winter weather that increased heating degree-days by 4.0 percent. Residential sector emissions attributable to purchased electricity also rose by 1.0 percent, and emissions from petroleum products increased by 1.9 percent.

Carbon dioxide emissions in the commercial sector increased by 0.6 percent, from 1,019.8 million metric tons in 2002 to 1,025.7 million metric tons in 2003. Emissions attributable to purchased electricity increased by

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1990-2003



Note: Sectoral emissions include both direct emissions and emissions attributable to purchased electricity.

Sources: Estimates presented in this report.

0.4 percent, from 793.9 million metric tons in 2002 to 796.7 million metric tons in 2003. Carbon dioxide emissions from the direct combustion of fossil fuels, primarily natural gas, in the commercial sector rose from 225.9 million metric tons in 2002 to 229.0 million metric tons in 2003, a 1.3-percent increase.

Energy-related carbon dioxide emissions in the industrial sector in 2003 are estimated at 1,666.2 million metric tons, which is slightly less than the level of emissions in 1990. After peaking in 1997 at 1,800.1 million metric tons, industrial emissions have generally fallen, with the exception of a slight upturn in 2000.

Industrial energy consumption and carbon dioxide emissions are concentrated in a few energy-intensive industries, and the output of the energy-intensive industries tends to be closely correlated with the industrial sector's total carbon dioxide emissions. Among the six energy-intensive industry groups, which traditionally account for about 65 to 70 percent of total industrial carbon dioxide emissions and 80 percent of carbon dioxide emissions from manufacturing, changes in output were mixed in 2003, with production increases in three and decreases in the other three (see text box in Chapter 2, page 23). Declines in output were seen in 2003 for primary metals (-2.3 percent), chemicals (-1.5 percent), and food (-3.6 percent), while increases in output were seen for paper (5.1 percent), nonmetallic minerals (0.9 percent), and petroleum refining (1.5 percent). Although the paper industry showed robust growth in 2003, the manufacture of paper produces relatively small amounts of carbon per energy consumed, because much of the energy used is supplied by wood waste, and the resulting emissions are part of the natural carbon cycle. By fuel type, industrial sector carbon dioxide emissions rose for purchased electricity (1.9 percent), coal (1.2 percent), and petroleum (2.2 percent), while emissions from natural gas fell by 6.3 percent. Because of the large decrease in emissions from natural gas use, total industrial emissions fell despite increases in emissions from the other three energy sources.

Carbon dioxide emissions in the transportation sector, at 1,874.7 million metric tons, were 0.5 percent higher in 2003 than in 2002 (1,866.0 million metric tons). Emissions of carbon dioxide from gasoline consumption (61.0 percent of transportation sector emissions) grew by 0.4 percent, while emissions from jet fuel use for air travel fell by 2.5 percent. Carbon dioxide emissions from distillate fuel use grew by 3.6 percent in 2003. Transportation sector carbon dioxide emissions have grown by an average of 1.4 percent annually since 1990.

Carbon dioxide emissions from the U.S. electric power sector increased by 1.0 percent (22.9 million metric tons), from 2,256.4 million metric tons in 2002 to 2,279.3 million metric tons in 2003. Carbon dioxide emissions from the electric power sector have grown by 27.5 percent since 1990, while total carbon dioxide emissions from all energy-related sources have grown by 16.0 percent. Carbon dioxide emissions from the electric power sector represented 39.4 percent of total U.S. energy-related carbon dioxide emissions in 2003; however, as noted above, in calculating emissions from the end-use sectors EIA distributes electric power sector emissions to the four sectors in proportion to their respective shares of total electricity purchases. Therefore, electric power emissions are already included in the sectoral totals.

By fuel, emissions from natural gas use for electricity generation in 2003 were down by 10.1 percent from 2002, emissions from coal use were up by 1.8 percent, and emissions from petroleum use were up by 25.8 percent. The increases in coal- and petroleum-fired generation, at the expense of natural-gas-fired generation, reflect the rapid rise in natural gas prices in 2003 (52.2 percent), while coal and petroleum prices increased by 1.6 and 29.0 percent, respectively. Petroleum-fired generation is a small component of total electricity generation in the United States.

Methane

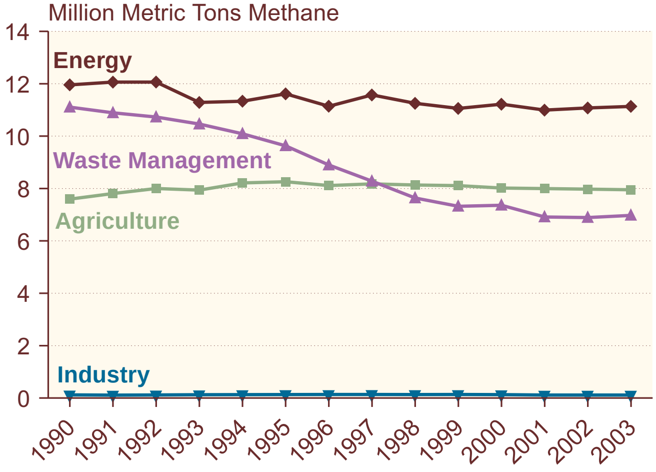
U.S. emissions of methane in 2003 were 0.5 percent higher than in 2002, at 26.2 million metric tons of methane or 601.9 million metric tons carbon dioxide equivalent (8.7 percent of total U.S. greenhouse gas emissions). Total U.S. methane emissions in 2002 were 26.1 million metric tons of methane. The 2003 increase resulted primarily from small increases in methane emissions from landfills, coal mines, animal waste, and natural gas systems. Despite the 0.5-percent increase from 2002, methane emissions in 2003 were 4.6 million metric tons (15 percent) below the 1990 level.

Methane emissions come from four categories of sources, three major and one minor. The major sources are energy, agriculture, and waste management, and the minor source is industrial processes. The three major sources accounted for 42.5, 30.4, and 26.6 percent, respectively, of total 2003 U.S. emissions of methane. Trends in the major sources of anthropogenic methane emissions since 1990 are illustrated in Figure ES4.

Methane emissions from energy sources (coal mining, natural gas systems, petroleum systems, stationary combustion, and mobile source combustion) increased from 254.7 million metric tons carbon dioxide equivalent in 2002 to 256.1 million metric tons carbon dioxide equivalent in 2003, representing a 0.5-percent increase in emissions from energy sources. Methane emissions from energy sources have fallen by 6.9 percent since 1990. The rise in 2003 was the result of increases in emissions from coal mines and natural gas systems.

Methane emissions from agricultural sources (182.8 million metric tons carbon dioxide equivalent) decreased by 0.3 percent in 2003. Agricultural methane emissions have several sources but are dominated by emissions from domestic livestock, including the animals themselves (enteric fermentation) and the anaerobic decomposition of their waste. Methane emissions from enteric fermentation in 2003 were 0.3 percent lower than in 2002, whereas methane emissions from animal waste were 0.6 percent higher than in 2002. The overall decline in agricultural methane emissions resulted mainly from one of the smallest sources, emissions from rice cultivation, which fell by 0.7 million metric tons carbon dioxide equivalent or 6.8 percent. Agricultural emissions have increased by 4.7 percent since 1990.

Figure ES4. U.S. Emissions of Methane by Source, 1990-2003



Source: Estimates presented in this report.

Methane emissions from waste management sources include two subcategories: emissions from the anaerobic decomposition of municipal solid waste in landfills and emissions from wastewater treatment facilities. Methane emissions from waste management rose by 1.2 percent, from 158.5 million metric tons carbon dioxide equivalent in 2002 to 160.4 million metric tons carbon dioxide equivalent in 2003. Contributing to the increase was a 1.3-percent increase in emissions from landfills, which would have been larger but for a 0.3 million metric ton increase in methane recovery for energy use. Methane emissions from wastewater increased by 0.8 percent to 15.5 million metric tons carbon dioxide equivalent. Emissions of methane from waste management have declined by 37.2 percent since 1990 as a result of an increase in the amount of methane recovered from landfills (5.0 million metric tons more in 2003 than in 1990) that would otherwise have been emitted to the atmosphere.

The estimates for methane emissions are more uncertain than those for carbon dioxide. U.S. methane emissions do not necessarily increase with growth in energy consumption or the economy. Energy-related methane emissions are strongly influenced by coal production from a relatively small number of mines; agricultural emissions are influenced in part by the public’s consumption of milk and beef and in part by animal husbandry practices; and waste management emissions are influenced by the volumes of municipal waste generated and recycled, as well as the amount of methane recaptured at landfills.

Nitrous Oxide

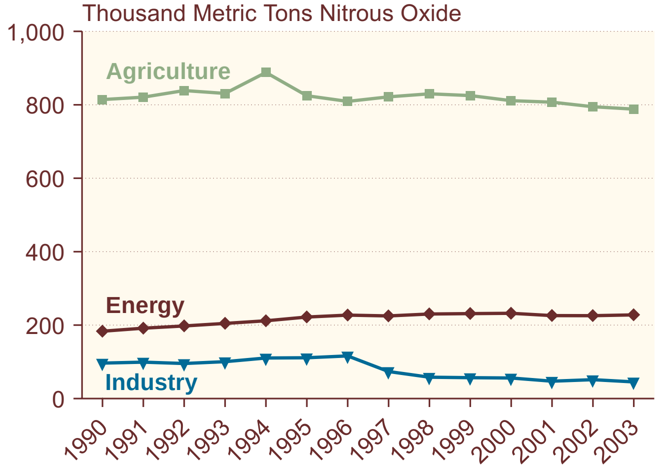
U.S. nitrous oxide emissions decreased by 0.9 percent from 2002 to 2003, to 1.1 million metric tons of nitrous oxide or 320.2 million metric tons carbon dioxide equivalent (4.6 percent of total U.S. greenhouse gas emissions). The 2003 decline in nitrous oxide emissions resulted mainly from decreases in emissions from agriculture (1.9 million metric tons carbon dioxide equivalent) and industrial processes (1.8 million metric tons carbon dioxide equivalent). Since 1990, U.S. nitrous oxide emissions have fallen by 2.6 percent. Emissions estimates for nitrous oxide are more uncertain than those for either carbon dioxide or methane. Nitrous oxide is not systematically measured, and for many sources of nitrous oxide emissions, including nitrogen fertilization of soils and motor vehicles, a significant number of assumptions are required for the derivation of emissions estimates.

U.S. nitrous oxide emissions include two large categories of sources, agriculture and energy use, and two smaller categories, industrial processes and waste management (Figure ES5). Agricultural sources, at 233.3 million metric tons carbon dioxide equivalent, accounted for 72.9 percent of total U.S. nitrous oxide emissions in 2003. Emissions associated with nitrogen fertilization of soils, at 172.1 million metric tons carbon dioxide equivalent, accounted for 73.8 percent of nitrous oxide emissions from agriculture. Emissions from the solid waste of animals, at 60.7 million metric tons carbon dioxide equivalent, made up 26.0 percent of agricultural nitrous oxide emissions. Nitrous oxide emissions from agriculture have decreased by 3.2 percent since 1990.

U.S. nitrous oxide emissions associated with fossil fuel combustion in 2003 were 67.5 million metric tons carbon dioxide equivalent, or 21.1 percent of total nitrous oxide emissions. Of these energy-related emissions, 78.1 percent were from mobile sources, principally motor vehicles equipped with catalytic converters. The remainder were from stationary source combustion of fossil fuels. Nitrous oxide emissions from energy sources have increased by 24.4 percent since 1990.

Industrial processes and wastewater treatment facilities were responsible for 4.2 and 1.8 percent, respectively, of total nitrous oxide emissions in 2003. Industrial process emissions decreased by 11.8 percent, from 15.2 million metric tons carbon dioxide equivalent in 2002 to 13.4 million metric tons carbon dioxide equivalent in 2003. The decrease can be attributed to a 7.9-percent drop in U.S. nitric acid production. Emissions of nitrous oxide from adipic acid production in 2003 were 22.9 percent lower than in 2002, due in large part to a decrease in adipic acid production from uncontrolled sources. Emissions from wastewater treatment facilities in 2003 were 6.0 million metric tons carbon dioxide equivalent, an increase of 0.1 million metric tons carbon dioxide equivalent or 0.9 percent from 2002 levels.

Figure ES5. U.S. Emissions of Nitrous Oxide by Source, 1990-2003



Source: Estimates presented in this report.

Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

HFCs, PFCs, and SF_6 are three classes of engineered gases that accounted for 2.1 percent of total U.S. greenhouse gas emissions in 2003. At 143.4 million metric tons carbon dioxide equivalent, their emissions were 0.3 percent lower than in 2002 (143.7 million metric tons). The decrease in emissions of the engineered gases from 2002 to 2003 resulted largely from an 18-percent reduction in PFC emissions that counteracted increases in emissions of HFCs (0.5 percent) and SF_6 (1.6 percent).

At 111.3 million metric tons carbon dioxide equivalent, emissions of HFCs made up the majority of this category, followed by SF_6 at 17.3 million metric tons carbon dioxide equivalent and PFCs at 7.3 million metric tons carbon dioxide equivalent. Another group of engineered gases, consisting of other HFCs, other PFCs, and perfluoropolyethers (PFPEs), includes HFC-152a, HFC-227ea, HFC-4310mee, and a variety of PFCs and PFPEs. They are grouped together in this report to protect confidential data. In 2003, their combined emissions totaled 7.1 million metric tons carbon dioxide equivalent. Emissions in this "other" group in 2003 were 5.9 percent higher than in 2002 and orders of magnitude higher than in 1990, when emissions were less than 0.3 million metric tons carbon dioxide equivalent. Since 1990, HFC emissions from U.S. sources have increased by 208.6 percent, PFC emissions have decreased by 62.9 percent, and SF_6 emissions have decreased by 47.1 percent.

Emissions of the high-GWP gases specified in the Kyoto Protocol are very small (at most a few thousand metric tons). On the other hand, some of the gases (including PFCs and SF_6) have atmospheric lifetimes measured in the thousands of years, and consequently they are potent greenhouse gases with GWPs thousands of times higher than that of carbon dioxide per unit of molecular weight. Some of the commercially produced HFCs (134a, 152a, 4310mee, 227ea), which are used as replacements for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), have shorter atmospheric lifetimes, ranging from 1 to 33 years.

Land Use and Forestry

Forest lands in the United States are net absorbers of carbon dioxide from the atmosphere. Absorption is enabled by the reversal of the extensive deforestation of the United States that occurred in the late 19th and early 20th centuries. Since then, millions of acres of formerly cultivated land have been abandoned and have returned to forest, with the regrowth of forests sequestering carbon on a large scale. The process is steadily diminishing, however, because the rate at which forests absorb carbon slows as the trees mature, and because the rate of reforestation has slowed. The U.S. Environmental Protection Agency (EPA) estimates annual U.S. carbon sequestration for the year 2002 at 690.7 million metric tons carbon dioxide, representing an offset of 11.9 percent of total 2002 U.S. anthropogenic carbon dioxide emissions (5,824.8 million metric tons carbon dioxide). In 1990, land use and forestry carbon sequestration was equivalent to 957.9 million metric tons carbon dioxide, or 19.2 percent of total 1990 U.S. anthropogenic carbon dioxide emissions (4,990.1 million metric tons).[4]

---

[4] Note that EIA does not include sequestration from land-use change and forestry as part of its annual emissions inventory.

1. U.S. Emissions of Greenhouse Gases: Background and Context

About This Report

The Energy Information Administration (EIA) is required by the Energy Policy Act of 1992 to prepare a report on aggregate U.S. national emissions of greenhouse gases for the period 1987-1990, with annual updates thereafter. This report is the eleventh annual update, covering national emissions over the period 1990-2002, with preliminary estimates of emissions for 2003. The methods used by EIA to estimate national emissions of greenhouse gases are subject to continuing review. As better methods and information become available, EIA revises both current and historical emissions estimates. Emissions estimates for carbon dioxide are reported in metric tons of carbon dioxide; estimates for other gases are reported in metric tons of gas (see "Units for Measuring Greenhouse Gases," in the Executive Summary, page xi) and in carbon dioxide equivalent units where appropriate. Estimates of total national emissions in carbon dioxide equivalent units are shown in Table ES2 on page x.

This introductory chapter briefly summarizes some background information about global climate change and the greenhouse effect and reviews recent developments in global climate change activities. Chapters 2 through 4 cover emissions of carbon dioxide, methane, and nitrous oxide, respectively. Chapter 5 focuses on emissions of engineered gases, including hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Chapter 6 describes potential sequestration and emissions of greenhouse gases as a result of land use changes.

What's New

Measures of Greenhouse Gas Intensity

This year, to be consistent with other EIA publications, we are using chain-weighted 2000 dollars for all calculations involving gross domestic product (GDP). This affects greenhouse gas (GHG) intensity calculations, because economic values expressed in 2000 dollars are 6.9 percent higher than those expressed in 1996 dollars, which were used in last year's report. The change to chain-weighted 2000 dollars does not affect calculations related to the rate of change in emissions intensity over time.

Methane

The data sources and methodologies used to estimate methane emissions from mobile sources for 1990 through 2003 have changed, resulting in revised emissions estimates. Data used to calculate vehicle miles traveled (VMT) for light-duty vehicles (passenger cars and light-duty trucks) during the years 1990-2000 are now based on the most recent Polk data on vehicle stocks, with VMT modified by the Oak Ridge National Laboratory (ORNL). The data for 1996-2000 are further adjusted to incorporate fleet-vehicle data, and the methodology adjusts for the aging population of vehicles by applying survival curves. These changes also apply to nitrous oxide emissions. For the years 2001 through 2003, methane emissions from mobile sources are estimated using data from fleet vehicles and econometrically modeled VMT, while also adjusting for the aging population of vehicles. The data sources replace those taken historically from subscription publications such as *Wards Automotive Yearbook*.

Estimates have also been revised to reflect the inclusion of methane emissions from organic decomposition in industrial landfills. Emissions from industrial landfills are estimated to equal 7 percent of emissions from municipal solid waste landfills based on a methodology developed by the U.S. Environmental Protection Agency (EPA).[1] Industrial landfills have been included because the use of more rigorously gathered data on landfilled municipal solid waste reduces the likelihood that emissions from industrial landfills will be double counted in estimates of methane emissions from municipal solid waste.

Nitrous Oxide

The data sources and methodologies used to estimate nitrous oxide (N_2O) emissions from mobile sources for 1990 through 2003 have been changed in the same way as described above for methane emissions from mobile

---

[1] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

sources. For the years 2001 through 2003, N_2O emissions from mobile sources are estimated using data from fleet vehicles and econometrically modeled VMT, while also adjusting for the aging population of vehicles. The data sources replace those taken historically from subscription publications such as *Wards Automotive Yearbook*.

Other Gases: HFCs, PFCs, and SF_6

The data presented in Chapter 5 for other gases—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—are provided by the EPA. Revisions in historical emissions estimates for specific sources are explained below:

- **Electricity Transmission and Distribution.** The changes in calculations of emissions from electricity transmission and distribution include both a revised methodology and updated activity data for 1990 through 1998. The revised methodology accounts for the quantity of SF_6 that is recaptured and/or released from operating electrical equipment, rather than assuming all SF_6 was released at the time of its initial installation into the equipment. The methodology assumes that only 22.5 percent of the SF_6 is emitted at the time of its installation and the remaining 77.5 percent is emitted over a 30-year period. The activity data were updated in two ways: first, with the results of a survey of SF_6 manufacturers conducted in 2002 by the RAND Corporation; and second, with revised data received from participants in the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems, which led to updated regression equations and extrapolations to non-reporting partners. These revisions resulted in a decrease in estimated SF_6 emissions from electric power systems of 9.0 percent for 1990, 18.2 percent for 1998, and 3.3 percent for 2001; and an increase in estimated emissions of 1.4 percent in 2000.
- **Magnesium Production and Processing.** The emissions estimates in this report were revised to reflect new historical data supplied by participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. This change resulted in a decrease of about 0.5 percent in estimated SF_6 emissions for 2001.
- **Substitution of Ozone-Depleting Substances.** The EPA updated assumptions for its Vintaging Model pertaining to market trends in chemicals and chemical substitutes. These changes resulted in an average annual increase of 9.1 percent in HFC and PFC emissions for the period 1990 through 2001.
- **Aluminum Production**. In cooperation with the EPA's Voluntary Aluminum Industrial Partnership program, participants provided additional smelter-specific information on aluminum production and emission factors. The new information resulted in a decrease in PFC emissions of 1.0 percent for 1990 through 1994, an increase of 12.0 percent for 2000, and a decrease of 4.0 percent for 2001.
- **Semiconductor Manufacture**. The EPA updated activity data provided by participants in EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry, as well as its PFC Emissions Vintaging Model (PEVM), which estimates emissions from entities that do not participate in the partnership program. The EPA also revised its methodology for estimating the historical distribution of emissions among HFCs, PFCs, and SF_6, by incorporating market information on sales volumes that was obtained in surveys. These updates resulted in an average decrease in emissions estimates from semiconductor manufacture of 9 percent for 1995 through 2001.

Land Use Issues

The U.S. Forest Service provides the data for net carbon dioxide fluxes due to changes in carbon stocks in forests, urban trees, agricultural soil, and landfilled yard trimmings. This year, updates are provided on treatment of land use issues under current climate change negotiations, scientific research detailing uncertainty in the ability of forest soils to store carbon, and the status of carbon dioxide capture and geologic storage technologies.

U.S. Emissions in a Global Perspective

It is estimated that U.S. energy-related carbon dioxide emissions in 2001 totaled 5,692 million metric tons.[2] To put U.S. emissions in a global perspective, total energy-related carbon dioxide emissions for the world in 2001 are estimated at 23,899 million metric tons, making U.S. emissions about 24 percent of the world total (Table 1). Emissions for the industrialized world (North America, Western Europe, and Industrialized Asia) in 2001 are estimated at 11,634 million metric tons, or about 49 percent of the world total, implying that U.S. emissions represent about 49 percent of the energy-related carbon dioxide emissions from the industrialized world. The remaining 51 percent of 2001 worldwide energy-related carbon dioxide emissions come from developing

[2] Energy Information Administration, *International Energy Outlook 2004*, DOE/EIA-0484(2004) (Washington, DC, April 2004). The estimate of U.S. emissions has been revised to 5,707.3 million metric tons carbon dioxide, but because emissions estimates for the rest of the world have not been similarly revised, this calculation uses the earlier estimate for consistency. Emissions of gases other than energy-related carbon dioxide are difficult to estimate for the developing world; however, emissions related to fossil fuel consumption are likely to make up 80 to 85 percent of all greenhouse gas emissions.

Table 1. World Carbon Dioxide Emissions by Region, 1990-2025
(Million Metric Tons Carbon Dioxide)

Region/Country	History			Projections				Average Annual Percent Change, 2001-2025
	1990	2000	2001	2010	2015	2020	2025	
Industrialized Countries								
North America	**5,769**	**6,731**	**6,613**	**7,677**	**8,255**	**8,876**	**9,659**	**1.6**
United States[a]	4,989	5,787	5,692	6,559	7,028	7,536	8,142	1.5
Canada	473	581	569	686	734	776	830	1.6
Mexico	308	364	352	433	492	565	687	2.8
Western Europe	**3,412**	**3,442**	**3,465**	**3,567**	**3,682**	**3,832**	**4,022**	**0.6**
United Kingdom	600	553	563	608	642	665	692	0.9
France	374	401	396	390	398	400	412	0.2
Germany	995	828	819	851	874	943	969	0.7
Italy	415	443	445	486	504	522	540	0.8
Netherlands	211	228	248	263	272	279	286	0.6
Other Western Europe	816	989	994	969	992	1,021	1,123	0.5
Industrialized Asia	**1,280**	**1,526**	**1,556**	**1,694**	**1,770**	**1,840**	**1,962**	**1.0**
Japan	987	1,138	1,158	1,239	1,274	1,300	1,356	0.7
Australia/New Zealand	294	387	398	455	497	541	605	1.8
Total Industrialized	**10,462**	**11,699**	**11,634**	**12,938**	**13,708**	**14,548**	**15,643**	**1.2**
EE/FSU								
Former Soviet Union	**3,798**	**2,338**	**2,399**	**2,600**	**2,840**	**3,118**	**3,393**	**1.5**
Russia	2,405	1,570	1,614	1,792	1,913	2,059	2,186	1.3
Other FSU	1,393	767	785	808	927	1,059	1,207	1.8
Eastern Europe	**1,104**	**756**	**748**	**797**	**827**	**888**	**920**	**0.9**
Total EE/FSU	**4,902**	**3,094**	**3,148**	**3,397**	**3,667**	**4,006**	**4,313**	**1.3**
Developing Countries								
Developing Asia	**3,994**	**5,709**	**6,012**	**7,647**	**8,863**	**10,240**	**11,801**	**2.9**
China	2,262	2,861	3,050	4,063	4,824	5,693	6,666	3.3
India	561	914	917	1,141	1,341	1,575	1,834	2.9
South Korea	234	425	443	563	620	662	720	2.0
Other Asia	937	1,509	1,602	1,881	2,078	2,310	2,581	2.0
Middle East	**846**	**1,262**	**1,299**	**1,566**	**1,729**	**1,910**	**2,110**	**2.0**
Turkey	129	184	184	249	280	309	340	2.6
Other Middle East	717	1,078	1,115	1,317	1,448	1,601	1,770	1.9
Africa	**656**	**811**	**843**	**971**	**1,110**	**1,259**	**1,413**	**2.2**
Central and South America	**703**	**961**	**964**	**1,194**	**1,358**	**1,578**	**1,845**	**2.7**
Brazil	250	343	347	451	531	617	720	3.1
Other Central/South America	453	618	617	744	827	961	1,125	2.5
Total Developing	**6,200**	**8,744**	**9,118**	**11,379**	**13,060**	**14,987**	**17,168**	**2.7**
Total World	**21,563**	**23,536**	**23,899**	**27,715**	**30,435**	**33,541**	**37,124**	**1.9**

[a] Includes the 50 States and the District of Columbia.

Notes: EE/FSU = Eastern Europe/Former Soviet Union. The U.S. numbers include carbon dioxide emissions attributable to renewable energy sources.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2001*, DOE/EIA-0219(2001) (Washington, DC, February 2003), web site www.eia.doe.gov/iea/. **Projections:** EIA, *Annual Energy Outlook 2004*, DOE/EIA-0383(2004) (Washington, DC, January 2004), Table A19; and *International Energy Outlook 2004*, DOE/EIA-0484(2004) (Washington, DC, April 2004), Table A9.

countries (9,118 million metric tons) and the former Soviet Union and Eastern Europe (3,148 million metric tons). By 2025, however, the U.S. share of total world emissions is projected to fall to 22 percent (8,142 million metric tons out of a global total of 37,124 million metric tons). The reason for the expected decline in the U.S. share is that energy-related carbon dioxide emissions from the developing countries are projected to increase at an annual rate of 2.7 percent, while emissions from the industrialized countries increase by 1.2 percent annually.

From an economic perspective, U.S. GDP in 2001 was $9,394 billion (in constant 1997 dollars), compared with an estimated global total GDP of $32,354 billion. Thus, the U.S. share of world economic output in 2001 was about 29 percent. In 2025, when the world's total GDP is projected to be $65,574 billion, U.S. share is projected to be $18,881 billion, or still about 29 percent. In other words, the United States is projected to maintain its share of economic output while its share of global emissions shrinks.

The Greenhouse Effect and Global Climate Change

The Earth is warmed by radiant energy from the Sun. Over time, the amount of energy transmitted to the Earth's surface is equal to the amount of energy re-radiated back into space in the form of infrared radiation, and the temperature of the Earth's surface stays roughly constant; however, the temperature of the Earth is strongly influenced by the existence, density, and composition of its atmosphere. Many gases in the Earth's atmosphere absorb infrared radiation re-radiated from the surface, trapping heat in the lower atmosphere. Without the natural greenhouse effect, it is likely that the average temperature of the Earth's surface would be on the order of -19º Celsius, rather than the +14º Celsius actually observed.[3] The gases that help trap the Sun's heat close to the Earth's surface are referred to as "greenhouse gases." All greenhouse gases absorb infrared radiation (heat) at particular wavelengths.

The most important greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several engineered gases, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Water vapor is by far the most common, with an atmospheric concentration of nearly 1 percent, compared with less than 0.04 percent for carbon dioxide. The effect of human activity on global water vapor concentrations is considered negligible, however, and anthropogenic (human-made) emissions of water vapor are not factored into national greenhouse gas emission inventories for the purposes of meeting the requirements of the United Nations Framework Convention on Climate Change (UNFCCC) or the Kyoto Protocol.[4] Concentrations of other greenhouse gases, such as methane and nitrous oxide, are a fraction of that for carbon dioxide (Table 2).

Scientists recognized in the early 1960s that concentrations of carbon dioxide in the Earth's atmosphere were increasing every year. Subsequently, they discovered that atmospheric concentrations of methane, nitrous oxide, and many engineered greenhouse gas chemicals also were rising. Because current concentrations of greenhouse gases keep the Earth at its present temperature, scientists began to postulate that increasing concentrations of greenhouse gases would make the Earth warmer.

In computer-based simulation models, rising concentrations of greenhouse gases nearly always produce an increase in the average temperature of the Earth. Rising temperatures may, in turn, produce changes in weather and in the level of the oceans that might prove disruptive to current patterns of land use and human settlement, as well as to existing ecosystems. To date, however, it has proven difficult to disentangle the human impact on climate from normal temporal and spatial variations in temperature on both a global scale and geologic timeframe. The most recent report of the Intergovernmental Panel on Climate Change (IPCC), an international assemblage of scientists commissioned by the United Nations to assess the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change,

---

[3] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 89-90. See also web site www.ipcc.ch.

[4] The UNFCCC, which "entered into force" in 1994, called on Annex I countries, including the United States, to return their greenhouse gas emissions to 1990 levels by the year 2000. The Kyoto Protocol, adopted in December 1997, is a set of quantified greenhouse gas emissions targets for Annex I countries for the 2008 to 2012 commitment period that are collectively about 5 percent lower than the 1990 emissions of those countries. The Protocol requires 55 countries and Annex I signatories with carbon dioxide emissions totaling 55 percent of total 1990 Annex I emissions to ratify the Protocol. Annex I nations include Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, European Union, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, and the United States. The United States, at UNFCCC negotiations in Bonn, Germany, in July 2001, indicated that it considers the Kyoto Protocol to be flawed and stated that it had no plans to ratify the Protocol. Russia, however, ratified the Protocol in November 2004. It will enter into force in February 2005, because signatories now account for 61 percent of 1990 Annex I emissions.

Table 2. Global Atmospheric Concentrations of Selected Greenhouse Gases

Item	Carbon Dioxide	Methane	Nitrous Oxide	Sulfur Hexafluoride	Perfluoro-methane
	(parts per million)			(parts per trillion)	
Pre-industrial (1750) Atmospheric Concentration	278	0.700	0.270	0	40
1998 Atmospheric Concentration	365	1.745	0.314	4.2	80
Average Annual Change, 1990-1999	1.5[a]	0.007[a]	0.0008	0.2	1.0
Atmospheric Lifetime (Years)	50–200[b]	12[c]	114[c]	3,200	>50,000

[a] The rate has fluctuated between 0.9 and 2.8 parts per million per year for CO_2 and between 0 and 0.013 parts per million per year for methane over the 1990-1999 period.

[b] No single lifetime can be defined for CO_2 because uptake rates differ for different removal processes.

[c] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 38 and 244.

estimates that the global average surface temperature has increased by 0.6 ± 0.2ºC since the late 19th century.[5] The IPCC goes on to conclude that: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[6]

In the aftermath of the IPCC report, the Domestic Policy Council, in May 2001 as part of its review of U.S. policy on climate change, requested that the National Academy of Sciences identify areas of uncertainty in the science of climate change, as well as review the IPCC report and summaries.[7] The National Academy of Sciences commissioned the National Research Council to carry out this review. The National Research Council in issuing its findings appeared to agree with some of the IPCC conclusions, but also seemed to suggest that further work needs to be done in identifying the impacts of natural climatic variability and reducing the uncertainty inherent in climate change modeling. Among the National Research Council findings are the following:[8]

> *Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising. The changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability.*
>
> *Because there is considerable uncertainty in current understanding of how the climate system varies naturally and reacts to emissions of greenhouse gases and aerosols, current estimates of the magnitude of future warming should be regarded as tentative and subject to future adjustments (either upward or downward).*
>
> *The committee generally agrees with the assessment of human-caused climate change presented in the IPCC Working Group I (WGI) scientific report, but seeks here to articulate more clearly the level of confidence that can be ascribed to those assessments and the caveats that need to be attached to them.*

Greenhouse Gas Sources and Sinks

Most greenhouse gases have both natural and human-made emission sources. There are, however, significant natural mechanisms (land-based or ocean-based sinks) for removing them from the atmosphere. However, increased levels of anthropogenic emissions have pushed the total level of greenhouse gas emissions (both natural and anthropogenic) above the natural absorption rates for these gases. This positive imbalance between emissions and absorption has resulted in the continuing growth in atmospheric concentrations of these gases. Table 3 illustrates the relationship between anthropogenic and natural emissions and absorption of the principal greenhouse gases on an annual average basis during the 1990s.

Water Vapor. Water vapor, as noted above, is the most common greenhouse gas present in the atmosphere. It is emitted into the atmosphere in enormous volumes

---

[5] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 26.

[6] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 10.

[7] National Research Council, *Climate Change Science, An Analysis of Some Key Questions* (Washington, DC: National Academy Press, 2001), Appendix A, "Letter from the White House," p. 27, web site http://nap.edu/html/climatechange/.

[8] National Research Council, *Climate Change Science, An Analysis of Some Key Questions* (Washington, DC: National Academy Press, 2001), p. 1, web site http://nap.edu/html/climatechange/.

Table 3. Global Natural and Anthropogenic Sources and Absorption of Greenhouse Gases in the 1990s

Gas	Sources			Absorption	Annual Increase in Gas in the Atmosphere
	Natural	Human-Made	Total		
Carbon Dioxide (Million Metric Tons of Gas)[a]	770,000	23,100	793,100	781,400	11,700
Methane (Million Metric Tons of Gas)[b]	239	359	598	576	22
Nitrous Oxide (Million Metric Tons of Gas)[c]	9.5	6.9	16.4	12.6	3.8

[a] Carbon dioxide natural source and absorption of 770,000 million metric tons carbon dioxide, based on balanced flux of 40,000 million metric tons between land and atmosphere and 330,000 million metric tons between oceans and atmosphere, from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Figure 3.1, p. 188. Human-made emissions of 23,100 million metric tons and distribution of those emissions (atmospheric absorption 11,700 million metric tons, ocean absorption 6,200 million metric tons, and land absorption 5,100 million metric tons), taken from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 39.

[b] Methane total sources, absorption, and annual atmospheric increases from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.2, p. 250. Distinction between natural and human-made sources based on the assumption that 60 percent of total sources are anthropogenic, from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 248.

[c] Nitrous oxide total and human-made sources, absorption, and atmospheric increases from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.4, p. 252. Nitrous oxide natural sources (9.5 million metric tons of gas) derived by subtracting human-made sources from total sources.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

through natural evaporation from oceans, lakes, and soils and is returned to Earth in the form of rain and snow. The recent IPCC report, however, cites a possible positive feedback from increased water vapor formation due to increased warming caused by rising atmospheric CO_2 concentrations.[9] Elevated atmospheric temperatures increase the water-holding capability of the atmosphere. According to some of the IPCC emission scenarios, higher water vapor content could double the predicted atmospheric warming above what it would be if water vapor concentration stayed constant. These scenarios, however, have an element of uncertainty due to the possible countervailing effect of increased cloud formation, which can act to cool the planet by absorbing and reflecting solar radiation or warm the planet through the emission of long-wave radiation. According to the IPCC, increases in atmospheric temperatures would not necessarily result in increased concentrations of water vapor, because most of the atmosphere today is undersaturated.

Carbon Dioxide. Carbon is a common element on the planet, and immense quantities can be found in the atmosphere, in soils, in carbonate rocks, and dissolved in ocean water. All life on Earth participates in the "carbon cycle," by which carbon dioxide is extracted from the air by plants and decomposed into carbon and oxygen, with the carbon being incorporated into plant biomass and the oxygen released to the atmosphere. Plant biomass, in turn, ultimately decays (oxidizes), releasing carbon dioxide back into the atmosphere or storing organic carbon in soil or rock. There are vast exchanges of carbon dioxide between the ocean and the atmosphere, with the ocean absorbing carbon from the atmosphere and plant life in the ocean absorbing carbon from water, dying, and spreading organic carbon on the sea bottom, where it is eventually incorporated into carbonate rocks such as limestone.

Records from Antarctic ice cores indicate that the carbon cycle has been in a state of imbalance for the past 200 years, with emissions of carbon dioxide to the atmosphere exceeding absorption. Consequently, carbon dioxide concentrations in the atmosphere have been steadily rising. Because of its relative abundance, total carbon dioxide in the atmosphere has a radiative forcing value of 1.46 watts per square meter.[10] (See page 11 for a discussion of radiative forcing.) According to the IPCC, before 1750, atmospheric carbon dioxide concentration was around 280 ± 10 parts per million for several thousand years. The IPCC goes on to say that the present carbon dioxide concentration has not been exceeded during

---

[9] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 49.

[10] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), Table 6.1, p. 358.

the past 420,000 years, and likely not during the past 20 million years.[11]

The most important natural sources of carbon dioxide are releases from the oceans (330 billion metric tons of carbon dioxide per year) and land (440 billion metric tons of carbon dioxide annually), including 220 billion metric tons of carbon dioxide from plant respiration, 202 billion metric tons of carbon dioxide from non-plant respiration (bacteria, fungi, and herbivores), and 15 billion metric tons of carbon dioxide from combustion of natural and human-made fires.[12] Known anthropogenic sources (including deforestation) were estimated to account for about 29 billion metric tons of carbon dioxide per year during the 1989 to 1998 time period.[13] The principal anthropogenic source is the combustion of fossil fuels, which accounts for about 80 percent of total anthropogenic emissions of carbon worldwide. Natural processes—primarily, uptake by the ocean and photosynthesis—absorb substantially all the naturally produced carbon dioxide and some of the anthropogenic carbon dioxide, leading to an annual net increase in carbon dioxide in the atmosphere of 11.4 to 12.1 billion metric tons.[14] Recent evidence indicates there has been an increase in the rate of growth in atmospheric concentrations of carbon dioxide in the northern hemisphere. The text box on page 8 discusses factors that may have influenced this situation.

Methane. Methane is also a common compound. The methane cycle is less well understood than the carbon cycle. Natural methane is released primarily by anaerobic decay of vegetation in wetlands, by the digestive tracts of termites in the tropics, by the ocean, and by leakage from methane hydrate deposits. The principal anthropogenic sources are leakages from the production of fossil fuels, human-promoted anaerobic decay in landfills, and the digestive processes of domestic animals. Anthropogenic sources are estimated to be 60 percent of total methane emissions.[15] The main sources of absorption are thought to be tropospheric reactions with hydroxyl (OH) radicals that break down methane into the methyl radical CH_3 and water vapor (506 million metric tons), stratospheric reactions with hydroxyl radicals and chlorine (40 million metric tons), and decomposition by bacteria in soils (30 million metric tons). Known and unknown sources of methane are estimated to total 598 million metric tons annually; known sinks (i.e., absorption by natural processes) total about 576 million metric tons. The annual increase in methane concentration in the atmosphere accounts for the difference of 22 million metric tons.[16] The radiative forcing of methane is 0.48 watts per square meter, about one-third that of carbon dioxide.[17]

Nitrous Oxide. The sources and absorption of nitrous oxide are much more speculative than those for other greenhouse gases. The principal natural sources are thought to be bacterial breakdown of nitrogen compounds in soils, particularly forest soils, fluxes from ocean upwellings, and stratospheric photo dissociation and reaction with electronically excited oxygen atoms. The primary human-made sources are enhancement of natural processes through application of nitrogen fertilizers, combustion of fuels (in fossil-fueled power plants and from the catalytic converters in automobiles), certain industrial processes (nylon and nitric acid production), biomass burning, and cattle and feedlots. Worldwide, estimated known sources of nitrous oxide total 16.4 million metric tons annually (6.9 million metric tons from anthropogenic sources), and known sinks total 12.6 million metric tons. The annual increase in concentrations in the atmosphere is thought to total 3.8 million metric tons.[18] The radiative forcing of nitrous oxide is 0.15 watts per square meter, about one-tenth that of carbon dioxide.[19]

Halocarbons and Other Gases. During the 20th century, human ingenuity created an array of "engineered" chemicals, not normally found in nature, whose special characteristics render them particularly useful. One family of engineered gases is the halocarbons. A

---

[11] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 185.

[12] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 188, 191.

[13] Intergovernmental Panel on Climate Change, *Land Use, Land-Use Change, and Forestry. A Special Report to the IPCC* (Cambridge, UK: Cambridge University Press, 2000).

[14] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 208.

[15] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 248.

[16] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.2, p. 250.

[17] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), Table 6.1, p. 358.

[18] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.4, p. 252.

[19] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), Table 6.1, p. 358.

halocarbon is a compound containing either chlorine, bromine, or fluorine and carbon. Halocarbons are powerful greenhouse gases. Halocarbons that contain bromine or chlorine also deplete the Earth's ozone layer. One of the best-known groups of halocarbons is the chlorofluorocarbons (CFCs), particularly CFC-12, often known by its trade name, "Freon-12." CFCs have many desirable features: they are relatively simple to

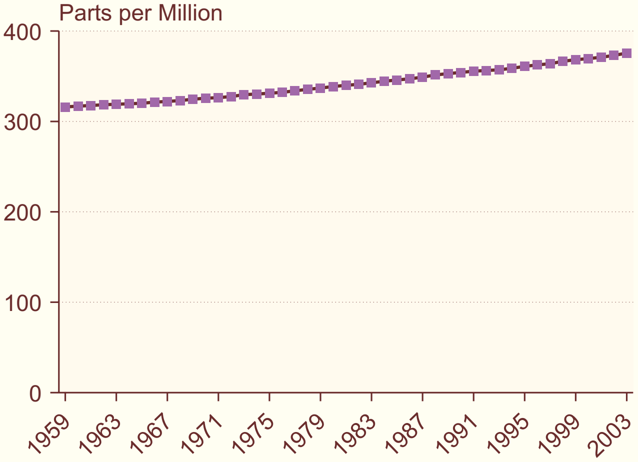
Yearly Changes in Atmospheric Carbon Dioxide Concentrations: The Mauna Loa Anomaly

Scientists at the Mauna Loa Observatory in Hawaii have been measuring atmospheric concentrations of carbon dioxide continuously since 1958. In the late 1950s their measurements showed average annual carbon dioxide concentrations below 320 parts per million (ppm). Since then, they have recorded steadily increasing concentrations, with no decrease in any year (see figure at right). By 2003, the average atmospheric concentration of carbon dioxide measured at Mauna Loa had increased to more than 375 ppm—an increase of nearly 19 percent since 1958.

From 1958 to 2001, the average annual rate of increase in carbon dioxide concentrations measured at Mauna Loa was 1.5 ppm, except for the years 1973, 1988, 1994, and 1998, in which there were El Niño events. (During an El Niño event, the warm ocean emits carbon dioxide rather than absorbing it.) In both 2002 and 2003, however, the observed annual increases exceeded 2 ppm (see figure below), even in the absence of El Niño events. The unexplained jump in the rate at which carbon dioxide concentrations increased in 2002 and 2003 is now widely referred to as the "Mauna Loa anomaly."

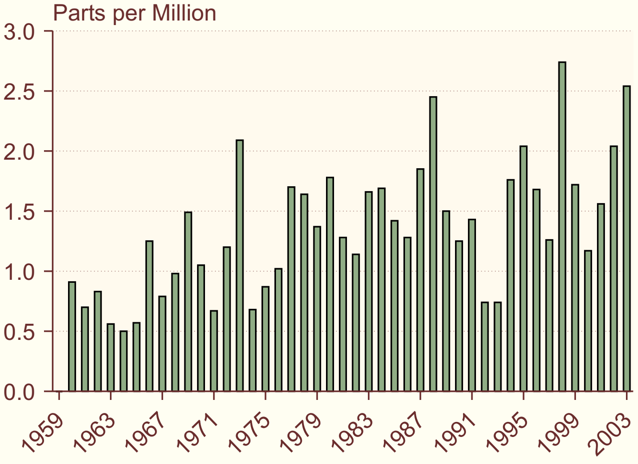
Some scientists have speculated that a greater number of forest fires in the northern hemisphere than is typical, along with unusually hot summer weather in Europe (which killed some vegetation and caused an incremental release of carbon from the soil) may have combined to increase global carbon dioxide concentrations in 2002 and 2003. Others have noted that atmospheric carbon dioxide concentrations in Australia and at the South Pole were slightly lower than normal in both years, indicating a regional rather than global increase. In any event, the chief concern raised by the Mauna Loa observations is that the accelerated growth of atmospheric concentrations could indicate a reduction in the Earth's capacity to absorb carbon dioxide. Scientists will watch this situation closely during the next several years to ascertain whether the Mauna Loa anomaly is merely a short-term deviation or an indication of a shift in global climate conditions, in which case computer models would have to be adjusted to reflect more rapid rates of increase in carbon dioxide concentrations in the future.

Annual Measurements of Atmospheric Carbon Dioxide Concentration at Mauna Loa, Hawaii, 1959-2003



Source: C.D. Keeling and T.P. Whorf, "Atmospheric Carbon Dioxide Record from Mauna Loa," web site http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm.

Annual Increases in Atmospheric Carbon Dioxide Concentration at Mauna Loa, Hawaii, 1960-2003



Source: C.D. Keeling and T.P. Whorf, "Atmospheric Carbon Dioxide Record from Mauna Loa," web site http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm.

Source: P. Brown, "Climate Fear as Carbon Levels Soar," *The Guardian* (October 12, 2004), web site www.guardian.co.uk/international/story/0,,1324276,00.html.

manufacture, inert, nontoxic, and nonflammable. Because CFCs are chemically stable, once emitted, they remain in the atmosphere for hundreds or thousands of years. Because they are not found in nature, these molecules absorb reflected infrared radiation at wavelengths that otherwise would be largely unabsorbed, and they are potent greenhouse gases, with direct global warming potentials hundreds or thousands of times greater, gram-per-gram, than that of carbon dioxide. However, because of their relatively small concentrations in the atmosphere, their current levels of radiative forcing are low (see page 11 for a discussion of global warming and radiative forcing).

Because of their long atmospheric lives, a portion of the CFCs emitted into the atmosphere eventually find their way into the stratosphere, where they can be destroyed by sunlight. This reaction, however, releases free chlorine atoms into the stratosphere, and the free chlorine atoms tend to combine with stratospheric ozone, which protects the surface of the Earth from certain wavelengths of potentially damaging solar ultraviolet radiation (ultraviolet radiation, for example, causes human and animal skin cancers).

The threat posed by CFCs to the ozone layer has caused the United States and many other countries to commit themselves to phasing out the production of CFCs and their chemical cousins, hydrochlorofluorocarbons (HCFCs), pursuant to an international treaty, the 1987 Montreal Protocol. As use of CFCs has declined, many related chemicals have emerged as alternatives, including HCFCs and hydrofluorocarbons (HFCs). HCFCs are similar to CFCs, but they are more reactive and consequently have shorter atmospheric lives, with less effect on the ozone layer and smaller direct global warming effects. HCFCs are also being phased out, but over a longer time scale. The ozone-depleting substances with the most potential to influence climate, CFC-11, CFC-12 and CFC-113, are beginning to show reduced growth rates in atmospheric concentrations in the aftermath of the Montreal Protocol. The present radiative forcing of CFC-11 is about 0.065 watts per square meter, and that of CFC-12 is around 0.2 watts per square meter.[20]

HFCs have no chlorine and consequently have no effect on the ozone layer, but they are powerful greenhouse gases. The three most prominent HFCs in the atmosphere today are HFC-23, HFC-134a, and HFC-152a. HFC-23 is formed as a byproduct of HCFC-22 production, which is being phased out under the Montreal Protocol. Although HFC-23 is very long-lived (260 years), the growth rate in its atmospheric concentration has begun to level off in accordance with reductions in HCFC-22 production. HFC-134a production was rare before 1990, but in 1994 HFC-134a was adopted as the standard motor vehicle air conditioning refrigerant in virtually all new cars made in America. HFC-134a has a lifetime of 13.8 years, and emissions have grown rapidly from near zero in 1990 to 0.034 million metric tons in 2002.[21] HFC-152a emissions have risen steadily since about 1995, but its short lifetime of 1.4 years has kept concentration levels below 1 part per trillion.

Another new class of engineered halocarbons is the perfluorocarbons (PFCs), which include perfluoromethane (CF_4) and perfluoroethane (C_2F_6). PFCs are emitted as byproducts of aluminum smelting and are increasingly being used in the manufacture of semiconductors. They are powerful greenhouse gases and extremely long-lived. Perfluoromethane has a 100-year global warming potential (GWP) of 5,700 and a lifetime in excess of 50,000 years. Perfluoroethane has a GWP of 11,900 and a lifetime of 10,000 years. Perfluoromethane is a naturally occurring compound in fluorites, and emissions from this source create a natural abundance of 40 parts per trillion in the atmosphere. Increases in anthropogenic emissions, growing at about 1.3 percent annually, have raised atmospheric concentrations to 80 parts per trillion.[22] Perfluoroethane does not occur naturally in the atmosphere, and current concentrations (3.0 parts per trillion) are attributable to anthropogenic emissions, which are growing by 3.2 percent annually. Sinks for PFCs are photolysis and ion reactions in the mesosphere.[23]

Sulfur hexafluoride (SF_6) is used as an insulator in large-scale electrical equipment and as a cover gas in magnesium smelting. It is not a halocarbon, but it is a powerful greenhouse gas. SF_6 has a 100-year GWP of 22,200 and a lifetime of 3,200 years. Like perfluoromethane, SF_6 occurs naturally in fluorites, which produce a natural abundance of 0.01 parts per trillion in the atmosphere. Current atmospheric concentrations (3.0 parts per trillion) can be traced to anthropogenic emissions, which grew by approximately 7 percent annually during the 1980s and 1990s. Also like PFCs, sinks for SF_6 are photolysis and ion reactions in the mesosphere.

---

[20] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Figures 4.6 and 4.7, p. 255.

[21] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254; and estimates presented in this report.

[22] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

[23] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

There may be other chemicals not yet identified that exhibit radiative properties similar to those of the halocarbons and other gases described above. One recent discovery identified trifluoromethyl sulfur pentafluoride (SF_5CF_3) as a new anthropogenic greenhouse gas in the atmosphere.[24] It is believed that SF_5CF_3 is created by the breakdown of SF_6 in high-voltage equipment, which produces CF_3 that reacts with SF_5 radicals resulting from high-voltage discharges. Its atmospheric concentration has grown from near zero in 1960 to 0.12 parts per trillion in 1999. To date, SF_5CF_3 has the largest radiative forcing on a per-molecule basis of any gas found in the atmosphere.[25] The UNFCCC does not yet specifically address this gas.

A number of chemical solvents are also strong greenhouse gases. The solvents carbon tetrachloride (GWP of 1,800 and lifetime of 35 years) and methyl chloroform (GWP of 140 and lifetime of 4.8 years), however, are regulated in the United States for the purposes of both ozone depletion and toxicity. All these gases have direct radiative forcing effects, which are offset to some degree by their ozone-depleting effects.

With the advent of the United Nations Framework Convention and the Kyoto Protocol, the halocarbon and other industrial chemicals can be grouped into two categories:

- Ozone-depleting chemicals regulated under the Montreal Protocol but excluded from the Framework Convention (CFCs, HCFCs, and others)
- "Kyoto gases" (HFCs, PFCs, and SF_6).

The "Kyoto gases" are deemed to "count" for the purposes of meeting national obligations under the Framework Convention. The ozone depleters, however, are excluded from the Framework Convention because they are regulated by the Montreal Protocol.

Other Important Radiative Gases. There are a number of additional gases and particles, resulting in part from human sources, that produce radiative forcing of the Earth's climate but are not included under the Framework Convention or the Montreal Protocol. In general, these gases are short-lived, they have only indirect climate effects, or there is a fair amount of uncertainty about their climatic impacts. They can be broken down into three general classes: (1) ozone, both tropospheric and stratospheric; (2) criteria pollutants that are indirect greenhouse gases; and (3) aerosols, including sulfates and black soot.

Ozone (O_3) is present in both the troposphere and the stratosphere. Tropospheric ozone is not directly emitted into the atmosphere but instead forms through the photochemical reactions of various ozone precursors (primarily, nitrogen oxides and volatile organic compounds). In the troposphere, ozone acts as a direct greenhouse gas. The lifetime of ozone in the atmosphere varies from weeks to months, which imparts an element of uncertainty in estimating tropospheric ozone's radiative forcing effects. The IPCC estimates that the radiative forcing of tropospheric ozone is 0.35 ± 0.2 watts per square meter.[26] The depletion of stratospheric ozone due to the emission of halocarbons, on the other hand, has tended to cool the planet. The IPCC estimates that the cooling due to stratospheric ozone depletion is on the order of -0.15 ± 0.1 watts per square meter.[27] As the ozone layer recovers, however, due to the impacts of the Montreal Protocol, it is expected that stratospheric ozone will exert a positive radiative forcing effect on the Earth's climate.

There are also a number of compounds (carbon monoxide, nitrogen oxides, and volatile organic compounds) that are indirect greenhouse gases. These gases are regulated in the United States pursuant to the Clean Air Act, and they are often referred to as "criteria pollutants." They are emitted primarily as byproducts of combustion (both of fossil fuels and of biomass), and they influence climate indirectly through the formation of ozone and their effects on the lifetime of methane emissions in the atmosphere. Carbon monoxide, through its effects on hydroxyl radicals, can help promote the abundance of methane in the atmosphere, as well as increase ozone formation. Some IPCC model calculations indicate that 100 metric tons of carbon monoxide emissions is equivalent to the emissions of about 5 metric tons of methane.[28]

Nitrogen oxides, including NO and NO_2, influence climate by their impacts on other greenhouse gases. Nitrogen oxides not only promote ozone formation, they also impact (negatively) methane and HFC concentrations in the atmosphere. The deposition of nitrogen oxides could

---

[24] W.T. Sturges et al., "A Potent Greenhouse Gas Identified in the Atmosphere: SF_5CF_3," *Science*, Vol. 289 (July 28, 2000), pp. 611-613.

[25] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

[26] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 43.

[27] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 43.

[28] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 44.

also reduce atmospheric carbon dioxide concentrations by fertilizing the biosphere.[29]

Volatile organic compounds (VOCs), although they have some short-lived direct radiative-forcing properties, primarily influence climate indirectly via their promotion of ozone formation and production of organic aerosols. The main sources of global VOC emissions are vegetation (primarily tropical) (377 million metric tons carbon equivalent), fossil fuels (161 million metric tons carbon equivalent), and biomass burning (33 million metric ton carbon equivalent).[30]

Aerosols, which are small airborne particles or droplets, also affect the Earth's climate. Aerosols have both direct effects, through their ability to absorb and scatter solar and thermal radiation, and indirect effects, through their ability to modify the physical properties and amount of clouds. In terms of climate change, the most prominent aerosols are sulfates, fossil fuel black carbon aerosols (sometimes called "black soot"), fossil fuel organic carbon aerosols, and biomass-burning aerosols.

One of the primary precursors of sulfates is sulfur dioxide (SO_2), which is emitted largely as a byproduct from the combustion of sulfur-containing fossil fuels, particularly coal. Sulfur dioxide reacts in the air to form sulfate compounds. The major source of anthropogenic black soot and organic carbon aerosols is the burning of fossil fuels, primarily coal and diesel fuels. Biomass-burning aerosols are formed by the incomplete combustion of forest products. The IPCC estimates the direct radiative forcing for aerosols as follows: sulfates, -0.4 watts per square meter; black soot, +0.2 watts per square meter; fossil fuel organic carbon, -0.1 watts per square meter; and biomass-burning aerosols, -0.2 watts per square meter.[31] Although the indirect climate effects of aerosols are uncertain, some preliminary evidence points to an indirect cooling effect due to cloud formation.[32]

Relative Forcing Effects of Various Gases

The ability of a greenhouse gas to affect global temperatures depends not only on its radiative or heat-trapping properties but also on its lifetime or stability in the atmosphere. Because the radiative properties and lifetimes of greenhouse gases vary greatly, comparable increases in the concentrations of different greenhouse gases can have vastly different heat-trapping effects. The cumulative effect (radiative forcing—measured in watts per square meter) can vary substantially from the marginal impact of a gas. For example, among the "Kyoto gases," carbon dioxide is the most prominent in terms of emissions, atmospheric concentration, and radiative forcing (1.46 watts per square meter), but it is among the least effective as a greenhouse gas in terms of the marginal impact of each additional gram of gas added to the atmosphere. Other compounds, on a gram-per-gram basis, appear to have much greater marginal effects.

There has been extensive study of the relative effectiveness of various greenhouse gases in trapping the Earth's heat. Such research has led to the development of the concept of a "global warming potential," or GWP. The GWP is intended to illustrate the relative impacts on global warming of an additional unit of a given gas relative to carbon dioxide over a specific time horizon. The IPCC has conducted an extensive research program aimed at summarizing the effects of various greenhouse gases through a set of GWPs. The results of that work were originally released in 1995 in an IPCC report, *Climate Change 1994*,[33] and subsequently updated in *Climate Change 1995*[34] and *Climate Change 2001*.[35] The box on page 12 provides details on the differences in emission calculations using the GWP values from the two assessments.

The calculation of a GWP is based on the radiative efficiency (heat-absorbing ability) of the gas relative to the radiative efficiency of the reference gas (carbon dioxide), as well as the removal process (or decay rate) for the gas relative to the reference gas over a specified time horizon. The IPCC, however, has pointed out that there are elements of uncertainty in calculating GWPs.[36] The uncertainty takes several forms:

- The radiative efficiencies of greenhouse gases do not necessarily stay constant over time (as calculated in

---

[29] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 44.

[30] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.7(a), p. 258.

[31] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 45.

[32] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 45.

[33] Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

[34] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

[35] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

[36] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 385-386.

Comparison of Global Warming Potentials from the IPCC's Second and Third Assessment Reports

Global warming potentials (GWPs) are used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative efficiency (heat-absorbing ability) of each gas relative to that of carbon dioxide (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO_2. The GWP provides a construct for converting emissions of various gases into a common measure, which allows climate analysts to aggregate the radiative impacts of various greenhouse gases into a uniform measure denominated in carbon or carbon dioxide equivalents. The table at the right compares the GWPs published in the Second and Third Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC).

In compiling its greenhouse gas emission estimates, EIA attempts to employ the most current data sources. For that reason, the GWP values from the IPCC's Third Assessment Report are used in this report. It is important to point out, however, that countries reporting to the United Nations Framework Convention on Climate Change (UNFCCC), including the United States, have been compiling estimates based on the GWPs from the IPCC's Second Assessment Report. The UNFCCC Guidelines on Reporting and Review, adopted before the publication of the Third Assessment Report, require emission estimates to be based on the GWPs in the IPCC Second Assessment Report. This will probably continue in the short term, until the UNFCCC reporting rules are changed. Following the current rules, the U.S. Environmental Protection Agency (EPA), which compiles the official U.S. emissions inventory for submission to the UNFCCC, intends to present estimates based on the GWPs published in the Second Assessment Report in its report, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*, scheduled for release in April 2005.

Comparison of 100-Year GWP Estimates from the IPCC's Second (1996) and Third (2001) Assessment Reports

Gas	1996 IPCC GWP	2001 IPCC GWP
Methane	21	23
Nitrous Oxide	310	296
HFC-23	11,700	12,000
HFC-125	2,800	3,400
HFC-134a	1,300	1,300
HFC-143a	3,800	4,300
HFC-152a	140	120
HFC-227ea	2,900	3,500
HFC-236fa	6,300	9,400
Perfluoromethane (CF_4)	6,500	5,700
Perfluoroethane (C_2F_6)	9,200	11,900
Sulfur Hexafluoride (SF_6)	23,900	22,200

Sources: UNFCCC, Second Assessment Report (1996) and Third Assessment Report (2001).

The table below shows U.S. carbon dioxide equivalent greenhouse gas emissions calculated using the IPCC's 1996 (Second Assessment Report) and 2001 (Third Assessment Report) GWPs. The estimate for total U.S. emissions in 2003 is 0.6 percent higher when the revised GWPs are used. The estimates for earlier years generally follow the same pattern. Therefore, trends in growth of greenhouse gas emissions are similar for both sets of GWP values. Using the 2001 GWPs, estimates of carbon dioxide equivalent methane emissions are 9.5 percent higher, and carbon-equivalent nitrous oxide emissions are 4.5 percent lower. Carbon dioxide equivalent emissions of HFCs, PFCs, and SF_6 are lower for some years and higher for others, depending on the relative shares of the three gases.

Gas	IPCC GWP		Annual GWP-Weighted Emissions (Million Metric Tons Carbon Dioxide Equivalent)								
			1990			2002			2003		
	1996	2001	1996 GWP	2001 GWP	Percent Difference	1996 GWP	2001 GWP	Percent Difference	1996 GWP	2001 GWP	Percent Difference
Carbon Dioxide	1	1	5,000	5,000	0.0	5,810	5,810	0.0	5,861	5,861	0.0
Methane	21	23	646	708	9.5	547	599	9.5	550	602	9.5
Nitrous Oxide	310	296	344	329	-4.5	338	323	-4.5	335	320	-4.5
HFCs, PFCs, and SF_6	M	M	92	89	-4.0	139	144	3.6	138	143	4.1
Total	—	—	**6,083**	**6,125**	**0.7**	**6,834**	**6,876**	**0.6**	**6,884**	**6,927**	**0.6**

M = mixture of gases.

Sources: Estimates provided in this report; and UNFCCC, Second Assessment Report (1996) and Third Assessment Report (2001).

GWPs), particularly if the abundance of a gas in the atmosphere increases. Each gas absorbs radiation in a particular set of wavelengths, or "window," in the spectrum. In some cases, where concentrations of the gas are low and no other gases block radiation in the same window, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, a larger and larger portion of the total light passing through the "window" will already have been captured, and the marginal effects of additional emissions will not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or carbon dioxide, tends to be less than that of a rare gas, such as sulfur hexafluoride. This "diminishing return" effect implies that increasing the concentration of a particular gas reduces the impact of additional quantities of that gas. Thus, the relative impacts of various gases will change as their relative concentrations in the atmosphere change.

- The lifetime of a greenhouse gas (used in GWP calculations), particularly carbon dioxide, is also subject to uncertainty. Various natural processes cause many greenhouse gases to decompose into other gases or to be absorbed by the ocean or ground. These processes can be summarized in terms of the "atmospheric lifetime" of a particular gas, or the period of time it would take for natural processes to remove a unit of emissions from the atmosphere. Some gases, such as CFCs, have very long atmospheric lifetimes, in the hundreds of years. Others, such as carbon monoxide, have lives measured in hours or days. Methane, which decays into carbon dioxide over a period of a few years, has a much larger short-run effect on global warming than does an equivalent amount of carbon dioxide; however, over longer and longer periods—from 10 years to 100 years to 500 years, for example—the differences between the GWPs of methane and carbon dioxide become less significant, because carbon dioxide has a longer atmospheric lifetime than methane.

Table 4 summarizes the consensus results of the most recent studies by scientists working on behalf of the IPCC, showing estimates of atmospheric lifetimes and global warming potentials across various time scales. For the purposes of calculating "CO_2 equivalent" units for this report, 100-year GWPs are used.

The GWPs discussed above are direct GWPs in that they consider only the direct impact of the emitted gas. The IPCC has also devoted effort to the study of indirect GWPs. Indirect GWPs are based on the climatic impacts of the atmospheric decomposition of a gas into other gases. A number of gases—including methane, carbon monoxide, halocarbons, and nitrogen oxides—are thought to have indirect climatic effects. Methane indirectly influences the climate through ozone formation and the production of carbon dioxide. Carbon monoxide can promote ozone formation and extend the lifetime of methane in the atmosphere, which results in a positive indirect GWP. Some CFCs and HCFCs produce an indirect cooling effect by removing ozone from the stratosphere. The indirect cooling effect leads to lower net

Table 4. Numerical Estimates of Global Warming Potentials Compared With Carbon Dioxide
(Kilogram of Gas per Kilogram of Carbon Dioxide)

Gas	Lifetime (Years)	Direct Effect for Time Horizons of		
		20 Years	100 Years	500 Years
Carbon Dioxide	5 – 200[a]	1	1	1
Methane	12	62	23	7
Nitrous Oxide	114	275	296	156
HFCs, PFCs, and Sulfur Hexafluoride				
HFC-23	260	9,400	12,000	10,000
HFC-125	29	5,900	3,400	1,100
HFC-134a	13.8	3,300	1,300	400
HFC-152a	1.4	410	120	37
HFC-227ea	33	5,600	3,500	1,100
Perfluoromethane (CF_4)	50,000	3,900	5,700	8,900
Perfluoroethane (C_2F_6)	10,000	8,000	11,900	18,000
Sulfur Hexafluoride (SF_6)	3,200	15,100	22,200	32,400

[a] No single lifetime can be defined for carbon dioxide due to different rates of uptake by different removal processes.

Note: The typical uncertainty for global warming potentials is estimated by the Intergovernmental Panel on Climate Change at ±35 percent.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 38 and 388-389.

GWPs in a number of cases, but in most cases their net GWPs are still positive. Nitrogen oxides promote the formation of tropospheric ozone and, thus, have a positive indirect GWP—on the order of 5 for surface emissions and 450 for aircraft emissions.[37]

Current U.S. Climate Change Initiatives

The Bush Administration is pursuing a broad range of strategies to address the issues of global climate change through the implementation of multiple new initiatives. Details of these initiatives were initially provided on February 14, 2002, when the President announced the Global Climate Change Initiative. This initiative sets a national goal for the United States to reduce its greenhouse gas intensity (total greenhouse gas emissions per unit of GDP) by 18 percent between 2002 and 2012 through voluntary measures (see box on page 15).

To meet this goal and encourage the development of strategies and technologies that can be used to limit greenhouse gas emissions both at home and abroad, the Administration has implemented a number of related initiatives, including the following:[38]

- **Climate Change Technology Program (CCTP)**: The CCTP is a multi-agency program to accelerate the development and deployment of key technologies that can achieve substantial greenhouse gas emissions reductions. CCTP includes climate change-related technology research, development, and deployment efforts as well as voluntary programs.
- **Climate Change Science Program (CCSP)**: The CCSP is a Federal, multi-agency research program to investigate natural and human-induced changes in the Earth's global environmental system; to monitor, understand, and predict global change; and to provide a sound scientific basis for national and international decisionmaking.
- **International Cooperation**: The United States is engaged in international efforts on climate change, both through multilateral and bilateral activities. Multilaterally, the United States is the largest funder of activities under the UNFCCC and the IPCC. Since June 2001, the United States has launched bilateral partnerships with numerous countries on issues ranging from climate change science to energy and sequestration technologies to policy approaches. As an example, a new international effort to curb methane emissions is detailed in the text box below. Bilateral partners of the United States include Australia, Brazil, Canada, China, Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama, the European Union, India, Italy, Japan, Mexico, New Zealand, Republic of Korea, the Russian Federation, and South Africa.
- **Near-Term Greenhouse Gas Reduction Initiatives:** The Federal Government administers a wide array of voluntary, regulatory, and incentive-based programs on energy efficiency, agricultural practices, and greenhouse gas reductions. Major initiatives announced by the Bush Administration include:
  - **Climate VISION Partnership:** In February 2003, President Bush announced that twelve major

The Methane to Markets Partnership

On July 28, 2004, President Bush announced the Methane to Markets Partnership. Under this program, developed countries, developing countries, and countries with economies in transition will collaborate to recover and cost-effectively use methane from landfills, coal mines, and the natural gas and petroleum systems that otherwise would have been emitted to the atmosphere. On November 16, 2004, representatives from Argentina, Australia, Brazil, China, Colombia, India, Italy, Japan, Mexico, Nigeria, Russia, Ukraine, and the United Kingdom, joined the United States in signing Terms of Reference that formally created the Partnership.

The United States intends to commit up to $53 million over the next 5 years to facilitate the development and implementation of methane projects in developing countries and countries with economies in transition. The EPA will have the lead U.S. role in the Partnership, coordinating efforts with the Department of State, DOE, the U.S. Agency for International Development and the U.S. Trade and Development Agency. According to the EPA, the Partnership has the potential to generate reductions of as much as 50 million metric tons of carbon equivalent annually through 2015, the equivalent of removing 33 million cars from the road for one year, or planting 55 million acres of trees. The energy embodied in the methane recovered, equal to about 500 billion cubic feet of natural gas, could heat approximately 7.2 million households for one year.

---

[37] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 387-390.

[38] See "White House Reviews Action on Global Climate Change," Office of the Press Secretary, The White House, updated by the Council on Environmental Quality (September 22, 2004), web site www.usembassy.org.uk/eande079.html.

Trends in U.S. Carbon Intensity and Total Greenhouse Gas Intensity

From 2002 to 2003, the greenhouse gas intensity of the U.S. economy fell from 684 to 668 metric tons per million 2000 dollars of GDP (2.3 percent), continuing a trend of decreases in both carbon intensity (see figure at right) and total greenhouse gas intensity. As shown in the table below, declines in carbon intensity by decade have ranged from a low of 3.3 percent in the 1960s to 25.9 percent in the 1980s. From 1990 to 2003, total U.S. greenhouse gas intensity fell by 22.3 percent, at an average rate of 1.9 percent per year.

Historical Growth Rates for U.S. Carbon Intensity

	Overall Change in Intensity (Percent)		Average Annual Change in Intensity (Percent)	
Decade	Carbon Dioxide	Total GHG	Carbon Dioxide	Total GHG
History				
1950-1960	-12.9	—	-1.4	—
1960-1970	-3.3	—	-0.3	—
1970-1980	-17.7	—	-1.9	—
1980-1990	-25.9	—	-2.7	—
1990-2000	-15.2	-17.9	-1.6	-1.9

Source: Energy Information Administration, *Annual Energy Review 2003*, DOE/EIA-0384(2003) (Washington, DC, September 2004), and estimates presented in Appendix B of this report.

The carbon intensity and greenhouse gas intensity of the U.S. economy move in lockstep, because carbon dioxide emissions make up most of the total for U.S. greenhouse gas emissions. Energy-related carbon dioxide emissions represent approximately 83 percent of total U.S. greenhouse gas emissions. As such, trends in energy-related carbon dioxide emissions have a significant impact on trends in total greenhouse gas emissions. Historical trends in U.S. carbon intensity (energy-related carbon dioxide emissions per unit of economic output) are described below.

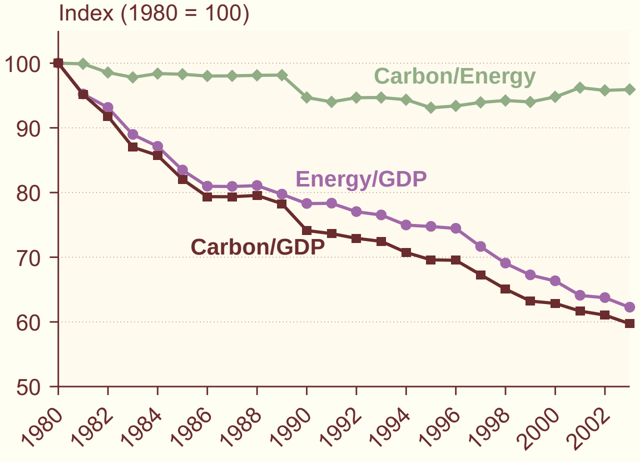
The carbon intensity of the economy can largely be decomposed into two basic elements: (1) energy intensity, defined as the amount of energy consumed per dollar of economic activity; and (2) carbon intensity of energy supply, defined as the amount of carbon emitted per unit of energy. As illustrated by the formulas below, the multiplication of the two elements produces a numerical value for U.S. carbon intensity, defined as the amount of carbon dioxide emitted per dollar of economic activity:

Energy Intensity x *Carbon Intensity of Energy Supply* =
Carbon Intensity of the Economy ,

or, algebraically,

(Energy/GDP) x *(Carbon Emissions/Energy)* =
(Carbon Emissions/GDP) .

Intensity Ratios: Carbon/GDP, Carbon/Energy, and Energy/GDP



Source: Estimates presented in Appendix B of this report.

Components of Energy Intensity. Since World War II the U.S. economy has been moving away from traditional "smokestack" industries towards more service-based or information-based enterprises. This has meant that over the second half of the 20th century economic growth was less tied to growth in energy demand than it was during the period of industrialization in the 19th and early 20th century. Other factors contributing to decreases in energy intensity include:

- Improvements in the energy efficiency of industrial equipment as new materials and methods improved performance in terms of energy inputs versus outputs
- Increased efficiency of transportation equipment as lighter materials and more efficient engines entered the marketplace
- Improvements in commercial and residential lighting, refrigeration, and heating and cooling equipment
- Developments in new electricity generating technologies, such as combined-cycle turbines.

Further reductions in energy intensity, which are projected to continue, will among other things promote deeper reductions in U.S. carbon intensity.

Components of the Carbon Intensity of Energy Supply. Changes in the carbon intensity of energy supply have been less dramatic than changes in energy intensity. There was a slow but steady decline from 1980 until about the mid-1990s, after which it has remained relatively unchanged. The primary reason

(continued on page 16)

Trends in U.S. Carbon Intensity and Total Greenhouse Gas Intensity (Continued)

for the decline has been the development of nuclear power, which is carbon-free and therefore weights the fuel mix toward lower carbon intensity. Other factors that can decrease the carbon intensity of the energy supply include:

- Development of new renewable resources, such as wind power, for electricity generation
- Substitution of natural gas for coal and oil in power generation
- Transportation fuels with a higher biogenic component, such as ethanol.

industrial sectors and the membership of the Business Roundtable had committed to work with the EPA and three Federal departments (Energy, Transportation, and Agriculture) to reduce greenhouse gas emissions in the next decade. Participating industries include electric utilities; petroleum refiners and natural gas producers; automobile, iron and steel, chemical and magnesium manufacturers; forest and paper producers; railroads; and the cement, mining, aluminum, lime, and semiconductor industries.

- **Climate Leaders:** Announced in February 2002, Climate Leaders is an EPA partnership encouraging individual companies to develop long-term, comprehensive climate change strategies. Under this program, partners set corporate-wide GHG reduction goals and inventory their emissions to measure progress. More than 50 major companies are now participating, including General Motors, Alcoa, BP, Pfizer, Staples, International Paper, IBM, Miller Brewing, Eastman Kodak, and Target.
- **Voluntary Greenhouse Gas Reporting Program:** Responding to President Bush's February 2002 Global Climate Change Initiative, the Secretaries of Energy, Commerce, and Agriculture, and the EPA Administrator provided the President with their initial recommendations for enhancing and improving the Department of Energy's (DOE's) greenhouse gas emissions reduction registry. The improvements are intended to enhance the accuracy, reliability, and verifiability of greenhouse gas reductions measurements. Revised guidelines were released for public comment in late 2003, and DOE held a public workshop in January 2004 to receive further input from the public and potential users of the program.

International Developments in Global Climate Change

The primary international agreement addressing climate change is the UNFCCC, which opened for signature at the "Earth Summit" in Rio de Janeiro, Brazil, in June 1992 and entered into force in March 1994.[39] The agreement currently has 185 signatories, including the United States. The objective of the Framework Convention is stated as follows:

> *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.*[40]

The Framework Convention divided its signatories into three groups: the countries listed in Annex I; Annex II, which comprises the Annex I countries minus the countries with economies in transition; and non-Annex I countries, which include countries that ratified or acceded to the UNFCCC but are not included in Annex I. The Annex I countries include the 24 original members of the Organization for Economic Cooperation and Development (OECD) (including the United States), the European Union, and 14 countries with economies in transition (Russia, Ukraine, and Eastern Europe).[41]

---

[39] The Framework Convention was "adopted" by a vote of the conference of the parties on May 9th, while the signatures and ratifications of member states flowed in over a period of years. The treaty "entered into force" in 1994. There is a discussion of the development of the Convention in D. Bodanzky, "Prologue to the Climate Convention," in I. Mintzer and J.A. Leonard (eds.), *Negotiating Climate Change: The Inside Story of the Rio Convention* (Cambridge, UK: Cambridge University Press, 1994), pp. 49-66.

[40] The official text of the Framework Convention can be found at web site www.unfccc.de/index.html.

[41] The Annex I nations include Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, European Community, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States of America. Turkey has not ratified the Framework Convention. Turkey will be placed in a different situation from that of other Annex I parties when it becomes a Party to the Convention. Kazakhstan has announced its intention to be bound by Annex I commitments, but is not formally classified as an Annex I party. Kazakhstan will, however, be considered an Annex I party when the Kyoto Protocol enters into force in February 2005.

The Convention requires all parties to undertake "policies and measures" to limit emissions of greenhouse gases, and to provide national inventories of emissions of greenhouse gases (Article 4.1a and b). Annex I parties are further required to take actions "with the aim of returning . . . to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases" (Article 4.2a and b). The signatories subsequently agreed that Annex I parties should provide annual inventories of greenhouse gas emissions.

The Kyoto Protocol

The Kyoto Protocol to the UNFCCC, negotiated in December 1997, is a set of quantified greenhouse gas emissions targets for Annex I countries, which collectively are about 5 percent lower than the 1990 emissions of those countries taken as a group.[42] Developing country signatories do not have quantified targets. Some of the key features of the Protocol are summarized below:

- **Differentiated Targets.** Each Annex I signatory has a "quantified emissions reduction limitation commitment," which limits the signatory to some fraction, ranging from 90 to 110 percent, of its 1990 greenhouse gas emissions.[43] Among other Annex I countries that have signed the Protocol, both the European Union (EU) and the individual members of the EU have signed and are responsible for meeting their commitments.
- **Commitment Period.** Each target is defined as the average of the signatory's emissions over the 5-year period 2008-2012, called "the commitment period."
- **Six Gases.** Participants are to limit their emissions of carbon dioxide, methane, nitrous oxide, HFCs, PFCs, and sulfur hexafluoride, weighted by the GWP of each gas. HFCs and PFCs are actually classes of gases with multiple members, but the term "six gases" has stuck. Participants may use 1995 as the baseline for HFCs, PFCs, and sulfur hexafluoride, instead of 1990.
- **Demonstrable Progress.** Annex I countries are required to have made "demonstrable progress" toward achieving their commitments by 2005.
- **Land Use and Forestry.** The Protocol includes complicated provisions on forestry, the implication being that some emissions and sequestration arising from changes in land use and forestry since 1990 can be counted against the target.
- **Flexibility Mechanisms.** The Protocol includes an array of methods by which Annex I countries can spread and reduce the cost of emissions limitations. The flexibility mechanisms include:
  - **Emissions Trading.** Annex I countries can transfer portions of their quotas to one another.
  - **Joint Implementation.** Annex I countries can undertake emissions reduction projects in other Annex I countries and receive a negotiated share of the emissions reductions generated by the projects.
  - **Joint Fulfillment.** Like-minded Annex I countries may band together to reallocate national targets within the group, so long as the collective target is met. The European Union has such an agreement, with a collective goal of achieving an 8-percent reduction below 1990 levels. Individual countries participating in the agreement have negotiated different percentage reduction goals.
  - **Clean Development Mechanism.** Annex I countries may undertake emissions reduction projects in non-Annex I countries and receive credits countable against national targets.
- **Entry into Force.** The Protocol enters into force 90 days after 55 countries and Annex I signatories with carbon dioxide emissions totaling 55 percent of total Annex I emissions in 1990 "have deposited their instruments of ratification, acceptance, approval, or accession." These conditions were set to be met in November 2004, following the Protocol's formal acceptance by the Russian Parliament and President Putin's signing of the ratifying legislation. Those actions bring the number of signatory countries to 118, representing 61.2 percent of total Annex I carbon dioxide emissions in 1990. The Protocol will enter into force in February 2005.

Under the U.S. Constitution, no international treaty (including the Kyoto Protocol) can be made binding on the United States without the "advice and consent" of the U.S. Senate, which requires a two-thirds vote of its members. Although the Clinton Administration negotiated and subsequently signed the Kyoto Protocol, it did not submit the treaty to the Senate for ratification. In 2001, President Bush stated that he did not intend to submit the Protocol to the Senate for ratification and that the United States would not agree to the Kyoto Protocol because "it exempts 80 percent of the world, including major population centers such as China and India, from compliance, and would cause serious harm to the U.S. economy."[44]

---

[42] The text of the Kyoto Protocol can also be found at web site www.unfccc.de/index.html.

[43] Several Eastern European states have been permitted to use emissions from the late 1980s, rather than 1990, as their baseline.

[44] Letter from President Bush to Senators Hagel, Helms, Craig, and Roberts, Office of the Press Secretary, The White House (March 13, 2001).

Beyond the Kyoto Protocol

Since the negotiation of the Kyoto Protocol in 1997, much of the work done at periodic meetings (usually annual) of the UNFCCC Conference of the Parties (COP) has been focused on filling in details related to the operation of the UNFCCC and the Protocol and their respective mechanisms. The Ninth Session of the Conference of the Parties (COP-9) was held in Milan, Italy, from December 1 to December 12, 2003.[45] Discussion continued on the Kyoto Protocol and the implementation of the UNFCCC. Although the Kyoto Protocol was not in force, some technical rules for the CDM were developed.

The most important decisions reached pertained to rules for carbon sink projects during the first commitment period. Two years before, at COP-7, parties agreed that afforestation and reforestation projects would be allowed under the CDM, but did not establish detailed rules for these projects. At COP-9, however, procedures were addressed in more detail. The difficulty with establishing rules for afforestation and reforestation projects is that forests are non-permanent. Prior to COP-9, parties had not decided who should be liable if a sink begins releasing its sequestered carbon dioxide into the atmosphere—the project developer, the host country, or the holder of emissions reductions credits for that project. At COP-9, parties decided to create temporary emissions reductions credits that are valid for only one commitment period, as well as long-term emissions reductions credits that can be renewed for 20-year periods. This accounting system assigns responsibility for maintaining sinks to the holder of emissions reductions credits and ensures that holders take credit only for current emission reductions.

COP-10, which is being held in Buenos Aires, Argentina, from December 6 through December 17, 2004, marks the 10th anniversary of the entry into force of the Framework Convention on Climate Change, which is a central theme for the meeting. In addition to the accomplishments of the past 10 years and future challenges, discussions at COP-10 highlight a range of climate-related issues, including the impacts of climate change and adaptation measures, mitigation policies and their impacts, and technology. Participants are also considering the entry into force of the Kyoto Protocol, which has been enabled by Russia’s recent ratification.

---

[45] Earlier COP sessions are described in previous editions of this report.

2. Carbon Dioxide Emissions

Overview

U.S. Anthropogenic Carbon Dioxide Emissions, 1990-2003

	Carbon Dioxide	Carbon Equivalent
Estimated 2003 Emissions (Million Metric Tons)	5,870.2	1,601.0
Change Compared to 2002 (Million Metric Tons)	45.5	12.4
Change from 2002 *(Percent)*	*0.8%*	*0.8%*
Change Compared to 1990 (Million Metric Tons)	880.1	240.0
Change from 1990 *(Percent)*	*17.6%*	*17.6%*
Average Annual Increase, 1990-2003 *(Percent)*	*1.3%*	*1.3%*

Total emissions of carbon dioxide in the United States and its territories were 5,870.2 million metric tons in 2003, 45.5 million metric tons (0.8 percent) more than the 2002 total (Table 5). The increase in emissions from 2002 to 2003 can be attributed in large part to an increase in overall U.S. economic growth in 2003, and colder winter weather that increased the demand for heating fuels. The increase in emissions from 2002 to 2003 followed the same percentage increase of 0.8 percent, or 47.8 million metric tons, from 2001 to 2002 (Figure 1). Since 1990, total U.S. carbon dioxide emissions have increased by an average of about 1.3 percent per year.

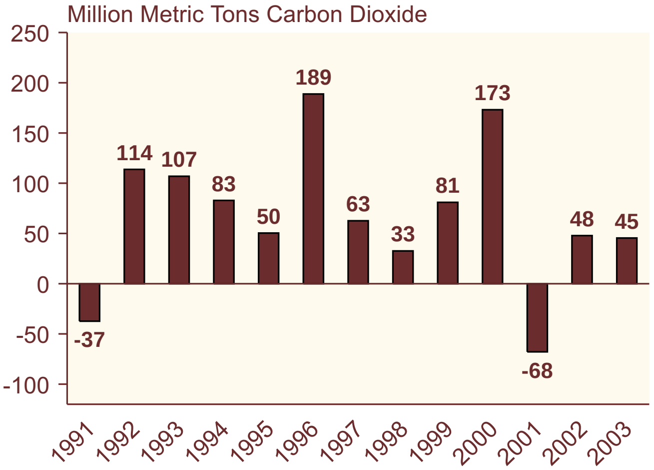
In the United States, most carbon dioxide (98 percent) is emitted as the result of the combustion of fossil fuels; consequently, carbon dioxide emissions and energy use are highly correlated. Historically, economic growth, the weather, the carbon and energy intensity of the economy, and movements in energy prices have caused year-to-year fluctuations in energy consumption and resulting carbon dioxide emissions. Annual economic growth in 2003 (3.0 percent) was higher than in 2002 (1.9 percent). In addition, there was a colder winter in 2003 than in 2002, with heating degree-days up 4 percent. The colder winter led to increased demand for heating fuels, such as natural gas and distillate fuel.

The increased demand for natural gas as a heating fuel can be seen in the residential and commercial sectors (Tables 7 and 8), where energy consumption is dominated by electricity use for air conditioning during the summer and fuel use for heating during the winter. In the residential sector (Table 7), emissions of carbon dioxide increased by 1.7 percent, from 1,193.9 million metric tons of carbon dioxide in 2002 to 1,214.8 million metric tons in 2003. In the commercial sector (Table 8), carbon dioxide emissions increased by 0.6 percent (from 1,019.8 million metric tons in 2002 to 1,025.7 million metric tons in 2003).

Industrial production rose by 0.2 percent in 2003, although industrial emissions of carbon dioxide fell by 0.3 percent, from 1,671.5 million metric tons in 2002 to 1,666.2 million metric tons in 2003 (Table 9). Trends in industrial emissions are driven in part by growth patterns in the six most energy-intensive manufacturing industries, which account for about two-thirds of total industrial emissions of carbon dioxide. In 2003, three of those manufacturing industries (primary metals, food, and chemicals) had declines in output compared with 2002 (2.3 percent, 3.6 percent, and 1.5 percent, respectively). Output from the three other energy-intensive industries increased: paper by 5.1 percent, nonmetallic minerals by 0.9 percent, and petroleum refining by 1.5 percent.

Estimates for 2003 indicate that carbon dioxide emissions in the transportation sector (Table 10) increased by

Figure 1. Annual Change in U.S. Carbon Dioxide Emissions, 1990-2003



Source: Estimates presented in this chapter.

0.5 percent, from 1,866.0 million metric tons in 2002 to 1,874.7 million metric tons in 2003. This is the lowest growth rate in transportation-sector emissions of carbon dioxide during the 1990 to 2003 time period, except for 1991 and 2001 when those emissions actually declined.

Net generation of electricity increased by 0.6 percent from 2002 to 2003, although carbon dioxide emissions from the electric power sector increased by 1.0 percent, from 2,256.4 million metric tons in 2002 to 2,279.3 million metric tons in 2003 (Table 11). Accordingly, the overall carbon intensity of U.S. electricity production rose by 0.4 percent. The rise in carbon intensity was driven by the increased utilization of coal as a fuel to generate electricity, and coal has a higher carbon content than the natural gas fuel it displaced. This displacement of natural gas by coal can be attributed to the increased price of natural gas compared with the price of coal.

In this report, the electric power sector is defined as all utilities, nonutilities, and combined heat and power (CHP) facilities whose primary business is the production of electric power. Carbon dioxide emissions from generators that produce electric power as part of an industrial or commercial operation—that is, businesses that produce electricity primarily for their own use—are not included in the electric power sector total but are assigned to the industrial or commercial sector according to the classification of the business. In addition, the emissions totals reported above for the energy end-use sectors (residential, commercial, industrial, and transportation) include their shares of total electric power sector emissions.

Nonfuel uses of fossil fuels, principally petroleum, resulted in carbon sequestration equal to 298.2 million metric tons carbon dioxide equivalent in 2003, about the same as 2002 (Table 12).[46] The major fossil fuel products that sequester carbon include liquefied petroleum gas (LPG), feedstocks for plastics and other petrochemicals, and asphalt and road oils. It is estimated that, of the amount of carbon dioxide sequestered in the form of plastic, about 18.8 million metric tons was emitted as carbon dioxide from the burning of the plastic components of municipal solid waste to produce electricity as well as other waste burning in 2002. The 2002 estimate of 18.8 million metric tons is used in this report as an estimate for 2003 emissions of carbon dioxide from the burning of wastes. Emissions of carbon dioxide from other sources—including cement production, industrial processes, waste combustion, carbon dioxide in natural gas, and gas flaring—increased by 0.5 percent, from 109.6 million metric tons in 2002 to 110.2 million metric tons in 2003 (Table 5).

Energy Consumption

Energy End-Use Sector Sources of U.S. Carbon Dioxide Emissions, 1990-2003

	Million Metric Tons Carbon Dioxide		*Percent Change*	
Sector	1990	2003	1990-2003	2002-2003
Residential	948.3	1,214.8	*28.1%*	*1.7%*
Commercial	777.2	1,025.7	*32.0%*	*0.6%*
Industrial	1,686.9	1,666.2	*-1.2%*	*-0.3%*
Transportation	1,569.5	1,874.7	*19.4%*	*0.5%*

Note: Electric power sector emissions are distributed across sectors.

The consumption of energy in the form of fossil fuel combustion is the largest single contributor to greenhouse gas emissions in the United States and the world. Of total 2003 U.S. carbon dioxide emissions (adjusting for U.S. Territories and bunker fuels), 98.0 percent, or 5,760.1 million metric tons of carbon dioxide, resulted from the combustion of fossil fuels. This figure represents an increase of 0.8 percent from 2002 levels. In the short term, year-to-year changes in energy consumption and carbon dioxide emissions tend to be dominated by weather, economic fluctuations, and movements in energy prices. Over longer time spans, changes in energy consumption and emissions are influenced by other factors such as population shifts and energy consumers' choice of fuels, appliances, and capital equipment (e.g., vehicles, aircraft, and industrial plant and equipment). The energy-consuming capital stock of the United States—cars and trucks, airplanes, heating and cooling plants in homes and businesses, steel mills, aluminum smelters, cement plants, and petroleum refineries—changes slowly from one year to the next, because capital stock usually is retired only when it begins to break down or becomes obsolete.

EIA divides energy consumption into four general end-use categories: residential, commercial, industrial, and transportation. Emissions from electricity generators, which provide electricity to the end-use sectors, are allocated in proportion to the electricity consumed in, and losses allocated to, each sector (Table 6).

---

[46] Unlike emissions of carbon that occur in the form of carbon dioxide, carbon is sequestered in combination with other chemicals. Therefore, carbon sequestration is estimated in carbon dioxide equivalent units, rather than simply as carbon dioxide.

Residential Sector

At 1,214.8 million metric tons, residential carbon dioxide emissions represented 21.0 percent of U.S. energy-related carbon dioxide emissions in 2003. The residential sector's pro-rated share of electric power sector emissions accounts for more than two-thirds of that amount (833.5 million metric tons).[47] Natural gas accounted for 22.8 percent (276.8 million metric tons) and petroleum (mainly distillate fuel oil) represented 8.5 percent (103.3 million metric tons). Since 1990, residential electricity-related emissions have grown by 2.4 percent annually. In contrast, emissions from the direct combustion of fuels, primarily natural gas, have grown by 0.9 percent annually since 1990.

Total carbon dioxide emissions from the residential sector increased by 1.7 percent in 2003 (Table 7). Year-to-year, residential sector emissions are strongly influenced by weather. For example, in 1996, a relatively cold year, carbon dioxide emissions from the residential sector grew by 5.8 percent relative to 1995. In 1997, emissions declined by 0.8 percent due to warmer winter weather. The colder winter in 2003, relative to 2002, was a contributor to the 2003 increase in residential sector emissions. Additionally, the housing stock in the United States increased by 1.1 percent in 2003, contributing further impetus to the demand for residential fuels and the associated emissions of carbon dioxide.[48]

Since 1990, the growth in carbon dioxide emissions attributable to the residential sector has averaged 1.9 percent per year. Residential sector emissions in 2003 were 266.5 million metric tons higher than in 1990, representing 33.3 percent of the total increase in U.S. energy-related carbon dioxide emissions since 1990. Long-term trends in residential carbon dioxide emissions are strongly influenced by demographic factors, living space attributes, and building shell and appliance efficiency choices. For example, the movement of population into warmer climates tends to increase summer air conditioning consumption and promote the use of electric heat pumps, which increases emissions from electricity use (although the increase could be offset by a reduction in emissions from heating fuel combustion). Growth in the number of households, resulting from increasing population and immigration, contributes to more residential energy consumption.

Commercial Sector

Commercial sector carbon dioxide emissions, at 1,025.7 million metric tons, accounted for about 17.7 percent of total energy-related carbon dioxide emissions in 2003, of which 77.7 percent (796.7 million metric tons) is the sector's pro-rated share of electricity-related emissions. Natural gas contributes 16.6 percent and petroleum 4.8 percent of the sector's emissions. Commercial sector emissions largely have their origin in the lighting, space heating, and space cooling requirements of commercial structures such as office buildings, shopping malls, schools, hospitals, and restaurants. Lighting is a significantly more important component of energy demand in the commercial sector (approximately 21 percent of total demand in 2002) than it is in the residential sector (approximately 12 percent of total demand in 2002). Heating and cooling demand accounted for approximately 41 percent of energy demand in the residential sector in 2002, and about 21 percent in the commercial sector.[49] Thus, commercial sector emissions are affected less by the weather than residential sector emissions. In the longer run, because commercial activity is a factor of the larger economy, emissions from the commercial sector are more affected by economic trends and less affected by population growth than are emissions from the residential sector.

Emissions attributable to the commercial sector's pro-rated share of electricity consumption increased by 0.4 percent in 2003, and emissions from the direct combustion of fuels (dominated by natural gas, as in the residential sector) increased by 1.3 percent. Overall, carbon dioxide emissions related to commercial sector activity increased by 0.6 percent—from 1,019.8 to 1,025.7 million metric tons—between 2002 and 2003 (Table 8). Since 1990, commercial emissions growth has averaged 2.2 percent per year, the largest growth of any end-use sector. Commercial sector carbon dioxide emissions have risen by 248.5 million metric tons since 1990, accounting for 31.1 percent of the total increase in U.S. energy-related carbon dioxide emissions.

---

[47] Sectoral (residential, commercial, and industrial) energy-related carbon dioxide emissions include the share of total electric power sector carbon dioxide emissions that can be attributed to each end-use sector. The share is based on the percentage of total electricity sales purchased by the sector and losses attributed to the sector. (For values used to calculate sectoral shares, see Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035, Tables 2.2, 2.3, 2.4, and 2.5, web site www.eia.doe.gov/emeu/mer/consump.html.) All carbon dioxide emissions associated with industrial or commercial enterprises whose primary business is not the production of electricity are allocated to the sectors in which they occur.

[48] Energy Information Administration, *Short-Term Energy Outlook* (Washington, DC, July 2004), Appendix A, Table A2, p. 2, web site www.eia.doe.gov/emeu/steo/pub/pdf/a2tab.pdf.

[49] Energy Information Administration, *Annual Energy Outlook 2004 with Projections to 2025*, DOE/EIA-0383(2004) (Washington, DC, January 2004), Tables A4 and A5, Figures 50 and 53, web site www.eia.doe.gov/oiaf/aeo/excel/figure50_data.xls, and web site www.eia.doe.gov/oiaf/aeo/excel/figure53_data.xls.

Industrial Sector

Industrial sector emissions, at 1,666.2 million metric tons of carbon dioxide, accounted for 28.8 percent of total U.S. energy-related carbon dioxide emissions in 2003. In terms of fuel shares, electricity consumption was responsible for 38.7 percent of total industrial sector emissions (645.6 million metric tons), petroleum for 24.8 percent (413.2 million metric tons), natural gas for 25.3 percent (421.3 million metric tons), and coal for 10.8 percent (180.3 million metric tons).

Estimated 2003 energy-related carbon dioxide emissions in the industrial sector, at 1,666.2 million metric tons (Table 9), were 0.3 percent lower than the 2002 emissions level of 1,671.5 million metric tons. Carbon dioxide emissions attributable to industrial sector energy consumption have declined by an average of 0.1 percent per year since 1990. As a result, total energy-related industrial emissions in 2003 were 1.2 percent (20.7 million metric tons) lower than in 1990, despite a much larger economy.

A contributing factor to the decline in industrial sector carbon dioxide emissions is the erosion of the older energy-intensive (and specifically coal-intensive) industrial base. For example, coke plants consumed 38.9 million short tons of coal in 1990, as compared with 24.2 million short tons in 2003. Other industrial coal consumption declined from 76.3 million short tons in 1990 to 61.2 million short tons in 2003. Energy-intensive industries have been replaced by others that are less energy-intensive, such as computer chip and electronic component manufacturing.

Transportation Sector

Carbon dioxide emissions from the transportation sector, at 1,874.7 million metric tons, accounted for 32.4 percent of total U.S. energy-related carbon dioxide emissions in 2003. Almost all (97.9 percent) of transportation sector emissions result from the consumption of petroleum products: motor gasoline, at 61.0 percent of total transportation sector emissions; middle distillates (diesel fuel) at 21.6 percent; jet fuel at 12.2 percent of the total; and residual oil (i.e., heavy fuel oil, largely for maritime use) at 2.7 percent of the sector's total emissions. Motor gasoline is used primarily in automobiles and light trucks, and middle distillates are used in heavy trucks, locomotives, and ships.

Emissions attributable to the transportation sector increased by 0.5 percent in 2003, from 1,866.0 to 1,874.7 million metric tons of carbon dioxide (Table 10). The fuel-use patterns and related emissions sources in the transportation sector are different from those in the other end-use sectors. By far the largest single source of emissions, motor gasoline, at 1,143.7 million metric tons of carbon dioxide, grew by 0.4 percent. Emissions from motor gasoline were mitigated somewhat by a 35-percent increase in the consumption of ethanol. Carbon dioxide emissions from ethanol consumption are considered to be zero because the carbon in the fuel is derived primarily from corn, and it is assumed that an equivalent amount of carbon will be sequestered during the corn growing season.

Since 1990, carbon dioxide emissions related to the transportation sector have increased at an average annual rate of 1.4 percent. The growth since 1990 has meant that transportation emissions have increased by a total of 296.4 million metric tons, representing 37.1 percent of the growth in energy-related carbon dioxide emissions from all sectors. Transportation is the largest contributing end-use sector to total emissions.

Electric Power Sector

Electric Power Sector Carbon Dioxide Emissions by Fuel Input, 1990-2003

Fuel	Million Metric Tons Carbon Dioxide 1990	2003	*Percent Change* 1990-2003	2002-2003
Petroleum	102.1	96.5	*-5.5%*	*25.8%*
Natural Gas	175.3	275.3	*57.1%*	*-10.1%*
Coal	1,507.1	1,904.3	*26.4%*	*1.8%*
Total	1,787.9	2,279.3	*27.5%*	*1.0%*

The data in Table 11 represent estimates of carbon dioxide emissions for the electric power sector. These emissions when taken as a whole account for 39.4 percent of total U.S. energy-related carbon dioxide emissions; electric power sector emissions are distributed to the end-use sectors. The electric power sector includes traditional regulated utilities, as well as independent power producers whose primary business is the generation and sale of electricity. The industrial sector and, to a much lesser extent, the commercial sector also include establishments that generate electricity; however, their primary business is not electricity generation, and so their electricity-related emissions are included in the totals for those sectors, not in the electric power sector.

Preliminary estimates indicate that carbon dioxide emissions from the electric power sector increased by 1.0 percent (22.9 million metric tons), from 2,256.4 million metric tons in 2002 to 2,279.3 million metric tons in 2003 (Table 11). Emissions from natural-gas-fired generation decreased by 10.1 percent, emissions from coal-fired

Energy-Related Carbon Dioxide Emissions in Manufacturing

Manufacturing is the single largest source of energy-related carbon dioxide emissions in the U.S. industrial sector, which also includes agriculture, forestry, and fisheries; mining; and construction. The manufacturing subsector accounted for about 83 percent of both energy-related carbon dioxide emissions and energy consumption in the industrial sector in 1998. The table below shows estimates of energy-related carbon dioxide emissions from manufacturing in 1998, based on energy consumption statistics from EIA's Manufacturing Energy Consumption Survey (MECS), which surveys more than 15,000 manufacturing plants every 4 years. The most recent MECS data available are from the 1998 survey. The table on page 24 shows estimates of manufacturing emissions by fuel, based on statistics from the 1991, 1994, and 1998 surveys.

The 1991 MECS reported energy consumption (for fuel and nonfuel purposes) that yielded carbon dioxide emissions from the manufacturing subsector as a whole totaling 1,251.4 million metric tons. The corresponding estimate for 1998 is 1,485.8 million metric tons—an increase of 234.4 million metric tons or 18.7 percent. Over the same interval, the demand for manufacturing products (as measured by the value of shipments) increased by 36.4 percent. Therefore, the overall carbon intensity of U.S. manufacturing, measured as metric tons of carbon dioxide emitted per million 1996 dollars of product shipments, was 408.8 in 1991 but had dropped to 356.0 by 1998, a decrease of 12.9 percent.

The *overall carbon intensity* of the U.S. manufacturing subsector is the ratio of its total carbon dioxide emissions (C) to manufacturing output (Y), as measured by the value of shipments (in constant dollars). That ratio (C/Y) is calculated as the product of the subsector's aggregate *carbon intensity of energy supply*—carbon dioxide emissions (C) per unit of energy consumed (E)—and its *energy intensity*—energy consumed (E) per unit of product shipped (Y). That is:

$$C/Y = (C/E) \times (E/Y) \quad .$$

For the manufacturing subsector as a whole, energy intensity (the ratio E/Y) is a function primarily of the energy intensities of different production groups and their contributions to the total product mix in the subsector. The subsector's carbon intensity of energy supply (the ratio C/E) is determined primarily by the mix of energy fuel inputs and the mix of fuel and nonfuel (sequestering) uses of the inputs. Thus, the overall carbon intensity of manufacturing (C/Y) is a combination of the energy intensity of manufacturing output and the carbon intensity of the energy consumed to meet manufacturing energy demand.[a]

The manufacturing C/Y ratio fell by 12.9 percent from 1991 to 1998; however, the reduction was largely the result of a structural shift (i.e., a change in relative market shares in the subsector). The energy intensity for the "all other manufacturing" category declined by 12 percent, and at the same time its share of total manufacturing output grew from 57.2 percent in 1991 to 63.4 percent in 1998, as newer, less energy-intensive industries accounted for an increasing share of manufacturing activity. In 1991 the four most energy-intensive industries (petroleum, chemicals, primary metals, and paper) accounted for 26.3 percent of total manufacturing output, but by 1998 their share had

(continued on page 24)

Carbon Dioxide Emissions from Manufacturing by Industry Group, 1998

Industry Group	SIC[a] Code	Carbon Dioxide Emissions (Million Metric Tons)	Share of Total Manufacturing Emissions (Percent)	Carbon Intensity of Energy Supply (Million Metric Tons per Quadrillion Btu of Energy Consumed)
Petroleum	29	320.4	21.6	45.26
Chemicals. . . .	28	319.2	21.5	45.84
Metals.	33	251.0	16.9	68.17
Paper	26	118.4	8.0	37.40
Food	20	90.4	6.1	59.05
Glass	32	82.9	5.6	67.76
Other Manufacturing . . .		303.6	20.4	55.20
Total		**1,485.8**	**100.0**	**50.91**

[a]Standard Industrial Classification.

Sources: Energy Information Administration, Form EIA-846, "Manufacturing Energy Consumption Survey," and Form EIA-810, "Monthly Refinery Report" (1998).

---

[a] The ratios presented here are estimated as aggregations of several manufacturing industries. Specifically, 20 manufacturing industries were aggregated into 7 groups for the calculation of industry-specific E/Y and C/Y ratios. Therefore, quantifying influences on the change in overall carbon intensity is valuable to the extent that these groupings represent changes in the U.S. manufacturing sector. It should be noted, however, that these ratios are based on survey data that are subject to sampling errors.

Energy-Related Carbon Dioxide Emissions in Manufacturing (Continued)

Carbon Dioxide Emissions from Manufacturing by Fuel, 1991, 1994, and 1998

	SIC[a] Code						Other	
Fuel Type	**29**	**28**	**33**	**26**	**20**	**32**	**Mfg.**	**Total**
1991								
CO_2 Emissions (Million Metric Tons)								
Petroleum	149.9	42.1	3.4	13.6	3.7	6.4	10.4	**229.6**
Natural Gas	44.2	102.3	37.4	29.1	27.0	20.1	46.4	**306.6**
Coal	1.4	25.2	83.2	28.3	14.4	27.9	12.8	**193.2**
Electricity	19.8	83.1	94.3	38.0	31.9	19.8	160.8	**447.8**
Other	61.0	9.7	3.0	0.2	0.0	0.0	0.5	**74.3**
Total	**276.3**	**262.4**	**221.3**	**109.2**	**77.0**	**74.3**	**230.8**	**1,251.4**
Share of Total Value of Shipments (Percent)	5.5	11.1	4.9	4.9	14.2	2.2	57.2	**100.0**
Share of Total Energy Use (Percent)	24.8	23.3	13.2	11.9	5.3	4.5	17.0	**100.0**
Share of Total CO_2 Emissions (Percent)	22.1	21.0	17.7	8.7	6.2	5.9	18.4	**100.0**
1994								
CO_2 Emissions (Million Metric Tons)								
Petroleum	174.8	42.3	4.9	15.7	4.3	7.4	10.1	**259.4**
Natural Gas	42.8	117.7	42.8	30.4	33.3	22.8	53.1	**343.0**
Coal	0.0	28.5	96.1	28.6	15.6	26.4	12.9	**208.2**
Electricity	21.9	94.1	89.2	40.4	35.8	22.3	177.0	**480.6**
Other	60.6	4.4	3.5	1.1	0.4	0.2	1.6	**71.8**
Total	**300.1**	**287.1**	**236.5**	**116.0**	**89.4**	**79.1**	**254.6**	**1,363.0**
Share of Total Value of Shipments (Percent)	4.9	10.4	5.0	4.7	13.3	2.2	59.6	**100.0**
Share of Total Energy Use (Percent)	24.4	23.6	12.8	11.5	5.9	4.4	17.4	**100.0**
Share of Total CO_2 Emissions (Percent)	22.0	21.1	17.4	8.5	6.6	5.8	18.7	**100.0**
1998								
CO_2 Emissions (Million Metric Tons)								
Petroleum	174.8	56.5	3.6	15.1	3.0	6.7	10.4	**270.1**
Natural Gas	53.2	127.7	47.9	31.1	31.8	23.4	59.7	**374.9**
Coal	0.0	26.9	94.3	25.8	13.6	27.7	10.0	**198.3**
Electricity	22.9	103.2	101.8	45.6	41.8	24.4	221.9	**561.6**
Other	69.5	4.9	3.4	0.8	0.1	0.7	1.5	**80.9**
Total	**320.4**	**319.2**	**251.0**	**118.4**	**90.4**	**82.9**	**303.6**	**1,485.8**
Share of Total Value of Shipments (Percent)	4.3	9.6	4.6	4.0	11.9	2.2	63.4	**100.0**
Share of Total Energy Use (Percent)	25.2	24.0	12.2	10.8	5.2	4.1	18.4	**100.0**
Share of Total CO_2 Emissions (Percent)	21.6	21.5	16.9	8.0	6.1	5.6	20.4	**100.0**

[a] Standard Industrial Classification: 29, petroleum; 28, chemicals; 33, metals; 26, paper; 20, food; 32, glass.

Notes: Totals may not equal sum of components due to independent rounding. To calculate intensity and consumption values, electricity was calculated as primary electricity: 10,436 Btu per kilowatthour for 1991, 10,316 for 1994, and 10,346 for 1998. These conversion factors represent the average energy input to the generation process for fossil-fired utility plants in the United States. See Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(2002/09) (Washington, DC, September 2002), Table A6.

Sources: Energy Information Administration, Form EIA-846, “Manufacturing Energy Consumption Survey,” and Form EIA-810, “Monthly Refinery Report” (1991, 1994, and 1998); and U.S. Department of Commerce, Bureau of Economic Analysis, Industry Economics Division.

(continued on page 25)

Energy-Related Carbon Dioxide Emissions in Manufacturing (Continued)

fallen to 22.5 percent. For three of the seven manufacturing categories, energy intensity increased from 1991 to 1998 (petroleum by 15.3 percent, chemicals 7.4 percent, and food 5.7 percent). For paper and allied products, energy intensity remained unchanged. For nonmetallic minerals (stone, clay, and glass products) and for primary metals, energy intensity declined by 15.8 percent and 12.8 percent, respectively.

The mix and quantity of energy fuels consumed by manufacturers (for both fuel and nonfuel uses) affect the subsector's aggregate carbon intensity of energy supply. Overall, manufacturing industries had *C/E* ratios equal to 50.92 million metric tons carbon dioxide equivalent per quadrillion Btu in 1991 and 49.42 million metric tons carbon dioxide equivalent per quadrillion Btu in 1998; however, the carbon dioxide factors of the various industries differed markedly.[b]

The petroleum and chemical industries both transform some energy products into products that sequester carbon, such as petrochemical feedstocks, asphalt, and plastics. Because of that use, both the petroleum and chemical industries have lower aggregate *C/E* ratios than the manufacturing average (45.27 and 42.32 million metric tons carbon dioxide equivalent per quadrillion Btu for the petroleum industry and 45.84 and 44.26 for the chemicals industry in 1991 and 1998, respectively).

The paper industry makes extensive use of wood byproducts as an energy source. Carbon dioxide emissions from wood consumption are considered to be zero, because the carbon that is emitted has been sequestered recently, and the regrowing of trees will again sequester an equivalent amount of carbon dioxide. Consequently, the paper industry has a relatively low *C/E* ratio, at 37.41 and 36.32 million metric tons carbon dioxide equivalent per quadrillion Btu in 1991 and 1998, respectively. In contrast, the primary metals industry, which uses large amounts of coal and other carbon-intensive fuels, has a high *C/E* ratio: 68.18 in 1991 and 68.52 in 1998.

Between 1994 and 1998, manufacturing industries had statistically significant increases in carbon dioxide emissions associated with their use of electricity (81.0 million metric tons or 16.9 percent) and natural gas (31.9 million metric tons or 9.3 percent). Moreover, electricity use continues to account for the largest share of manufacturers' energy-related carbon dioxide emissions: 35.3 percent (480.6 million metric tons) in 1994 and 37.8 percent (561.6 million metric tons) in 1998.

As a result of the above changes in energy intensity, in combination with the structural shift in the subsector, the overall manufacturing energy intensity (*E/Y*) declined by 10.3 percent from 1991 to 1998. When the influence of the structural shift is removed, however, decomposition analysis suggests that the aggregate energy intensity of the manufacturing sector is virtually unchanged.[c]

Changes in Key Measures of Carbon Intensity in Manufacturing, 1991-1998

Industry Group	SIC[a] Code	1991			1998			Percent Change, 1991-1998		
		E/Y	*C/E*	*C/Y*	*E/Y*	*C/E*	*C/Y*	*E/Y*	*C/E*	*C/Y*
Petroleum	29	36	45.26	1,647.2	42	42.32	1,776.3	15.3	-6.5	7.8
Chemicals	28	17	45.84	771.3	18	44.25	800.0	7.4	-3.5	3.7
Metals	33	22	68.17	1,484.4	19	68.53	1,301.3	-12.8	0.5	-12.3
Paper	26	20	37.40	731.9	20	36.32	709.6	-0.2	-2.9	-3.0
Food	20	3	59.05	176.9	3	57.37	181.6	5.7	-2.9	2.6
Glass	32	16	67.76	1,104.7	14	66.57	913.7	-15.8	-1.8	-17.3
Other Manufacturing		2	55.20	131.7	2	54.81	114.7	-12.3	-0.7	-12.9
Total		**8**	**50.91**	**408.8**	**7**	**49.42**	**356.0**	**-10.3**	**-2.9**	**-12.9**
Total Without Structural Shift		**8**	**—**	**—**	**8**	**—**	**—**	**0.7**	**—**	**—**

[a] Standard Industrial Classification.

Notes: *E/Y* = energy consumed (thousand Btu) per constant 1996 dollar value of shipments. *C/E* = million metric tons CO_2 emitted per quadrillion Btu of energy consumed. *C/Y* = metric tons CO_2 emitted per million chained 1996 dollars value of shipments.

Sources: Energy Information Administration, Form EIA-846, "Manufacturing Energy Consumption Survey," and Form EIA-810, "Monthly Refinery Report" (1998).

[b] Carbon dioxide emission factors include indirect emissions from electricity consumed in the manufacturing process. These emission factors are based on a national average for electricity and are assumed for the purposes of this analysis to be uniform across industries.

[c] There are several approaches, based on index number theory, that can be used to decompose aggregate values and trends. The values reported here are based on a discrete approximation of the Divisia integral index. Statistically, the positive change for energy intensity of 0.7 percent is not significantly different from zero.

generation increased by 1.8 percent, and emissions from petroleum-fired generation increased by 25.8 percent. Carbon dioxide emissions from the electric power sector have grown by 27.5 percent since 1990, while total energy-related carbon dioxide emissions have grown by 16.0 percent.

Nonfuel Use of Energy Inputs

In 2003, carbon sequestration through nonfuel uses of fossil fuels totaled 298.2 million metric tons carbon dioxide equivalent (Table 12). The vast majority was sequestered in petroleum-based products (275.0 million metric tons carbon dioxide equivalent), with smaller amounts in natural-gas-based products (21.7 million metric tons) and coal-based products (1.5 million metric tons). The main products that sequester carbon include feedstocks for plastics and other petrochemicals, asphalt and road oil, liquefied petroleum gas, lubricants, and waxes. The amount sequestered in 2003 was about the same as in 2002, when 298.3 million metric tons carbon dioxide equivalent was sequestered. Since 1990, the annual sequestration of carbon in this manner has increased by 47.0 million metric tons or 18.7 percent. This translates to an average annual growth rate of 1.3 percent.

Adjustments to Energy Consumption

Total energy consumption and the carbon dioxide emissions upon which they are based correspond to EIA's coverage of energy consumption, which includes the 50 States and the District of Columbia. Under the United Nations Framework Convention on Climate Change (UNFCCC), however, the United States is also responsible for counting emissions emanating from its territories, and their emissions are added to the U.S. total. Conversely, because the Intergovernmental Panel on Climate Change (IPCC) definition of energy consumption excludes international bunker fuels from the statistics of all countries, emissions from international bunker fuels are subtracted from the U.S. total. Additionally, military bunker fuels are subtracted because they are also excluded by the IPCC from the national total. These sources and subtractions are enumerated and described as "adjustments to energy."

U.S. Territories

Energy-related carbon dioxide emissions for the U.S. territories are added as an adjustment in keeping with IPCC guidelines for national emissions inventories. The territories included are Puerto Rico, the U.S. Virgin Islands, American Samoa, Guam, the U.S. Pacific Islands, and Wake Island. Most of these emissions are from petroleum products; however, Puerto Rico and the Virgin Islands consume coal in addition to petroleum products. For 2003, total energy-related carbon dioxide emissions from the U.S. Territories are estimated at 61.8 million metric tons (Table 5).

International Bunker Fuels

In keeping with the IPCC guidelines for estimating national greenhouse gas emissions, carbon dioxide emissions from international bunker fuels are subtracted from the estimate of total U.S. energy-related emissions of carbon dioxide. The estimate for bunker fuels is based on purchases of distillate and residual fuels by foreign-bound ships at U.S. seaports, as well as jet fuel purchases by international air carriers at U.S. airports. Additionally, U.S. military operations for which fuel was originally purchased in the United States but consumed in international waters or airspace are subtracted from the total, because they are also considered international bunker fuels under this definition.

For 2002, the carbon dioxide emissions estimate for military bunker fuels was 8.1 million metric tons.[50] In 2003, approximately 89.2 million metric tons of carbon dioxide was emitted in total from international bunker fuels, including 81.2 million metric tons attributed to civilian consumption of bunker fuels. The total amount is subtracted from the U.S. total in Table 5. Just over half of the carbon dioxide emissions associated with international bunker fuels are from the combustion of jet fuels; residual and distillate fuels account for the other half, with most coming from residual fuel.

Other Carbon Dioxide Emissions

U.S. Carbon Dioxide Emissions from Other Sources, 1990-2003

Estimated 2003 Emissions (Million Metric Tons Carbon Dioxide)	110.2
Change Compared to 2002 (Million Metric Tons Carbon Dioxide)	0.6
Change from 2002 *(Percent)*	*0.5%*
Change Compared to 1990 (Million Metric Tons Carbon Dioxide)	19.1
Change from 1990 *(Percent)*	*21.0%*

---

[50] Data for 2003 military bunker fuels were not available at the time of publication. It should also be noted that only bunker fuels purchased in the United States are subject to adjustment.

Energy Production

In addition to emissions resulting from fossil energy consumed, oil and gas production leads to emissions of carbon dioxide from sources other than the combustion of those marketed fossil fuels. The two energy production sources estimated for this report are:

- Flared natural gas (gas burned at the production site), which is flared either because the cost of bringing the gas to market is prohibitive or because the gas is of insufficient quality to sell
- Carbon dioxide scrubbed from natural gas to improve its heat content and quality and subsequently vented to the atmosphere.

Because many States require flaring of natural gas, EIA assumes that all gas reported under the category "Vented and Flared" is actually flared and therefore should be counted as carbon dioxide emissions rather than methane emissions. In 2003, about 6.0 million metric tons of carbon dioxide was emitted in this way (Table 5).

By computing the difference between the estimated carbon dioxide content of raw gas and the carbon dioxide content of pipeline gas, the amount of carbon dioxide that has been removed (scrubbed) in order to improve the heat content and quality of natural gas can be calculated. This amount was about 18.0 million metric tons in 2003 (Table 5). Data on additional energy production sources that are excluded from this report are available in Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2002*.[51]

Industrial Process Emissions

Industrial emissions of carbon dioxide not caused by the combustion of fossil fuels accounted for only 1.2 percent (70.3 million metric tons) of total U.S. carbon dioxide emissions in 2003 (Table 5). Process-related emissions from industrial sources depend largely on the level of activity in the construction industries and on production at oil and gas wells. These sources include limestone and dolomite calcination, soda ash manufacture and consumption, carbon dioxide manufacture, cement manufacture, and aluminum production.

Estimated industrial process emissions of carbon dioxide in 2003 totaled 70.3 million metric tons, 17.0 percent higher than in 1990 and 0.6 million metric tons (0.9 percent) higher than in 2002 (Table 13). Sixty-two percent of the carbon dioxide emissions from industrial processes are from cement manufacture. When calcium carbonate is heated (calcined) in a kiln, it is converted to lime and carbon dioxide. The lime is combined with other materials to produce clinker (an intermediate product from which cement is made), and the carbon dioxide is released to the atmosphere. In 2003, the United States produced an estimated 91.0 million metric tons of cement, resulting in the direct release of 43.3 million metric tons of carbon dioxide into the atmosphere.[52] This calculation is independent of the carbon dioxide released by the production of energy consumed in making cement. The estimate for 2003 represents an increase in carbon dioxide emissions of 9.9 million metric tons (29.7 percent) compared with 1990 and an increase of about 0.3 million metric tons (0.6 percent) compared with 2002.

There are numerous other industrial processes in which carbonate minerals are used in ways that release carbon dioxide into the atmosphere, including the use of limestone in the production of lime and in flue gas desulfurization and the manufacture and some uses of soda ash. Carbon dioxide is also released during aluminum smelting, when carbon anodes (with the carbon derived from nonfuel use of fossil fuels) are vaporized in the presence of aluminum oxide. Approximately 27.1 million metric tons of carbon dioxide was released in emissions from these other industrial process sources in 2003.

Municipal solid waste that is combusted contains, on average, a portion that is composed of plastics, synthetic rubber, synthetic fibers, and carbon black. The carbon in these plastics has normally been accounted for as sequestered carbon, as reported in Table 12. However, according to the IPCC, to properly account for that carbon, emissions from the plastics portion of the municipal solid waste must be counted in total national emissions inventories. These emissions produce about 18.8 million metric tons of carbon dioxide, as calculated by the U.S. EPA, with the most recent estimate being for 2002. The 2002 value has been used as an estimate for 2003.

---

[51] Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0638(2002) (Washington, DC, January 2004), web site www.eia.doe.gov/oiaf/1605/ggrpt/documentation/pdf/0638(2002).pdf. See also Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2003* (to be published).

[52] U.S. Department of the Interior, U.S. Geological Service, "Cement," *Mineral Commodity Summary*, web site http://minerals.usgs.gov/minerals/pubs/commodity/cement/cemenmcs04.pdf.

Table 5. U.S. Carbon Dioxide Emissions from Energy and Industry, 1990 and 1995-2003
(Million Metric Tons Carbon Dioxide)

Fuel Type or Process	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Energy Consumption										
Petroleum	2,180.8	2,194.9	2,278.8	2,296.7	2,348.9	2,416.5	2,438.4	2,475.0	2,456.5	2,498.4
Coal	1,771.6	1,876.5	1,958.8	2,002.6	2,016.1	2,020.0	2,114.8	2,047.2	2,063.8	2,100.4
Natural Gas	1,026.0	1,182.4	1,204.2	1,209.8	1,187.2	1,190.0	1,237.8	1,186.1	1,227.7	1,179.4
Renewables[a]	3.5	3.0	3.0	3.1	3.1	3.1	3.0	3.1	3.2	3.1
Energy Subtotal[b]	**4,981.9**	**5,256.8**	**5,444.8**	**5,512.2**	**5,555.3**	**5,629.6**	**5,793.9**	**5,711.4**	**5,751.2**	**5,781.4**
Adjustments to Energy										
U.S. Territories (+)	30.9	38.0	37.9	39.1	42.3	40.4	42.2	53.6	53.1	61.8
Military Bunker Fuels (-)	13.6	8.9	8.9	9.6	10.0	9.8	7.8	8.2	8.0	8.0
International Bunker Fuels (-)	100.1	91.9	93.3	100.1	104.9	97.4	93.5	89.6	81.2	75.2
Total Energy Adjustments	**-82.7**	**-62.8**	**-64.3**	**-70.6**	**-72.6**	**-66.8**	**-59.1**	**-44.2**	**-36.1**	**-21.3**
Adjusted Energy Subtotal	**4,899.1**	**5,194.1**	**5,380.5**	**5,441.6**	**5,482.7**	**5,562.8**	**5,734.8**	**5,667.2**	**5,715.2**	**5,760.1**
Other Sources										
Gas Flaring	9.1	17.2	16.5	15.5	6.2	6.7	5.5	5.9	6.0	5.7
CO_2 in Natural Gas	14.0	16.7	17.8	18.0	18.0	17.8	18.2	18.6	18.0	18.1
Cement Production	33.3	36.9	37.2	38.4	39.3	40.1	41.3	41.4	43.0	43.3
Other Industrial	26.8	28.4	29.0	29.5	30.0	29.3	29.6	27.7	26.7	27.1
Waste Combustion	7.8	13.5	14.6	15.1	14.4	14.9	15.4	16.1	15.9	16.0
Total Other Sources	**91.0**	**112.6**	**115.0**	**116.5**	**107.9**	**108.8**	**110.0**	**109.7**	**109.6**	**110.2**
Total	**4,990.1**	**5,306.7**	**5,495.5**	**5,558.1**	**5,590.7**	**5,671.6**	**5,844.8**	**5,777.0**	**5,824.8**	**5,870.2**

P = preliminary data.

[a] Includes emissions from electricity generation using municipal solid waste and geothermal energy.

[b] Includes emissions from nonfuel uses of fossil fuels.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding. Adjusted energy total includes U.S. Territories.

Sources: EIA estimates presented in this chapter.

Table 6. U.S. Carbon Dioxide Emissions from Energy Consumption by End-Use Sector, 1990 and 1995-2003
(Million Metric Tons Carbon Dioxide)

End-Use Sector	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Residential	948.3	1,026.5	1,086.1	1,077.5	1,083.3	1,107.1	1,170.4	1,163.3	1,193.9	1,214.8
Commercial	777.2	837.3	868.5	911.9	930.3	943.7	1,004.3	1,021.0	1,019.8	1,025.7
Industrial	1,686.9	1,731.6	1,784.8	1,800.1	1,783.8	1,772.9	1,775.0	1,691.4	1,671.5	1,666.2
Transportation	1,569.5	1,661.4	1,705.3	1,722.7	1,757.9	1,806.0	1,844.2	1,835.8	1,866.0	1,874.7
Total[a]	**4,981.9**	**5,256.8**	**5,444.8**	**5,512.2**	**5,555.3**	**5,629.6**	**5,793.9**	**5,711.4**	**5,751.2**	**5,781.4**
Electric Power	1,787.9	1,924.8	1,996.1	2,063.9	2,152.1	2,164.7	2,271.6	2,232.5	2,256.4	2,279.3

P = preliminary data.

[a] Includes emissions from nonfuel uses of fossil fuels.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding. Electric power sector emissions are distributed across the end-use sectors. Emissions allocated to sectors are unadjusted. Adjustments are made to total emissions only (Table 5).

Sources: EIA estimates presented in this chapter.

Table 7. U.S. Carbon Dioxide Emissions from Residential Sector Energy Consumption, 1990 and 1995-2003
(Million Metric Tons Carbon Dioxide)

Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Petroleum										
Liquefied Petroleum Gas . .	22.6	25.1	29.3	28.6	26.9	33.1	34.9	33.2	35.1	33.7
Distillate Fuel	70.8	65.5	67.1	63.3	55.9	59.9	65.5	65.8	62.3	64.5
Kerosene	4.6	5.3	6.4	6.6	7.8	8.0	6.8	6.8	4.1	5.1
Petroleum Subtotal	**98.0**	**95.9**	**102.7**	**98.5**	**90.5**	**101.0**	**107.2**	**105.8**	**101.4**	**103.3**
Coal	2.4	1.6	1.6	1.5	1.2	1.3	1.1	1.1	1.0	1.1
Natural Gas	238.8	263.0	284.2	270.2	246.5	256.5	270.3	259.7	265.9	276.8
Electricity[a].	609.1	666.0	697.6	707.3	745.1	748.3	791.7	796.7	825.6	833.5
Total.	**948.3**	**1,026.5**	**1,086.1**	**1,077.5**	**1,083.3**	**1,107.1**	**1,170.4**	**1,163.3**	**1,193.9**	**1,214.8**

[a] Share of total electric power sector carbon dioxide emissions weighted by sales to the residential sector.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 8. U.S. Carbon Dioxide Emissions from Commercial Sector Energy Consumption, 1990 and 1995-2003
(Million Metric Tons Carbon Dioxide)

Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Petroleum										
Motor Gasoline	7.8	1.3	1.9	3.0	2.7	2.0	3.1	2.6	2.7	2.7
Liquefied Petroleum Gas. . .	4.0	4.4	5.2	5.0	4.7	5.8	6.2	5.9	6.2	5.9
Distillate Fuel.	38.8	34.7	35.0	32.1	31.1	31.8	35.6	36.8	32.2	33.3
Residual Fuel	17.9	11.0	10.7	8.7	6.6	5.7	6.6	6.5	6.2	5.9
Kerosene.	0.8	1.6	1.5	1.8	2.2	1.9	2.1	2.2	1.3	1.7
Petroleum Subtotal	**69.4**	**53.0**	**54.2**	**50.6**	**47.4**	**47.2**	**53.6**	**54.0**	**48.6**	**49.6**
Coal.	12.1	11.0	11.5	12.2	8.7	9.7	8.6	9.2	8.6	8.9
Natural Gas.	142.6	164.3	171.3	174.3	163.5	165.2	172.4	164.5	168.7	170.5
Electricity[a]	553.0	608.9	631.6	674.8	710.7	721.5	769.8	793.3	793.9	796.7
Total	**777.2**	**837.3**	**868.5**	**911.9**	**930.3**	**943.7**	**1,004.3**	**1,021.0**	**1,019.8**	**1,025.7**

[a] Share of total electric power sector carbon dioxide emissions weighted by sales to the commercial sector.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 9. U.S. Carbon Dioxide Emissions from Industrial Sector Energy Consumption, 1990 and 1995-2003

(Million Metric Tons Carbon Dioxide)

Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Petroleum										
Motor Gasoline	13.0	14.1	14.0	14.9	14.0	10.6	10.5	20.7	21.3	21.5
Liquefied Petroleum Gas	39.9	46.4	47.4	49.3	40.3	49.3	57.9	50.1	54.1	52.5
Distillate Fuel	83.1	81.6	85.6	86.7	87.3	85.5	86.5	93.7	86.8	89.9
Residual Fuel	30.3	24.2	24.1	20.5	15.7	14.0	15.2	16.6	12.6	12.0
Asphalt and Road Oil	*	*	*	*	*	*	*	*	*	*
Lubricants	6.8	6.5	6.3	6.7	7.0	7.1	7.0	6.4	6.3	5.9
Kerosene	0.9	1.1	1.3	1.3	1.6	0.9	1.1	1.7	1.0	1.3
Petroleum Coke	81.2	79.6	84.0	79.5	97.6	109.0	87.6	97.2	94.8	92.0
Other Petroleum	125.1	112.0	130.4	135.9	123.6	127.9	115.5	130.0	127.3	138.1
Petroleum Subtotal	**380.4**	**365.6**	**393.2**	**394.9**	**387.1**	**404.4**	**381.4**	**416.4**	**404.2**	**413.2**
Coal	**249.5**	**224.3**	**219.0**	**215.3**	**201.2**	**196.6**	**200.2**	**193.5**	**178.1**	**180.3**
Coal Coke Net Imports	**0.5**	**5.7**	**3.2**	**5.3**	**7.4**	**6.5**	**7.2**	**4.0**	**5.8**	**5.8**
Natural Gas	**433.5**	**489.4**	**505.7**	**506.1**	**495.0**	**473.6**	**479.7**	**438.7**	**449.8**	**421.3**
Electricity[a]	**623.1**	**646.7**	**663.7**	**678.6**	**693.1**	**691.7**	**706.6**	**638.8**	**633.5**	**645.6**
Total[b]	**1,686.9**	**1,731.6**	**1,784.8**	**1,800.1**	**1,783.8**	**1,772.9**	**1,775.0**	**1,691.4**	**1,671.5**	**1,666.2**

*Less than 50,000 metric tons carbon dioxide.

[a] Share of total electric power sector carbon dioxide emissions weighted by sales to the industrial sector.

[b] Includes emissions from nonfuel uses of fossil fuels.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003).Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 10. U.S. Carbon Dioxide Emissions from Transportation Sector Energy Consumption, 1990 and 1995-2003

(Million Metric Tons Carbon Dioxide)

Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Petroleum										
Motor Gasoline	955.2	1,015.5	1,034.0	1,042.5	1,072.9	1,099.9	1,105.9	1,111.2	1,138.7	1,143.7
Liquefied Petroleum Gas	1.3	1.0	0.9	0.8	1.0	0.8	0.7	0.8	0.8	0.8
Jet Fuel	220.4	219.9	229.8	232.1	235.6	242.9	251.2	240.4	234.4	228.6
Distillate Fuel	265.1	303.8	323.7	338.4	348.4	362.2	374.0	383.2	390.5	404.5
Residual Fuel	79.3	71.0	66.4	55.5	52.6	51.9	64.2	54.2	52.8	50.4
Lubricants[a]	6.5	6.2	6.0	6.3	6.6	6.7	6.6	6.0	6.0	5.6
Aviation Gasoline	3.1	2.7	2.6	2.7	2.4	2.7	2.5	2.4	2.3	2.2
Petroleum Subtotal	**1,530.9**	**1,620.1**	**1,663.3**	**1,678.4**	**1,719.5**	**1,767.1**	**1,805.2**	**1,798.2**	**1,825.5**	**1,835.8**
Coal	*	*	*	*	*	*	*	*	*	*
Natural Gas	**35.9**	**38.2**	**38.9**	**41.1**	**35.1**	**35.6**	**35.5**	**33.9**	**37.1**	**35.4**
Electricity[b]	**2.7**	**3.2**	**3.2**	**3.2**	**3.3**	**3.2**	**3.6**	**3.6**	**3.4**	**3.5**
Total	**1,569.5**	**1,661.4**	**1,705.3**	**1,722.7**	**1,757.9**	**1,806.0**	**1,844.2**	**1,835.8**	**1,866.0**	**1,874.7**

*Less than 50,000 metric tons carbon dioxide.

[a] Includes emissions from nonfuel uses of fossil fuels.

[b] Share of total electric power sector carbon dioxide emissions weighted by sales to the transportation sector.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 11. U.S. Carbon Dioxide Emissions from Electric Power Sector Energy Consumption, 1990 and 1995-2003

(Million Metric Tons Carbon Dioxide)

Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Petroleum										
Heavy Fuel Oil	77.0	44.6	49.6	56.7	82.7	75.7	68.8	78.3	51.4	67.9
Light Fuel Oil	23.4	7.7	7.8	7.7	9.7	10.0	12.5	12.3	8.2	11.4
Petroleum Coke	1.4	7.8	7.8	9.9	11.8	10.9	9.6	10.0	16.9	16.7
Petroleum Subtotal	**102.1**	**60.3**	**65.4**	**74.3**	**104.4**	**96.8**	**91.0**	**100.7**	**76.7**	**96.5**
Coal	**1,507.1**	**1,633.9**	**1,723.5**	**1,768.3**	**1,797.6**	**1,805.8**	**1,897.7**	**1,839.4**	**1,870.2**	**1,904.3**
Natural Gas	**175.3**	**227.5**	**204.2**	**218.1**	**247.1**	**259.1**	**279.9**	**289.4**	**306.2**	**275.3**
Municipal Solid Waste	**3.1**	**2.7**	**2.6**	**2.7**	**2.7**	**2.7**	**2.6**	**2.7**	**2.9**	**2.8**
Geothermal	**0.4**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**
Total	**1,787.9**	**1,924.8**	**1,996.1**	**2,063.9**	**2,152.1**	**2,164.7**	**2,271.6**	**2,232.5**	**2,256.4**	**2,279.3**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Emissions for total fuel consumption are allocated to end-use sectors in proportion to electricity sales. Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 12. U.S. Carbon Sequestered by Nonfuel Use of Energy Fuels, 1990 and 1995-2003

(Million Metric Tons Carbon Dioxide Equivalent)

End Use and Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Industrial										
Petroleum										
Liquefied Petroleum Gases	59.3	78.5	81.7	82.7	86.4	89.9	82.1	76.7	79.9	76.3
Distillate Fuel	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Residual Fuel	1.9	2.1	2.1	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Asphalt and Road Oil	88.5	89.1	88.9	92.5	95.5	100.1	96.4	95.0	93.7	92.0
Lubricants	6.9	6.6	6.4	6.8	7.1	7.2	7.0	6.5	6.4	6.0
Other *(Subtotal)*	*72.1*	*83.1*	*85.2*	*90.7*	*92.7*	*94.9*	*88.7*	*83.9*	*86.4*	*92.4*
Pentanes Plus	4.4	16.2	16.9	16.0	10.9	14.0	12.7	10.8	9.2	9.0
Petrochemical Feed	46.0	50.0	50.6	58.4	59.1	55.5	57.7	50.7	55.1	63.0
Petroleum Coke	9.1	6.8	7.6	6.0	10.9	14.5	7.2	10.6	9.8	8.8
Waxes and Miscellaneous	12.5	10.1	10.1	10.4	11.8	10.9	11.2	11.8	12.2	11.5
Petroleum Subtotal	*228.9*	*259.6*	*264.6*	*275.2*	*284.3*	*294.8*	*277.0*	*264.7*	*269.1*	*269.4*
Coal	1.4	2.1	2.0	1.9	1.8	1.8	1.8	1.7	1.5	1.5
Natural Gas	14.4	18.4	18.5	19.8	21.9	22.5	22.7	21.3	21.7	21.7
Transportation										
Lubricants	6.5	6.2	6.0	6.4	6.7	6.8	6.7	6.1	6.0	5.6
Total	**251.3**	**286.4**	**291.2**	**303.4**	**314.7**	**325.8**	**308.1**	**293.9**	**298.3**	**298.2**

P = preliminary data.

Notes: Emissions from nonfuel use of energy fuels are included in the energy consumption tables in this chapter. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 13. U.S. Carbon Dioxide Emissions from Industrial Processes, 1990 and 1995-2003
(Million Metric Tons Carbon Dioxide)

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Cement Manufacture										
Clinker Production	32.6	36.1	36.3	37.6	38.4	39.2	40.4	40.5	42.0	42.3
Masonry Cement	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cement Kiln Dust	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Cement Subtotal	**33.3**	**36.9**	**37.2**	**38.4**	**39.3**	**40.1**	**41.3**	**41.4**	**43.0**	**43.3**
Other Industrial										
Limestone Consumption										
Lime Manufacture	12.4	14.5	15.1	15.5	15.8	15.5	15.4	14.8	14.1	14.3
Iron Smelting	1.7	1.2	1.1	1.1	1.1	1.0	1.1	1.0	0.9	0.9
Steelmaking	0.3	0.5	0.4	0.3	0.4	0.3	0.5	0.6	0.5	0.5
Copper Refining	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Glass Manufacture	0.1	0.3	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.1
Flue Gas Desulfurization	0.7	0.9	0.9	1.0	1.0	1.1	1.2	1.4	1.4	1.4
Dolomite Manufacture	0.5	0.2	0.3	0.3	0.3	0.1	0.3	0.3	0.3	0.3
Limestone Subtotal	***15.9***	***17.8***	***18.3***	***18.5***	***18.9***	***18.3***	***18.7***	***18.4***	***17.4***	***17.6***
Soda Ash Manufacture	3.4	3.8	3.8	3.9	3.8	3.7	3.6	3.6	3.5	3.6
Soda Ash Consumption										
Glass Manufacture	0.1	0.3	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.1
Flue Gas Desulfurization	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
Sodium Silicate	0.2	0.3	0.2	0.3	0.3	0.2	0.2	0.3	0.2	0.3
Sodium Tripolyphosphate	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Soda Ash Subtotal	***0.5***	***0.8***	***0.6***	***0.6***	***0.6***	***0.6***	***0.6***	***0.6***	***0.5***	***0.5***
Carbon Dioxide Manufacture	0.9	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.5
Aluminum Manufacture	5.9	4.9	5.2	5.3	5.4	5.5	5.4	3.9	4.0	4.0
Shale Oil Production	0.2	*	*	*	*	*	*	*	*	*
Other Industrial Subtotal	**26.8**	**28.4**	**29.0**	**29.5**	**30.0**	**29.3**	**29.6**	**27.7**	**26.7**	**27.1**
Total	**60.1**	**65.3**	**66.1**	**67.9**	**69.3**	**69.4**	**70.9**	**69.2**	**69.7**	**70.3**

*Less than 50,000 metric tons carbon equivalent.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

3. Methane Emissions

Overview

U.S. Anthropogenic Methane Emissions, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	26.2	601.9
Change Compared to 2002 (Million Metric Tons)	0.1	2.7
Change from 2002 *(Percent)*	*0.5%*	*0.5%*
Change Compared to 1990 (Million Metric Tons)	-4.6	-105.9
Change from 1990 *(Percent)*	*-15.0%*	*-15.0%*

U.S. anthropogenic methane emissions totaled 26.2 million metric tons of methane (601.9 million metric tons carbon dioxide equivalent)[53] in 2003, up by 0.1 million metric tons from 2002 levels (Table 14). Small increases in methane emissions from landfills and coal mines more than offset decreases in methane emissions from mobile sources and rice cultivation.

Estimated U.S. emissions of methane in 2003 were 4.6 million metric tons below the 1990 level, a decrease equivalent to 105.9 million metric tons of carbon dioxide, or 1.5 percent of total U.S. anthropogenic greenhouse gas emissions. In addition to a 4.2 million metric ton decrease in methane emissions from landfills since 1990, there was also a 1.4 million metric ton decrease in methane emissions from coal mines during the same period (Table 15). The 32.4-percent decline in emissions from coal mining was the result of a 189-percent increase in methane recovery from coal mines and a shift in production away from gassy mines. Overall, methane emissions account for about 8.7 percent of total U.S. greenhouse gas emissions when weighted by methane's global warming potential factor.

Methane emissions from industrial landfills are included for the first time in this annual report. As a result, the overall estimated levels of methane emissions from 1990 through 2002 are 0.8 million metric tons higher each year than they would have been in the absence of the revision. Methane emissions from industrial landfills have been included in this year's report because the use of more rigorously gathered data on landfilled municipal solid waste[54] reduces the likelihood that methane emissions from industrial landfills will be double counted in estimates of emissions from municipal solid waste (MSW).

Methane emission estimates are much more uncertain than carbon dioxide emission estimates. Methane emissions usually are accidental or incidental to biological processes and may not be metered in any systematic way.[55] Thus, methane emission estimates must often rely on proxy measurements.

Estimated U.S. anthropogenic methane emissions for 2003 are based on incomplete data for several key sources; thus, the overall estimate is likely to be revised. Emissions from three of these sources—coal mining, natural gas systems, and landfills—represented about three-fifths of all U.S. methane emissions. Thus, comparisons between 2002 and 2003 numbers are more likely to be valid in the context of directional change rather than magnitude of change. For example, because 2003 data on waste generation are not yet available, waste generation has been scaled to economic output as a proxy. Less critical but still important data are also unavailable for natural gas systems, such as miles of gas transmission and distribution pipeline.

---

[53] Based on an estimated global warming potential factor of 23 for methane. For an expanded discussion of global warming potentials, see Chapter 1, page 12.

[54] "The State of Garbage in America," *Biocycle* (January 2004), p. 31.

[55] Wherever possible, estimates of methane emissions are based on measured data. In some cases, however, measured data are incomplete or unavailable. In the absence of measured data, emissions are indexed to some known activity data, such as coal production or natural gas throughput, and multiplied by an emissions factor derived from a small sample of the relevant emissions source or through laboratory experiments. For a more detailed discussion of where measured data were used and how emissions factors were developed, see Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0638(2002) (Washington, DC, January 2004), web site www.eia.doe.gov/oiaf/1605/ggrpt/documentation/pdf/0638(2002).pdf; and Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2003* (to be published).

Principal Sources of U.S. Anthropogenic Methane Emissions, 1990-2003

Source	Million Metric Tons Methane		*Percent Change*	
	1990	2003	1990-2003	2002-2003
Energy	11.96	11.13	*-6.9%*	*0.5%*
Waste Management	11.11	6.97	*-37.2%*	*1.2%*
Agriculture	7.60	7.95	*4.7%*	*-0.3%*
Industrial Processes	0.12	0.11	*-4.4%*	*

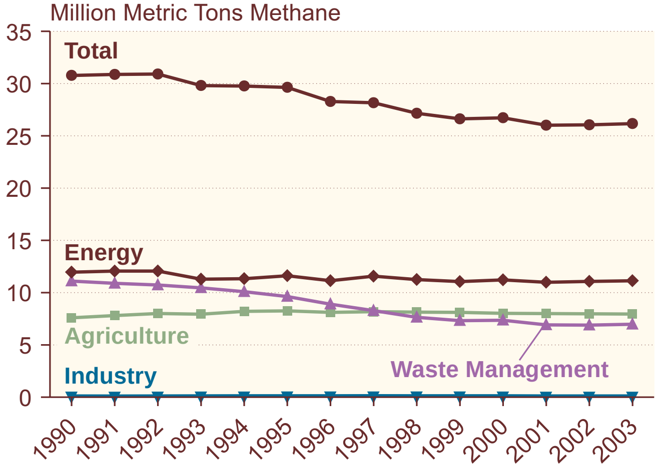
*Less than 0.05 percent.

Energy Sources

U.S. methane emissions from energy sources were estimated at 11.1 million metric tons in 2003 (256.1 million metric tons carbon dioxide equivalent), less than 0.1 million metric tons higher than 2002 levels and 0.8 million metric tons below 1990 levels (Figure 2). The drop in methane emissions from energy sources since 1990 can be traced primarily to decreased emissions from coal mines and, to a lesser extent, to lower emissions from petroleum systems and stationary combustion.

Methane emissions from coal mines dropped by 32.4 percent (1.4 million metric tons) between 1990 and 2003. This decline resulted partly from the increased capture and use of methane from coal mine degasification systems and a shift in production away from some of the Nation's gassiest underground mines in Central Appalachia. Also, between 1990 and 2003, the share of coal production represented by underground mines declined from 41.2 percent to 32.9 percent. Methane emissions from underground mines tend to have higher emission rates per ton of coal mined than surface mines because coal mined from the surface has been subjected to lower pressures and methane in the seams of surface mines has had earlier opportunities to migrate to the surface through cracks and fissures.

Figure 2. U.S. Emissions of Methane by Source, 1990-2003



Source: Estimates presented in this chapter.

Methane emissions from petroleum systems dropped from 1.3 million metric tons in 1990 to 1.0 million metric tons in 2003. A decrease of 0.2 million metric tons in estimated methane emissions from stationary combustion made a smaller contribution to the overall drop in emissions from energy sources between 1990 and 2003. Together, the declines in emissions from coal mining, petroleum systems, and stationary combustion more than compensated for the increase of 1.1 million metric tons in emissions from the natural gas system, attributed to increasing U.S. consumption of natural gas between 1990 and 2003.

Coal Mining

U.S. Methane Emissions from Coal Mining, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	2.9	66.0
Change Compared to 2002 (Million Metric Tons)	0.1	1.4
Change from 2002 *(Percent)*	*2.2%*	*2.2%*
Change Compared to 1990 (Million Metric Tons)	-1.4	-31.7
Change from 1990 *(Percent)*	*-32.4%*	*-32.4%*

*Less than 0.05 million metric tons.

The preliminary estimate of methane emissions from coal mines for 2003 is 2.9 million metric tons (Table 15), an increase of 2.2 percent from the 2002 level. This increase can be traced largely to a 0.1 million metric ton decrease in methane recovery from coal mines, more than offsetting a decline in emissions that resulted from lower levels of coal production.

U.S. coal production declined to 1.07 billion short tons in 2003, down for the second consecutive year from the record 2001 level of 1.13 billion short tons. The decline occurred despite an increase in coal consumption driven by increased demand from the electric power sector. The shortfall in production was offset by a drawing down of end-of-year coal stocks during 2003.[56] Between 1990 and 2003, methane emissions from coal mines dropped by 32.4 percent from the 1990 level of 4.2 million metric tons. The decline is attributed to three important trends: (1) methane recovery from active coal mines for use as an energy resource increased from 0.3 million metric tons in 1990 to about 0.8 million metric tons in 2003; (2) methane drainage from degasification in active mines decreased by nearly 0.2 million metric tons between 1990 and 2003; and (3) methane emissions from ventilation systems at gassy mines dropped by about 0.7 million metric tons between 1990 and 2003 (Table 15).[57]

Abandoned coal mines represent a significant source of additional emissions that have not been incorporated into the overall estimate of methane emissions in this report because of uncertainties associated with the data. The text box on page 36 contains a discussion of those uncertainties and the potential magnitude of additional emissions.

Natural Gas Systems

U.S. Methane Emissions from Natural Gas Systems, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	6.7	154.0
Change Compared to 2002 (Million Metric Tons)	*	0.1
Change from 2002 *(Percent)*	*0.1%*	*0.1%*
Change Compared to 1990 (Million Metric Tons)	1.1	25.1
Change from 1990 *(Percent)*	*19.4%*	*19.4%*

*Less than 0.05 million metric tons.

At 6.7 million metric tons, 2003 estimated methane emissions from natural gas production, processing, and distribution were unchanged from the revised estimate of 6.7 million metric tons for 2002 (Table 16). The 2003 estimate is preliminary, however, because pipeline data for 2003 have not been finalized as of the publication of this report. The estimated 2003 emissions level is 19.4 percent above the 1990 level, with more than three-fifths of the increase attributable to increased mileage of transmission and distribution pipelines and almost two-fifths attributable to increases in gas production.[58]

Petroleum Systems

U.S. Methane Emissions from Petroleum Systems, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	1.0	23.5
Change Compared to 2002 (Million Metric Tons)	*	*
Change from 2002 *(Percent)*	*-0.1%*	*-0.1%*
Change Compared to 1990 (Million Metric Tons)	-0.3	-6.4
Change from 1990 *(Percent)*	*-21.4%*	*-21.4%*

*Less than 0.05 million metric tons.

Methane emissions from petroleum systems are estimated at 1.0 million metric tons in 2003, nearly unchanged from 2002 levels and down by 21.4 percent from 1.3 million metric tons in 1990. Domestic oil production in 2003 was 78.0 percent of the 1990 level, accounting for the decline in methane emissions from this source. Approximately 96.3 percent of all emissions from petroleum systems occur during exploration and production. Of the roughly 1.0 million metric tons of methane emissions annually from this source, 90.2 percent was traced to venting, of which nearly half is attributable to venting from oil tanks (Table 17). A much smaller portion of methane emissions from petroleum systems can be traced to refineries and transportation of crude oil.

---

[56] Energy Information Administration, *U.S. Coal Supply and Demand: 2003 Review* (Washington, DC, April 2004), web site www.eia.doe.gov/cneaf/coal/page/special/feature.html.

[57] The EPA believes that a significant portion of methane recovery from coal mines should not be deducted from current-year emissions, because the gas is being drained from coal seams that will be mined only in future years, if at all. The relationship between estimates of emissions from degasification and estimates of gas recovery is under review and may be revised in the future.

[58] EPA estimates that companies participating in the Natural Gas STAR program together avoided emissions of 1.0 million metric tons of methane from the natural gas system in 2003 (Table 16). Program participants report annually on emissions reductions achieved through such activities as equipment replacement, enhanced inspection and maintenance, and improved operations management. Participating companies may either use their own techniques to estimate reductions achieved or employ default values developed by the EPA and the Gas Technology Institute (formerly the Gas Research Institute).

Methane Emissions from Abandoned Coal Mines

Thousands of coal mines in the United States have been closed and abandoned during the past 100 years. The U.S. Department of Labor's Mine Safety and Health Administration (MSHA) estimates that since 1980 more than 7,500 coal mines have been abandoned, and many continue to emit methane. In an April 2004 report,[a] the EPA estimates that methane emissions from abandoned coal mines ranged between 130,000 metric tons and 200,000 metric tons in 1990, and between 200,000 metric tons and 280,000 metric tons in 2002. Because access to abandoned mines is limited and a systematic measurement program at those sites would be time-intensive and costly, the EPA study relies on actual emissions data from when the mines were operating and assumes a decline function in emissions based on mine and coal-seam characteristics.

The most important variable in determining the amount of methane emissions from an abandoned mine is its post-mining status—whether the mine has been sealed, flooded, or continues to be vented. Sealed and flooded mines have much lower rates of emissions than vented mines. Another variable deemed important is whether the mine was gassy (emitting more than 100,000 cubic feet per day) when it was operating. Gassy mines are estimated to emit 98 percent of all methane emissions from operating coal mines, and EPA assumes that abandoned mines which had been gassy when operating represent a similarly predominant portion of emissions from abandoned mines. The EPA study thus focuses on abandoned mines that had been gassy prior to closure. Of the 364 gassy mines abandoned since 1972, EPA has data on the status of a portion of them (i.e., whether the mines were sealed, flooded, or continue to be vented), and calculates percentage shares of emissions by their respective status. EPA then assumes that those shares apply to mines for which it does not have data.

For abandoned mines that have been vented, EPA derives an emissions decline curve based on three primary factors: adsorption isotherms by coal basin, coal permeability estimates, and estimates of pressure at abandonment. For mines that are flooded, EPA assumes a decline curve equation based on measurements taken from eight abandoned mines in two basins. EPA treats sealed mines similar to those vented, adjusting the initial emissions rate and length of time for emissions to dissipate, given the slower release rate from sealed vents.

The EPA sought to calibrate its estimation methodology to field measurements, but restricted access precluded measurement at all but seven mines. Although results from those mines suggested the general accuracy of the estimation method, EIA believes the methodology has not yet been validated. EIA will reconsider including estimates of methane emissions from abandoned mines in its overall estimates of U.S. greenhouse gas emissions should additional field data confirm the EPA methodology.

[a] U.S. Environmental Protection Agency, Coalbed Methane Outreach Program, *Methane Emissions from Abandoned Coal Mines in the United States: Emission Inventory Methodology and 1990-2002 Emissions Estimates* (Washington, DC, April 2004), web site www.epa.gov/cmop/pdf/amm_final_report.pdf.

Stationary Combustion

U.S. methane emissions from stationary combustion in 2003 were 361 thousand metric tons, down by 0.1 percent from the 2002 level and 35.9 percent below 1990 levels (Table 18). Residential wood consumption typically accounts for about 85 percent of methane emissions from stationary combustion. Methane emissions are the result of incomplete combustion, and residential woodstoves and fireplaces provide much less efficient combustion than industrial or utility boilers. Estimates of residential wood combustion have fallen by 39.8 percent since 1990, although these estimates are very uncertain.[59]

The universe of wood consumers is large and heterogeneous, and EIA collects data on residential wood consumption only at 4-year intervals in its Residential Energy Consumption Survey (RECS). The most recently published EIA data on residential wood consumption are from the 2001 RECS. Updated data on residential wood consumption for calendar year 2003 will be available from the 2005 RECS.

Mobile Combustion

Estimated U.S. methane emissions from mobile combustion in 2003 were 188 thousand metric tons, down by 4.3 percent from 2002 levels and 22.6 percent lower than the

---

[59] For further details see Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0638(2002) (Washington, DC, January 2004), web site www.eia.doe.gov/oiaf/1605/ggrpt/documentation/pdf/0638(2002).pdf; and Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2003* (to be published).

U.S. Methane Emissions from Stationary Combustion, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	0.4	8.3
Change Compared to 2002 (Million Metric Tons)	*	*
Change from 2002 *(Percent)*	*-0.1%*	*-0.1%*
Change Compared to 1990 (Million Metric Tons)	-0.2	-4.7
Change from 1990 *(Percent)*	*-35.9%*	*-35.9%*

*Less than 0.05 million metric tons.

U.S. Methane Emissions from Mobile Sources, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	0.2	4.3
Change Compared to 2002 (Million Metric Tons)	*	-0.2
Change from 2002 *(Percent)*	*-4.3%*	*-4.3%*
Change Compared to 1990 (Million Metric Tons)	-0.1	-1.3
Change from 1990 *(Percent)*	*-22.6%*	*-22.6%*

*Less than 0.05 million metric tons.

1990 level (Table 19). Methane emissions from passenger cars have declined since 1990 as older vehicles with catalytic converters that are less efficient at destroying methane have been taken off the road. Estimates of methane emissions from mobile sources have been revised downwards from previous reports, reflecting a change in the source of data for vehicle miles traveled and a related adjustment in the emission factors for light duty trucks. The difference in estimates of methane emissions from mobile sources from those previously reported grows steadily for the period 1990 through 2002, reaching 45 thousand metric tons in 2002.[60]

Waste Management

Methane emissions from waste management accounted for 26.6 percent of U.S. anthropogenic methane emissions in 2003 (Figure 2), down from 36.1 percent in 1990. Landfills represent 90.4 percent of the 7.0 million metric tons of methane emissions from waste management and are the second largest source, after natural gas systems, of U.S. anthropogenic methane emissions (Table 14). The remainder of emissions from waste management is associated with domestic wastewater treatment. Estimated emissions from waste management would increase if sufficient information were available to develop a reliable estimate of emissions from industrial wastewater treatment.

EIA's methodology for calculating the 2003 estimates of methane emissions from waste management has changed from that used in previous years. The new methodology, which incorporates data on landfilled waste published in *Biocycle*,[61] has reduced the estimated amount of municipal solid waste reaching landfills by more accurately accounting for construction and demolition waste mixed with municipal solid waste. EIA's estimates have also been revised to reflect the inclusion of methane emissions from organic decomposition in industrial landfills, which based on a methodology developed by EPA are estimated to represent 7 percent of emissions from municipal solid waste landfills.[62] The combined effects of these revisions have reduced emissions estimates by between 0.3 and 0.7 million metric tons for the years 1990 through 2003.

Landfills

Due to increased levels of waste disposed in landfills, estimated methane emissions from landfills rose to 6.3 million metric tons (144.9 million metric tons carbon dioxide equivalent) in 2003, 1.3 percent above the 2002 level of 6.2 million metric tons but still 4.2 million metric tons (40.1 percent) below 1990 levels (Table 20). The dramatic decrease in methane emissions since 1990 is directly attributable to a 5.0 million metric ton increase in methane captured at landfills that otherwise would have been emitted to the atmosphere. Of the 6.3 million

---

[60] For a more detailed discussion of the revisions in estimation methods for mobile sources, see Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2003* (to be published).

[61] "The State of Garbage in America," *Biocycle* (January 2004), p. 31.

[62] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

U.S. Methane Emissions from Landfills, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	6.3	144.9
Change Compared to 2002 (Million Metric Tons)	0.1	1.8
Change from 2002 *(Percent)*	*1.3%*	*1.3%*
Change Compared to 1990 (Million Metric Tons)	-4.2	-97.2
Change from 1990 *(Percent)*	*-40.1%*	*-40.1%*

metric tons of methane believed to be captured from this source in 2003, 3.0 million metric tons was recovered for energy use, and 3.3 million metric tons was recovered and flared. In 2003, methane recovery for energy increasingly took the form of direct use of medium-Btu gas in industrial boilers. The acceleration of this practice was driven by higher natural gas prices, which made landfill gas more competitive.[63]

Estimates of methane recovered for energy are drawn from data collected by the EPA's Landfill Methane Outreach Program,[64] while estimates of methane recovered and flared are based on data collected from flaring equipment vendors.[65] There is less uncertainty in the estimate of methane recovered and used for energy, and it is likely that estimates of methane flared are biased downward due to a lack of comprehensive industry data.

The rapid growth in methane recovery has been aided by a combination of regulatory and tax policy. The Federal Section 29 (of the Internal Revenue Code) tax credit for alternative energy sources, added to the tax code as part of the Crude Oil Windfall Profits Act of 1980, provided a subsidy roughly equivalent to 1 cent per kilowatthour for electricity generated from landfill gas. However, this tax credit expired on June 30, 1998. As part of the recently enacted American Jobs Creation Act of 2004, a tax credit for electricity generation using landfill gas was added to Section 45 of the Internal Revenue Code. To be eligible for the credit, a landfill gas-to-energy project must be put in service between October 22, 2004, and December 31, 2005. Those facilities that qualify are eligible for a 5-year tax credit valued at 0.9 cent per kilowatthour.

Increases in methane recovery have also resulted from the implementation of the EPA's New Source Performance Standards and Emission Guidelines. These regulations require all landfills with more than 2.5 million metric tons of waste in place and annual emissions of nonmethane volatile organic compounds (NMVOCs) exceeding 50 metric tons to collect and burn their landfill gas, either by flaring or for use as an energy source.

Domestic and Commercial Wastewater Treatment

U.S. Methane Emissions from Domestic and Commercial Wastewater Treatment, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	0.7	15.5
Change Compared to 2002 (Million Metric Tons)	*	0.1
Change from 2002 *(Percent)*	*0.8%*	*0.8%*
Change Compared to 1990 (Million Metric Tons)	0.1	2.2
Change from 1990 *(Percent)*	*16.6%*	*16.6%*

*Less than 0.05 million metric tons.

With the U.S. population growing slowly, methane emissions from domestic and commercial wastewater treatment are estimated to have grown by 0.8 percent between 2002 and 2003 to 0.67 million metric tons—about 16.6 percent above the 1990 level of 0.58 million metric tons (Table 14). Methane emissions from industrial wastewater treatment are discussed in the text box on page 39.

Methane emissions from domestic and commercial wastewater treatment are a function of the share of organic matter in the wastewater stream and the conditions under which it decomposes. Wastewater may be treated aerobically or anaerobically. Because aerobic decomposition does not yield methane, whereas

---

[63] Personal communication with Brian Guzzone, U.S. Environmental Protection Agency, Landfill Methane Outreach Program.

[64] U.S. Environmental Protection Agency, Landfill Methane Outreach Program, web site www.epa.gov/lmop.

[65] U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002, EPA-430-R-04-003 (Washington, DC, April 2004), pp. Q-3 and Q-4, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublications GHGEmissions USEmissionsInventory2004.html.

Methane Emissions from Industrial Wastewater Treatment

When wastewater containing large amounts of organic material is treated through anaerobic decomposition, methane is emitted. The best estimate of those emissions would be based on a systematic measurement of all point sources; however, the number and diversity of U.S. industrial wastewater sources make such an approach unaffordable and impractical. As an alternative, methane emissions from industrial wastewater treatment are calculated by the following equation:

$$M = P \times O \times COD \times A \times EF \quad ,$$

where M = methane emissions, P = product output, O = wastewater outflow per unit of product output, COD = organic loading in outflow, A = percentage of outflow treated anaerobically, and EF = emissions factor for anaerobically treated outflow.

The Intergovernmental Panel on Climate Change, in its *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*,[a] provides default data for wastewater generation and *COD* on an industry-specific basis. The default data, often based on one or two literature sources, are assumed to have an uncertainty range of minus 50 percent to plus 100 percent (although no justification for the range is provided). The IPCC also provides a single default factor of 0.25 kilograms methane per kilogram of *COD*, premised on a general approximation of the theoretical maximum for this emission factor, and identifies an uncertainty of plus or minus 30 percent for this estimate.

There are currently no specific U.S. data that could be used to improve on the IPCC defaults, and the uncertainties make it impossible for EIA to provide a reliable estimate of emissions from this source. It can be noted, however, that depending on the extent to which industrial wastewater from such industries as meat and poultry processing, pulp and paper manufacturing, and vegetable, fruit and juice processing—which is likely to have a high content of organic material—is treated anaerobically, excluding the methane emissions that would result from the U.S. emissions total will tend to produce an underestimate of U.S. methane emissions. The U.S. Environmental Protection Agency estimates that U.S. methane emissions from industrial wastewater treatment could be as high as 0.7 million metric tons (14.6 million metric tons carbon dioxide equivalent) per year.[b] If more comprehensive data on industrial wastewater flows become available, EIA will consider adding this source to its estimate of U.S. methane emissions.

[a] Intergovernmental Panel On Climate Change, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (Montreal, Canada, May 2000), web site www.ipcc-nggip.iges.or.jp/public/gp/english/.

[b] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-004 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

anaerobic decomposition does, the method of treatment is a critical determinant of emissions; however, there is little information available on wastewater treatment methods. Data on flaring or energy recovery from methane generated by wastewater are also sparse. EIA believes that emissions from this source are relatively small, representing 2.6 percent of all U.S. methane emissions in 2003. Thus, emissions are estimated using a default per-capita emissions factor and U.S. population data.

Agricultural Sources

Estimated agricultural methane emissions decreased by 0.3 percent between 2002 and 2003 due mainly to small decreases in emissions from rice cultivation. At an estimated 7.9 million metric tons of methane (182.8 million metric tons carbon dioxide equivalent), methane emissions from agricultural activities in 2003 represent 30.4 percent of total U.S. anthropogenic methane emissions (Table 14) and approximately 2.6 percent of total U.S. greenhouse gas emissions. Ninety-four percent of methane emissions from agricultural activities result from livestock management. Sixty-six percent of these emissions can be traced to enteric fermentation in ruminant animals, and the remainder is attributable to the anaerobic decomposition of livestock wastes. A small portion of U.S. methane emissions result from crop residue burning and wetland rice cultivation.

Enteric Fermentation in Domesticated Animals

In 2003, estimated methane emissions from enteric fermentation in domesticated animals declined 0.3 percent to 5.0 million metric tons (Table 21). Because cattle account for 95.1 percent of all emissions from enteric fermentation, trends in emissions correlate with trends in cattle populations. Between 2002 and 2003, cattle populations were nearly constant, with small declines in beef cattle populations. Estimated methane emissions from enteric fermentation in 2003 are 4.7 percent below 1990 levels.

U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	5.0	114.3
Change Compared to 2002 (Million Metric Tons)	*	-0.3
Change from 2002 *(Percent)*	*-0.3%*	*-0.3%*
Change Compared to 1990 (Million Metric Tons)	-0.2	-5.6
Change from 1990 *(Percent)*	*-4.7%*	*-4.7%*

*Less than 0.05 million metric tons.

U.S. Methane Emissions from Solid Waste of Domesticated Animals, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	2.5	57.9
Change Compared to 2002 (Million Metric Tons)	*	0.4
Change from 2002 *(Percent)*	*0.6%*	*0.6%*
Change Compared to 1990 (Million Metric Tons)	0.6	13.4
Change from 1990 *(Percent)*	*30.2%*	*30.2%*

*Less than 0.05 million metric tons.

Solid Waste of Domesticated Animals

Estimated methane emissions from the solid waste of domesticated animals increased from 2.50 million metric tons in 2002 to 2.52 million metric tons in 2003 (Table 22). The increase reinforced a larger trend over the past decade: in 2003, emissions from the solid waste of domesticated animals were 0.6 million metric tons above 1990 levels, an increase of 30.2 percent. Between 1990 and 2003 there was a shift in livestock management to larger facilities, which are believed to be more likely to manage waste using liquid systems that tend to promote methane generation.[66]

Rice Cultivation

Estimated methane emissions from U.S. rice cultivation declined to 0.41 million metric tons in 2003 from 0.44 million metric tons in 2002 (Table 14). The drop was the result of a 6.9-percent decrease in the number of acres harvested.[67] All U.S. rice producing states saw decreases in acres harvested during 2003. Methane emissions from rice cultivation in 2003 were 2.5 percent higher than in 1990.

Burning of Crop Residues

Crop residue burning, the smallest contributor to agricultural greenhouse gas emissions, represents 0.2 percent of total U.S. methane emissions. Estimated 2003 methane emissions from the burning of crop residues were 0.05 million metric tons, up 5.2 percent from 2002 levels and 8.5 percent above 1990 levels (Table 14). The increase between 2002 and 2003 is attributable mainly to large increases in corn and wheat production.

Industrial Sources

U.S. Methane Emissions from Industrial Sources, 1990-2003

	Methane	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Million Metric Tons)	0.1	2.6
Change Compared to 2002 (Million Metric Tons)	*	*
Change from 2002 *(Percent)*	*	*
Change Compared to 1990 (Million Metric Tons)	*	-0.1
Change from 1990 *(Percent)*	*-4.4%*	*-4.4%*

*Less than 0.05 million metric tons or less than 0.05 percent.

---

[66] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), p. 5-6, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions USEmissionsInventory2004.html.

[67] U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production—Annual Summary* (Washington, DC, various years), web site http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban.

Chemical Production

The preliminary estimate of methane emissions from U.S. chemical production in 2003 is 65.6 thousand metric tons, unchanged from 2002. Methane emissions from chemical production in 2003 were 18.1 percent above their level in 1990. The increase is attributable to increased production of carbon black, ethylene, and styrene, which more than offset a drop in methanol production (Table 23).[68]

Iron and Steel Production

With production of pig iron and sinter at their lowest levels since the early 1980s,[69] methane emissions from iron and steel production are estimated at 46.5 thousand metric tons, 24.7 percent below the 1990 level of 61.7 thousand metric tons (Table 23).

---

[68] American Chemistry Council (formerly the Chemical Manufacturers Association), *Guide to the Business of Chemistry*, Table 3.12, "Production of the Top 100 Chemicals" (Washington, DC, 2003).

[69] American Iron and Steel Institute, *Annual Statistical Report*, Tables 26, 31, and 32 (Washington, DC, various years).

Table 14. U.S. Methane Emissions from Anthropogenic Sources, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Million Metric Tons Methane										
Energy Sources										
Coal Mining	4.25	3.66	3.19	3.50	3.28	3.12	2.98	2.96	2.81	2.87
Natural Gas Systems	5.60	5.98	6.00	6.27	6.26	6.27	6.57	6.39	6.69	6.69
Petroleum Systems	1.30	1.17	1.15	1.14	1.11	1.04	1.03	1.03	1.02	1.02
Stationary Combustion	0.56	0.58	0.58	0.44	0.39	0.42	0.44	0.41	0.36	0.36
Mobile Sources	0.24	0.22	0.22	0.22	0.21	0.21	0.20	0.20	0.20	0.19
Total Energy Sources	**11.96**	**11.62**	**11.14**	**11.57**	**11.25**	**11.06**	**11.22**	**10.99**	**11.08**	**11.13**
Waste Management										
Landfills	10.53	9.02	8.28	7.66	7.01	6.69	6.71	6.25	6.22	6.30
Wastewater Treatment	0.58	0.61	0.61	0.62	0.63	0.63	0.65	0.66	0.67	0.67
Total Waste Management	**11.11**	**9.63**	**8.90**	**8.28**	**7.64**	**7.32**	**7.36**	**6.91**	**6.89**	**6.97**
Agricultural Sources										
Enteric Fermentation	5.21	5.42	5.31	5.19	5.11	5.11	5.06	4.99	4.98	4.97
Animal Waste	1.93	2.35	2.34	2.48	2.51	2.46	2.46	2.49	2.50	2.52
Rice Cultivation	0.40	0.44	0.41	0.45	0.47	0.50	0.45	0.47	0.44	0.41
Crop Residue Burning	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Total Agricultural Sources	**7.60**	**8.26**	**8.11**	**8.18**	**8.13**	**8.11**	**8.02**	**8.00**	**7.97**	**7.95**
Industrial Processes	**0.12**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.11**	**0.11**	**0.11**
Total	**30.78**	**29.64**	**28.28**	**28.16**	**27.16**	**26.62**	**26.72**	**26.01**	**26.05**	**26.17**
Million Metric Tons Carbon Dioxide Equivalent										
Energy Sources										
Coal Mining	97.68	84.18	73.46	80.39	75.55	71.67	68.44	68.11	64.58	66.03
Natural Gas Systems	128.91	137.62	138.06	144.30	143.89	144.24	151.04	146.98	153.82	153.97
Petroleum Systems	29.87	26.93	26.36	26.33	25.54	24.03	23.79	23.71	23.48	23.46
Stationary Combustion	12.97	13.33	13.35	10.06	9.07	9.63	10.05	9.47	8.31	8.31
Mobile Sources	5.60	5.09	4.99	5.07	4.74	4.74	4.70	4.56	4.52	4.33
Total Energy Sources	**275.02**	**267.15**	**256.22**	**266.16**	**258.80**	**254.31**	**258.02**	**252.83**	**254.73**	**256.10**
Waste Management										
Landfills	242.16	207.52	190.52	176.16	161.28	153.88	154.27	143.81	143.14	144.93
Wastewater Treatment	13.27	13.98	14.11	14.25	14.38	14.51	15.01	15.15	15.34	15.47
Total Waste Management	**255.43**	**221.50**	**204.63**	**190.41**	**175.66**	**168.39**	**169.28**	**158.96**	**158.48**	**160.41**
Agricultural Sources										
Enteric Fermentation	119.87	124.67	122.21	119.45	117.44	117.42	116.40	114.80	114.58	114.28
Animal Waste	44.48	54.06	53.82	57.14	57.78	56.53	56.64	57.30	57.53	57.90
Rice Cultivation	9.30	10.22	9.42	10.32	10.71	11.47	10.24	10.73	10.23	9.53
Crop Residue Burning	1.04	0.97	1.12	1.12	1.14	1.10	1.15	1.12	1.07	1.12
Total Agricultural Sources	**174.69**	**189.92**	**186.57**	**188.04**	**187.07**	**186.52**	**184.42**	**183.95**	**183.41**	**182.83**
Industrial Processes	**2.70**	**3.04**	**3.08**	**3.09**	**3.05**	**3.07**	**2.93**	**2.59**	**2.58**	**2.58**
Total	**707.84**	**681.61**	**650.50**	**647.70**	**624.58**	**612.29**	**614.65**	**598.33**	**599.20**	**601.92**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter. Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.83-4.84, web site www.ipcc.ch/pub/guide.htm; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

Table 15. U.S. Methane Emissions from Coal Mining and Post-Mining Activities, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Million Metric Tons Methane										
Surface Mining										
Mining	0.43	0.45	0.46	0.47	0.49	0.50	0.49	0.53	0.52	0.51
Post-Mining	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.04
Subtotal	*0.46*	*0.49*	*0.50*	*0.51*	*0.54*	*0.54*	*0.54*	*0.57*	*0.57*	*0.55*
Underground Mining										
Ventilation (Gassy Mines)[a]	2.13	1.91	1.71	1.79	1.80	1.76	1.67	1.62	1.51	1.45
Ventilation (Nongassy Mines)	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03
Degasification Systems	1.26	1.21	1.02	1.06	0.95	0.79	0.87	0.93	1.00	1.07
Post-Mining	0.64	0.60	0.62	0.63	0.63	0.59	0.56	0.57	0.54	0.53
Methane Recovery for Energy (-)	0.26	0.57	0.69	0.54	0.67	0.61	0.70	0.76	0.83	0.77
Subtotal	*3.78*	*3.17*	*2.69*	*2.98*	*2.75*	*2.57*	*2.44*	*2.39*	*2.24*	*2.32*
Net Emissions	**4.25**	**3.66**	**3.19**	**3.50**	**3.28**	**3.12**	**2.98**	**2.96**	**2.81**	**2.87**
Million Metric Tons Carbon Dioxide Equivalent										
Surface Mining										
Mining	9.82	10.34	10.63	10.87	11.37	11.51	11.37	12.11	11.96	11.66
Post-Mining	0.85	0.90	0.92	0.95	0.99	1.00	0.99	1.05	1.04	1.01
Subtotal	*10.68*	*11.24*	*11.55*	*11.82*	*12.36*	*12.51*	*12.36*	*13.16*	*13.00*	*12.68*
Underground Mining										
Ventilation (Gassy Mines)[a]	48.91	43.86	39.32	41.22	41.51	40.55	38.31	37.18	34.70	33.38
Ventilation (Nongassy Mines)	0.62	0.80	0.85	0.84	0.94	0.92	0.87	0.84	0.79	0.76
Degasification Systems	28.88	27.76	23.46	24.44	21.80	18.08	20.00	21.33	22.90	24.62
Post-Mining	14.69	13.71	14.19	14.56	14.46	13.56	12.93	13.17	12.37	12.21
Methane Recovery for Energy (-)	6.09	13.19	15.91	12.49	15.51	13.96	16.03	17.57	19.17	17.61
Subtotal	*87.01*	*72.94*	*61.91*	*68.57*	*63.20*	*59.15*	*56.08*	*54.95*	*51.59*	*53.35*
Net Emissions	**97.68**	**84.18**	**73.46**	**80.39**	**75.55**	**71.67**	**68.44**	**68.11**	**64.58**	**66.03**

[a] A "gassy" mine is an underground mine with ventilation emissions of 100,000 cubic feet of methane or more per day, as measured by the U.S. Mine Safety and Health Administration.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: Coal production numbers from Energy Information Administration, *Coal Production*, DOE/EIA-0118 (Washington, DC, various years), and *Coal Industry Annual*, DOE/EIA-0584 (Washington, DC, various years). Methane recovery rates from U.S. Environmental Protection Agency, Office of Air and Radiation, Non-CO_2 Gases and Sequestration Branch, Coalbed Methane Outreach Program. Ventilation data for 1985, 1988, and 1990 provided by G. Finfinger, U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center. Ventilation data for all other years provided by U.S. Environmental Protection Agency, Office of Air and Radiation, Non-CO_2 Gases and Sequestration Branch, Coalbed Methane Outreach Program.

Table 16. U.S. Methane Emissions from Natural Gas Systems, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Million Metric Tons Methane										
Production	1.47	1.57	1.58	1.65	1.67	1.62	1.73	1.83	1.84	1.84
Gas Processing	0.65	0.72	0.73	0.71	0.69	0.70	0.71	0.69	0.67	0.68
Transmission and Storage	2.10	2.14	2.11	2.27	2.22	2.30	2.41	2.13	2.42	2.41
Distribution	1.39	1.55	1.58	1.64	1.67	1.65	1.71	1.74	1.76	1.76
Total	**5.60**	**5.98**	**6.00**	**6.27**	**6.26**	**6.27**	**6.57**	**6.39**	**6.69**	**6.69**
Natural Gas STAR Reductions	0.01	0.01	0.30	0.39	0.48	0.54	0.63	0.75	1.04	1.04
Million Metric Tons Carbon Dioxide Equivalent										
Production	33.77	36.06	36.28	37.98	38.43	37.32	39.90	42.05	42.21	42.43
Gas Processing	14.85	16.50	16.90	16.39	15.97	16.13	16.43	15.97	15.52	15.62
Transmission and Storage	48.26	49.33	48.54	52.12	51.00	52.84	55.42	48.97	55.59	55.42
Distribution	32.03	35.73	36.34	37.81	38.49	37.95	39.29	40.00	40.50	40.50
Total	**128.91**	**137.62**	**138.06**	**144.30**	**143.89**	**144.24**	**151.04**	**146.98**	**153.82**	**153.97**
Natural Gas STAR Reductions	0.23	0.23	6.90	8.97	11.04	12.42	14.49	17.25	23.92	23.92

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding. Data for Natural Gas STAR reductions are estimates provided by the EPA, based on annual submissions to the EPA by companies participating in the program, which report activities undertaken to avoid methane emissions from natural gas and petroleum systems.

Sources: National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996), Appendix A; American Gas Association, *Gas Facts* (various years); Energy Information Administration, *Natural Gas Annual,* DOE/EIA-0131 (various years); Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(2004/07) (Washington, DC, July 2004); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Table 17. U.S. Methane Emissions from Petroleum Systems, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Million Metric Tons Methane										
Refineries	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Exploration and Production	1.26	1.13	1.11	1.11	1.07	1.01	1.00	0.99	0.98	0.98
Crude Oil Transportation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	**1.30**	**1.17**	**1.15**	**1.14**	**1.11**	**1.04**	**1.03**	**1.03**	**1.02**	**1.02**
Natural Gas STAR Reductions	0.00	0.05	0.06	0.08	0.08	0.09	0.09	0.09	0.09	0.09
Million Metric Tons Carbon Dioxide Equivalent										
Refineries	0.57	0.58	0.59	0.61	0.62	0.62	0.64	0.62	0.62	0.63
Exploration and Production	29.00	26.08	25.50	25.45	24.66	23.16	22.92	22.85	22.63	22.59
Crude Oil Transportation	0.30	0.27	0.27	0.27	0.26	0.24	0.24	0.23	0.24	0.24
Total	**29.87**	**26.93**	**26.36**	**26.33**	**25.54**	**24.03**	**23.79**	**23.71**	**23.48**	**23.46**
Natural Gas STAR Reductions	0.05	1.24	1.40	1.73	1.82	2.05	2.05	1.96	2.02	2.02

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding. Data for Natural Gas STAR reductions are estimates provided by the EPA, based on annual submissions to the EPA by companies participating in the program, which report activities undertaken to avoid methane emissions from natural gas and petroleum systems.

Sources: U.S. Environmental Protection Agency, Office of Air and Radiation, *Draft Estimates of Methane Emissions from the U.S. Oil Industry* (Draft Report, Washington, DC); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years); and *Oil and Gas Journal*, Worldwide Refining Issue and Pipeline Economics Issue (various years).

Table 18. U.S. Methane Emissions from Stationary Combustion Sources, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
	Thousand Metric Tons Methane									
Residential										
Coal	*	*	*	*	*	*	*	*	*	*
Fuel Oil[a]	5	5	5	4	4	4	5	5	5	5
Natural Gas	4	5	5	5	4	5	5	5	5	5
LPG	*	*	1	1	1	1	1	1	1	1
Wood	512	526	525	382	341	365	382	359	309	309
Total	**522**	**535**	**535**	**392**	**350**	**374**	**392**	**369**	**319**	**319**
Commercial										
Coal	1	1	1	1	1	1	1	1	1	1
Fuel Oil[a]	1	1	1	*	*	*	*	*	*	*
Natural Gas	3	4	4	4	4	4	4	4	4	4
LPG	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*
Total	**5**	**5**	**6**	**6**	**5**	**5**	**5**	**5**	**5**	**5**
Industrial										
Coal	7	6	6	6	5	5	5	5	5	5
Fuel Oil[a]	1	1	1	1	1	1	1	1	1	1
Natural Gas	11	13	13	13	13	13	13	12	12	11
LPG	2	3	3	3	3	3	3	3	3	3
Wood	4	4	5	5	4	4	4	4	4	4
Total	**25**	**27**	**28**	**28**	**26**	**26**	**26**	**25**	**25**	**24**
Electric Power										
Coal	10	11	11	11	12	12	12	12	12	12
Fuel Oil[a]	1	*	*	1	1	1	1	1	*	*
Natural Gas	*	*	*	*	*	*	1	1	1	*
Wood	*	*	*	*	*	*	*	*	*	*
Total	**11**	**11**	**12**	**12**	**13**	**13**	**13**	**13**	**13**	**13**
Total All Sectors										
Coal	18	18	18	18	18	18	18	18	18	18
Fuel Oil[a]	8	7	7	6	6	6	7	6	6	6
Natural Gas	19	22	23	23	22	21	22	21	21	20
LPG	3	3	4	4	3	4	4	4	4	4
Wood	516	530	529	387	346	370	386	363	313	313
Total	**564**	**579**	**580**	**437**	**394**	**419**	**437**	**412**	**361**	**361**

*Less than 500 metric tons methane.

[a] Fuel oil use in the residential sector consists of distillate fuel only. In the other sectors it includes both distillate and residual fuel oil.

P = preliminary data.

See notes and sources at end of table.

Table 18. U.S. Methane Emissions from Stationary Combustion Sources, 1990 and 1995-2003 (Continued)

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Carbon Dioxide Equivalent										
Residential										
Coal	*	*	*	*	*	*	*	*	*	*
Fuel Oil[a]	113	105	107	101	89	96	105	105	104	108
Natural Gas	100	110	119	113	103	107	113	108	111	116
LPG	10	11	13	12	12	14	15	14	15	14
Wood	11,783	12,087	12,067	8,782	7,849	8,396	8,782	8,254	7,098	7,098
Total	**12,006**	**12,313**	**12,306**	**9,008**	**8,053**	**8,613**	**9,014**	**8,482**	**7,328**	**7,336**
Commercial										
Coal	30	27	28	30	21	24	21	22	23	23
Fuel Oil[a]	16	12	12	10	9	9	10	10	10	10
Natural Gas	72	82	86	87	82	83	86	82	85	86
LPG	2	2	2	2	2	3	3	3	3	3
Wood	3	3	3	3	3	4	4	3	3	3
Total	**122**	**126**	**132**	**133**	**118**	**122**	**124**	**120**	**122**	**124**
Industrial										
Coal	151	136	133	130	122	119	121	124	115	116
Fuel Oil[a]	32	27	27	24	20	18	21	18	20	19
Natural Gas	263	298	307	308	303	291	295	269	276	258
LPG	51	64	66	68	65	71	72	65	69	66
Wood	89	102	104	107	99	100	101	89	93	93
Total	**585**	**626**	**637**	**637**	**608**	**599**	**609**	**565**	**572**	**552**
Electric Power										
Coal	225	242	256	262	267	268	281	273	278	284
Fuel Oil[a]	19	9	10	12	17	16	14	16	*	*
Natural Gas	7	10	9	9	10	11	12	12	13	11
Wood	1	*	*	*	*	*	*	*	*	*
Total	**252**	**261**	**274**	**283**	**294**	**294**	**306**	**301**	**291**	**295**
Total All Sectors										
Coal	406	405	417	423	410	410	422	419	415	423
Fuel Oil[a]	180	152	156	147	135	138	150	149	134	137
Natural Gas	442	500	521	518	499	492	506	472	484	471
LPG	62	77	81	82	78	88	90	82	87	83
Wood	11,875	12,192	12,174	8,891	7,951	8,499	8,886	8,346	7,194	7,194
Total	**12,965**	**13,326**	**13,348**	**10,061**	**9,073**	**9,628**	**10,053**	**9,468**	**8,313**	**8,308**

*Less than 500 metric tons carbon dioxide equivalent.

[a] Fuel oil use in the residential sector consists of distillate fuel only. In the other sectors it includes both distillate and residual fuel oil.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, web site www.epa.gov/ttn/chief; Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.ipcc.ch/pub/guide.htm; and Energy Information Administration, *State Energy Data Report*, DOE/EIA-0214 (Washington, DC, various years), *Monthly Energy Review*, DOE/EIA-0035(2004/07) (Washington, DC, July 2004), and *Annual Energy Review*, DOE/EIA-0384 (Washington, DC, various years).

Table 19. U.S. Methane Emissions from Mobile Sources, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Methane										
Motor Vehicles										
Passenger Cars	143	111	107	106	96	96	94	91	90	83
Buses	1	1	1	1	1	1	1	1	1	1
Motorcycles	4	4	4	4	4	4	4	4	4	4
Light-Duty Trucks	61	68	68	72	68	67	66	64	64	63
Other Trucks	12	14	15	15	16	16	17	17	16	16
Total	**220**	**199**	**195**	**199**	**186**	**185**	**182**	**177**	**176**	**167**
Other Transport	23	23	23	21	21	21	23	21	21	21
Total Transport	**243**	**221**	**217**	**221**	**206**	**206**	**204**	**198**	**197**	**188**
Thousand Metric Tons Carbon Dioxide Equivalent										
Motor Vehicles										
Passenger Cars	3,284	2,557	2,450	2,447	2,217	2,201	2,156	2,093	2,070	1,900
Buses	21	24	24	25	26	28	28	26	29	29
Motorcycles	92	94	95	97	99	102	101	92	98	98
Light-Duty Trucks	1,402	1,564	1,566	1,654	1,566	1,540	1,512	1,471	1,481	1,456
Other Trucks	271	330	339	354	363	375	380	384	363	363
Total	**5,070**	**4,569**	**4,475**	**4,578**	**4,271**	**4,246**	**4,178**	**4,067**	**4,041**	**3,846**
Other Transport	525	521	518	494	473	494	519	489	484	483
Total Transport	**5,596**	**5,090**	**4,993**	**5,072**	**4,745**	**4,740**	**4,696**	**4,556**	**4,525**	**4,329**

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003).

Sources: For passenger cars and light-duty trucks, 1990-2000 vehicle miles traveled (VMT) data are based on 2002 data on vehicle stocks provided by R.L. & Polk Co., with VMT modified by Oak Ridge National Laboratory (ORNL), *Transportation Energy Data Book: Edition 23* (Oak Ridge, TN, October 2003), Chapter 7. 1996-2000 data were further adjusted using fleet data and survival curves for the population of aging vehicles. For years after 2000, emissions data are based on fleet data, econometrically modeled VMT, and survival curves for the population of aging vehicles. Calculations for buses, motorcycles, and other trucks are based on VMT from Federal Highway Administration, U.S. Department of Transportation, *Federal Highway Statistics*, Table VM-1 (various years). Vehicle emissions coefficients are from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.65-1.75, web site www.ipcc.ch/pub/guide.htm. Fuel consumption data for non-highway sources are from Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, various years); *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years), and ORNL, *Transportation Energy Data Book: Edition 23* (Oak Ridge, TN, October 2003), Chapter 9, web site http://www-cta.ornl.gov/data/chapter9.html.

Table 20. U.S. Methane Emissions from Landfills, 1990 and 1995-2003

Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Million Metric Tons Methane										
Gross Emissions from MSW Landfills	11.06	10.99	10.94	10.90	10.88	10.86	11.07	11.24	11.49	11.80
Emissions from Industrial Landfills	0.77	0.77	0.77	0.76	0.76	0.76	0.78	0.79	0.80	0.83
Methane Recovered for Energy (-)	0.82	1.06	1.36	1.62	1.94	2.18	2.38	2.63	2.75	3.00
Methane Assumed Flared (-)	0.48	1.67	2.06	2.39	2.69	2.75	2.76	3.15	3.33	3.33
Net Emissions	**10.53**	**9.02**	**8.28**	**7.66**	**7.01**	**6.69**	**6.71**	**6.25**	**6.22**	**6.30**
Million Metric Tons Carbon Dioxide Equivalent										
Gross Emissions from MSW Landfills	254.31	252.67	251.55	250.79	250.25	249.72	254.66	258.56	264.31	271.48
Emissions from Industrial Landfills	17.80	17.69	17.61	17.56	17.52	17.48	17.83	18.10	18.50	19.00
Methane Recovered for Energy (-)	18.95	24.47	31.28	37.21	44.57	50.07	54.65	60.49	63.20	69.07
Methane Assumed Flared (-)	10.99	38.36	47.36	54.97	61.92	63.25	63.57	72.36	76.48	76.48
Net Emissions	**242.16**	**207.52**	**190.52**	**176.16**	**161.28**	**153.88**	**154.27**	**143.81**	**143.14**	**144.93**

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003).

Sources: Municipal solid waste landfilled in 2002 from “Nationwide Survey: The State of Garbage in America,” *Biocycle* (January 2004). Municipal solid waste generated and landfilled in previous years from “Nationwide Survey: The State of Garbage in America,” *Biocycle* (various years), adjusted on the basis of residential demolitions, to reflect exclusion of construction and demolition waste as in the 2002 data. Municipal waste landfilled in 2003 based on 2002 estimate, scaled to annual economic growth. Emissions calculations based on S.A. Thorneloe et al., “Estimate of Methane Emissions from U.S. Landfills,” Prepared for the U.S. Environmental Protection Agency, Office of Research and Development (April 1994), and D. Augenstein, “The Greenhouse Effect and U.S. Landfill Methane,” *Global Environment Change* (December 1992), pp. 311-328. Methane recovered and flared from U.S. Environmental Protection Agency, Landfill Methane Outreach Program, web site www.epa.gov/lmop/. Emissions from industrial landfills estimated at 7 percent of methane emissions from municipal solid waste landfills, based on U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington DC, April 2004), web site http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

Table 21. U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990 and 1995-2003

Animal Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Million Metric Tons Methane										
Cattle	4.94	5.16	5.06	4.94	4.85	4.86	4.82	4.74	4.74	4.73
Swine	0.08	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Sheep	0.09	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.05	0.05
Goats	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Horses	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10
Total	**5.21**	**5.42**	**5.31**	**5.19**	**5.11**	**5.11**	**5.06**	**4.99**	**4.98**	**4.97**
Million Metric Tons Carbon Dioxide Equivalent										
Cattle	113.59	118.67	116.37	113.54	111.53	111.75	110.75	109.11	108.96	108.72
Swine	1.88	2.01	1.94	2.11	2.15	2.05	2.04	2.06	2.05	2.07
Sheep	2.09	1.65	1.56	1.48	1.44	1.33	1.29	1.28	1.23	1.16
Goats	0.22	0.21	0.22	0.19	0.16	0.16	0.15	0.16	0.14	0.14
Horses	2.10	2.12	2.13	2.14	2.17	2.14	2.17	2.19	2.19	2.19
Total	**119.87**	**124.67**	**122.21**	**119.45**	**117.44**	**117.42**	**116.40**	**114.80**	**114.58**	**114.28**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: Cattle, sheep, and pig population data provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Service. Goat and horse population figures extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982, 1987, 1992, and 1997. Emissions calculations based on U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html; and P.J. Crutzen, I. Aselmann, and W.S. Seiler, “Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans,” *Tellus*, Vol. 38B (1986), pp. 271-284.

Table 22. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1990 and 1995-2003

Animal Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Methane										
Cattle										
Beef Cattle	176	210	209	204	200	198	195	194	194	193
Dairy Cattle	553	662	695	732	738	743	758	772	783	791
Swine										
Market Swine	879	1,111	1,070	1,171	1,199	1,147	1,141	1,156	1,155	1,168
Breeding Swine	152	165	160	169	163	152	152	151	147	145
Poultry										
Layers	72	79	80	81	83	86	88	89	90	91
Broilers	69	94	96	99	100	103	98	99	102	101
Other Animals										
Sheep	5	2	1	1	1	1	1	1	1	1
Goats	1	1	1	1	1	*	*	1	*	*
Horses	27	27	28	28	28	28	28	28	28	28
Total	**1,934**	**2,351**	**2,340**	**2,485**	**2,512**	**2,458**	**2,462**	**2,491**	**2,501**	**2,517**
Thousand Metric Tons Carbon Dioxide Equivalent										
Cattle										
Beef Cattle	4,037	4,838	4,814	4,682	4,592	4,547	4,496	4,470	4,454	4,433
Dairy Cattle	12,717	15,236	15,992	16,829	16,970	17,092	17,430	17,746	18,014	18,185
Swine										
Market Swine	20,217	25,547	24,610	26,922	27,579	26,377	26,248	26,585	26,573	26,860
Breeding Swine	3,502	3,788	3,681	3,893	3,739	3,488	3,507	3,470	3,390	3,338
Poultry										
Layers	1,663	1,814	1,838	1,871	1,913	1,979	2,016	2,052	2,076	2,082
Broilers	1,590	2,158	2,199	2,266	2,298	2,372	2,255	2,284	2,339	2,312
Other Animals										
Sheep	115	35	33	31	31	28	28	27	26	25
Goats	16	15	16	14	12	11	11	12	10	10
Horses	624	631	633	636	644	636	645	652	652	652
Total	**44,481**	**54,063**	**53,818**	**57,144**	**57,777**	**56,531**	**56,636**	**57,298**	**57,534**	**57,897**

*Less than 500 metric tons methane.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: Population data for horses and goats extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982, 1987, 1992, and 1997. Population data for all other animals from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress* (Washington, DC, April 1993), p. 6-8; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), Table M-2, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html. Cattle sizes adjusted by annual slaughter weight from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Maximum methane production, and waste management systems used from L.M. Safley, M.E. Casada, et al., *Global Methane Emissions from Livestock and Poultry Manure* (Washington, DC: U.S. Environmental Protection Agency, February 1992), pp. 24-27; U.S. Environmental Protection Agency, Cost Methodology Report for Beef and Dairy Animal Feeding Operations, EPA-821-R-01-019 (Washington, DC, January 2001), pp.1-13–1-14; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), Table M-2. General methane conversion factors from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 4.25, web site www.ipcc.ch/pub/guide.htm. State methane conversion factors for dairy cattle from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2001); and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), Table M-4.

Table 23. U.S. Methane Emissions from Industrial Processes, 1990 and 1995-2003
(Thousand Metric Tons Methane)

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Methane										
Chemical Production										
Ethylene	17	21	22	23	23	25	23	20	21	21
Ethylene Dichloride	3	3	3	4	4	4	4	3	3	3
Styrene	15	21	22	21	21	22	20	16	18	18
Methanol	8	10	11	12	11	11	9	9	6	6
Carbon Black	14	17	17	17	18	18	17	16	17	17
Total	**56**	**72**	**75**	**77**	**77**	**80**	**72**	**64**	**66**	**66**
Iron and Steel Production										
Coke[a]	11	9	8	7	7	6	7	6	6	6
Sinter	6	6	6	6	5	6	5	5	5	5
Pig Iron	45	46	44	45	43	42	43	38	36	36
Total	**62**	**61**	**59**	**58**	**56**	**54**	**55**	**48**	**46**	**46**
Total Industrial Processes	**117**	**132**	**134**	**134**	**133**	**133**	**127**	**112**	**112**	**112**
Thousand Metric Tons Carbon Dioxide Equivalent										
Chemical Production										
Ethylene	380	488	511	531	540	578	521	470	493	493
Ethylene Dichloride	58	72	79	84	82	91	82	78	78	78
Styrene	335	475	496	476	477	499	452	357	415	415
Methanol	174	225	245	267	262	254	218	211	137	137
Carbon Black	331	386	395	402	407	415	384	363	386	386
Total	**1,277**	**1,646**	**1,726**	**1,760**	**1,767**	**1,837**	**1,658**	**1,479**	**1,509**	**1,509**
Iron and Steel Production										
Coke[a]	251	201	193	172	163	148	155	130	132	132
Sinter	141	144	136	132	125	127	124	106	104	104
Pig Iron	1,028	1,053	1,023	1,027	998	958	991	872	833	833
Total	**1,420**	**1,399**	**1,352**	**1,330**	**1,286**	**1,233**	**1,271**	**1,108**	**1,068**	**1,068**
Total Industrial Processes	**2,697**	**3,044**	**3,078**	**3,090**	**3,053**	**3,070**	**2,928**	**2,587**	**2,577**	**2,577**

[a] Based on total U.S. production of metallurgical coke, including non-iron and steel uses.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: American Iron and Steel Institute, *Annual Statistical Report* (Washington, DC, various years); American Chemical Council (formerly the Chemical Manufacturers Association), *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years); and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.23, web site www.ipcc/pub/guide.htm.

4. Nitrous Oxide Emissions

Overview

U.S. Anthropogenic Nitrous Oxide Emissions, 1990-2003

	Nitrous Oxide	Carbon Dioxide Equivalent
Estimated 2003 Emissions (Thousand Metric Tons)	1,082	320,181
Change Compared to 2002 (Thousand Metric Tons)	-10	-2,999
Change from 2002 *(Percent)*	*-0.9%*	*-0.9%*
Change Compared to 1990 (Thousand Metric Tons)	-29	-8,486
Change from 1990 *(Percent)*	*-2.6%*	*-2.6%*

Estimated U.S. anthropogenic nitrous oxide emissions totaled 1,082 thousand metric tons in 2003, 0.9 percent less than in 2002 and 2.6 percent below 1990 levels (Table 24). Almost all of the decrease from 2002 can be attributed to reduced emissions from industrial sources and nitrogen fertilization of agricultural soils. Emissions from industrial sources decreased by 6 thousand metric tons of nitrous oxide compared with 2002 levels, and emissions from nitrogen fertilization of agricultural soils decreased by 5 thousand metric tons of nitrous oxide.

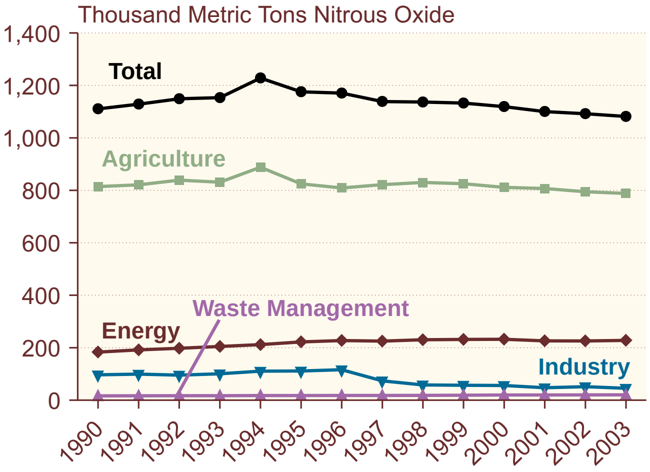
The 2003 decline in nitrous oxide emissions continues a downward trend that began in 1995 after emissions of nitrous oxide peaked at 1,228 thousand metric tons in 1994. The decrease in emissions of nitrous oxide from 1990 can also be attributed primarily to declines in the emissions from industrial sources (adipic acid and nitric acid production) and nitrogen fertilization of agricultural soils, which fell by a combined 73 thousand metric tons between 1990 and 2003, more than offsetting the increase of 39 thousand metric tons in emissions from mobile combustion sources since 1990.

Weighted by global warming potential, total nitrous oxide emissions in 2003 were equivalent to 320.2 million metric tons carbon dioxide, or 4.6 percent of total U.S. greenhouse gas emissions. In 2002, total nitrous oxide emissions were equivalent to 323.2 million metric tons of carbon dioxide, or 4.7 percent of total U.S. greenhouse gas emissions.

Sources of U.S. nitrous oxide emissions include energy use, agriculture, waste management, and industrial processes. The largest component of U.S. anthropogenic nitrous oxide emissions is emissions from agricultural activities, representing 72.9 percent of the total. Nitrogen fertilization of agricultural soils represents 73.8 percent of emissions from agricultural activities. Most of the remainder is from the handling of animal waste in managed systems. Small quantities of nitrous oxide are also released from the burning of crop residues. Estimated emissions of nitrous oxide from agricultural sources were 788 thousand metric tons (or 233.3 million metric tons carbon dioxide equivalent) in 2003, 0.8 percent below 2002 levels and 3.2 percent below 1990 levels (Figure 3).

The second-largest source of anthropogenic nitrous oxide emissions is energy consumption, which includes mobile source combustion from passenger cars, buses, motorcycles and trucks, and stationary source combustion from commercial, residential, industrial, and electric power sector energy use. Energy use was responsible for the release of 228 thousand metric tons of nitrous oxide or 67.5 million metric tons carbon dioxide equivalent in 2003 (21.1 percent of total U.S. nitrous oxide emissions). Although the 2003 level of emissions from energy sources is 1.0 percent lower than in 2002, it is 24.4 percent higher than in 1990.

Figure 3. U.S. Emissions of Nitrous Oxide by Source, 1990-2003



Source: Estimates presented in this chapter.

Sources of U.S. Anthropogenic Nitrous Oxide Emissions, 1990-2003

Source	Thousand Metric Tons Nitrous Oxide 1990	Thousand Metric Tons Nitrous Oxide 2003	*Percent Change* 1990-2003	*Percent Change* 2002-2003
Energy	183	228	*24.4%*	*1.0%*
Agriculture	814	788	*-3.2%*	*-0.8%*
Industrial	96	45	*-53.0%*	*-11.8%*
Waste Management	16	20	*23.7%*	*0.9%*

Industrial production of adipic and nitric acid, which releases nitrous oxide as a byproduct, accounted for emissions of 45 thousand metric tons of nitrous oxide or 13.4 million metric tons carbon dioxide equivalent in 2003 (4.2 percent of total U.S. nitrous oxide emissions), an 11.8-percent decrease from 2002 levels and a 53-percent decrease from 1990 levels. The decrease in emissions from this source in 2003 is primarily the result of a 7.9-percent reduction (608 thousand metric tons) in nitric acid production compared with 2002. The large decline in emissions of nitrous oxide from adipic acid production since 1990 is a result of the continuing utilization of emissions control technology at three of the four adipic acid plants operating in the United States.

Energy Use

U.S. Nitrous Oxide Emissions from Energy, 1990-2003

Estimated 2003 Emissions (Thousand Metric Tons Nitrous Oxide)	228
Change Compared to 2002 (Thousand Metric Tons Nitrous Oxide)	2
Change from 2002 *(Percent)*	*1.0%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	45
Change from 1990 *(Percent)*	*24.4%*

The energy use category includes nitrous oxide emissions from both mobile and stationary sources as byproducts of fuel combustion. Estimated 2003 energy-related emissions were 228 thousand metric tons, or 21.1 percent of total U.S. anthropogenic nitrous oxide emissions (Table 24). Emissions from energy use are dominated by mobile combustion (78.1 percent of nitrous oxide emissions from energy use in 2003).

Mobile Combustion

Nitrous oxide emissions from mobile source combustion in 2003 were 178 thousand metric tons or 52.7 million metric tons carbon dioxide equivalent, an increase of 1 thousand metric tons nitrous oxide or 0.4 million metric tons carbon dioxide equivalent (0.7 percent) from 2002 levels (Table 25). In addition to emissions from passenger cars and light-duty trucks, emissions from air, rail, and marine transportation and from farm and construction equipment are also included in the estimates. Motor vehicles, however, are the predominant source, accounting for 93.1 percent of nitrous oxide emissions from mobile combustion (Table 25).

Nitrous oxide emissions from motor vehicles are caused primarily by the conversion of nitrogen oxides (NO_x) into nitrous oxide (N_2O) by vehicle catalytic converters. The normal operating temperature of catalytic converters is high enough to cause the thermal decomposition of nitrous oxide. Consequently, it is probable that nitrous oxide emissions result primarily from “cold starts” of motor vehicles and from catalytic converters that are defective or operating under abnormal conditions. This implies that the primary determinant of the level of emissions is motor vehicle operating conditions; however, different types of catalytic converters appear to differ systematically in their emissions, and emissions probably vary with engine size. Thus, emissions also depend on the “mix” of vehicle age and type on the road.

Nitrous oxide emissions from mobile sources grew rapidly between 1990 and 1996 due to increasing motor vehicle use, the shifting composition of the light-duty vehicle fleet toward light trucks that have lower fuel economy and higher per-mile emission factors, and the gradual replacement of low emitting pre-1983 vehicles that did not use catalytic converters with higher emitting post-1983 vehicles that do use catalytic converters. This growth moderated between 1996 and 1999 due to the introduction of more advanced, lower-emitting catalytic converters. After peaking in 1999, emissions have declined slowly as vehicle turnover has led to a fleet dominated by the more advanced catalytic converters.

Stationary Combustion

In 2003, estimated nitrous oxide emissions from stationary combustion sources were 50 thousand metric tons or 14.8 million metric tons carbon dioxide equivalent, 1.9 percent higher than in 2002 and 12.2 percent higher than in 1990 (Table 26). The emissions increase from this source between 1990 and 2003 can be attributed principally to coal-fired electricity generation, which expanded by 26.1 percent during the period. This expansion, in response to the growing demand for electricity and lower costs associated with coal-fired generation, was achieved primarily through higher capacity utilization rates at existing facilities. Coal-fired combustion systems produced 64.0 percent (32 thousand metric tons) of the 2003 emissions of nitrous oxide from stationary combustion. Other fuels—including fuel oil (8 thousand metric tons), wood (8 thousand metric tons), and natural gas (2 thousand metric tons)—accounted for the balance. During combustion, nitrous oxide is produced as a result of chemical interactions between nitrogen oxides (mostly NO_2) and other combustion products. With most conventional stationary combustion systems, high temperatures destroy almost all nitrous oxide, limiting the quantity that escapes; therefore, emissions from these systems typically are low.

Agriculture

U.S. Nitrous Oxide Emissions from Agriculture, 1990-2003

Estimated 2003 Emissions (Thousand Metric Tons Nitrous Oxide)	788
Change Compared to 2002 (Thousand Metric Tons Nitrous Oxide)	-6
Change from 2002 *(Percent)*	*-0.8%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	-26
Change from 1990 *(Percent)*	*-3.2%*

Nitrous oxide emissions from agricultural activities fell by 6 thousand metric tons (0.8 percent) in 2003 compared with 2002 (788 and 795 thousand metric tons, respectively). Since 1990, nitrous oxide emissions from agricultural activities have fallen by 3.2 percent. Agricultural activities were responsible for 72.9 percent of U.S. nitrous oxide emissions in 2003, roughly the same percentage that agricultural practices contribute to nitrous oxide emissions globally.[70] At 233.3 million metric tons carbon dioxide equivalent, nitrous oxide emissions from agricultural activities represent 3.4 percent of total U.S. greenhouse gas emissions.

Nitrogen fertilization of agricultural soils accounted for 73.8 percent of U.S. agricultural emissions of nitrous oxide in 2003 (Table 24). Nearly all the remaining agricultural emissions can be traced to the management of the solid waste of domesticated animals. The disposal of crop residues by burning also produces nitrous oxide that is released into the atmosphere; however, the amount is relatively minor, at 2 thousand metric tons or 0.2 percent of total U.S. emissions of nitrous oxide from agricultural sources in 2003.

Nitrogen Fertilization of Agricultural Soils

EIA estimates that a total of 581 thousand metric tons of nitrous oxide (or 172.1 million metric tons carbon dioxide equivalent) was released into the atmosphere as a result of direct and indirect emissions associated with fertilization practices in 2003 (Table 27). Estimated emissions decreased by 0.8 percent compared with 2002 levels and were 3.7 percent lower than in 1990.

Nitrogen uptake and nitrous oxide emissions occur naturally as a result of nitrification and denitrification processes in soil and crops, generally through bacterial action. When nitrogen compounds are added to the soil, bacterial action is stimulated, and emissions generally increase, unless the application precisely matches plant uptake and soil capture.[71] Nitrogen may be added to the soil by synthetic or organic fertilizers, nitrogen-fixing crops, and crop residues. Nitrogen-rich soils, called "histosols," may also stimulate emissions. Direct emissions in 2003 (456 thousand metric tons) represented 78.3 percent of total emissions from nitrogen fertilization, with the primary components including the biological fixation of nitrogen in crops (176 thousand metric tons), nitrogen fertilizers (155 thousand metric tons), and crop residues (109 thousand metric tons).

Indirect emissions from nitrogen fertilization result from adding excess nitrogen to the soil, which in turn enriches ground and surface waters such as rivers and streams, and results in emissions of nitrous oxide. This source is referred to as "soil leaching." Additional indirect emissions occur from "atmospheric deposition," in which soils emit other nitrogen compounds that react to form nitrous oxide in the atmosphere. Indirect emissions in 2003 (126 thousand metric tons) represented 21.7 percent of total emissions from nitrogen fertilization, with soil leaching accounting for 107 thousand metric tons and atmospheric deposition totaling 19 thousand metric tons.

There are significant uncertainties associated with estimating the amount of emissions produced by adding nitrogen to agricultural soils. Models used to estimate the amount are based on limited sources of experimental data.[72] The uncertainty increases when moving from emissions associated with animal manure to soil

---

[70] A.R. Mosier, "Nitrous Oxide Emissions from Agricultural Soils," in A.R. van Amstel (ed.), *International IPCC Workshop Proceedings: Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control* (Bilthoven, Netherlands: RIVM, 1993), p. 277.

[71] A.F. Bouwman, "Exchange of Greenhouse Gases Between Terrestrial Ecosystems and the Atmosphere," in A.F. Bouwman (ed.), *Soils and the Greenhouse Effect* (New York, NY: John Wiley and Sons, 1990).

[72] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.87-4.100, web site www.ipcc.ch/pub/guide.htm.

mineralization and atmospheric deposition, where both estimating the amount of emissions and segmenting anthropogenic from biogenic sources become increasingly difficult.

Solid Waste of Domesticated Animals

Estimated 2003 nitrous oxide emissions from animal waste management were 205 thousand metric tons (or 60.7 million metric tons carbon dioxide equivalent), down by 0.8 percent from 2002 levels and 2.0 percent lower than 1990 levels (Table 28), making animal waste the second-largest U.S. agricultural source of nitrous oxide emissions, after nitrogen fertilization of soils. Nitrous oxide emissions from animal waste are dominated by emissions from cattle waste, which in 2003 accounted for 92.7 percent of emissions from the solid waste of domesticated animals.

Nitrous oxide is released as part of the microbial denitrification of animal manure. The total volume of nitrous oxide emissions is a function of animal size and manure production, the amount of nitrogen in the animal waste, and the method of managing the animal waste. Waste managed by a solid storage or pasture range method may emit 20 times more nitrous oxide per unit of nitrogen content than does waste managed in anaerobic lagoon and liquid systems. Generally, solid waste from feedlot beef cattle is managed with the solid storage or pasture range method, accounting for the majority of nitrous oxide emissions. Solid waste from swine is generally managed in anaerobic lagoons and other liquid systems. Anaerobic digestion yields methane emissions but only negligible amounts of nitrous oxide. Thus, changes in estimated emissions result primarily from changes in cattle populations. For example, beef cattle populations grew during the first half of the 1990s, leading to higher emissions through 1995, but have since declined slowly, lowering emissions to below 1990 levels.

Crop Residue Burning

In 2003, estimated emissions of nitrous oxide from crop residue burning were 2 thousand metric tons (or 0.5 million metric tons carbon dioxide equivalent), down by less than 0.03 thousand metric tons nitrous oxide (1.6 percent) from 2002 levels (Table 24). The small decrease is mainly attributable to decreased corn and soybean production. Emissions from this source remain very small, at 0.2 percent of all U.S. nitrous oxide emissions. When crop residues are burned, the incomplete combustion of agricultural waste results in the production of nitrous oxide, as well as methane (discussed in Chapter 3).

Waste Management

U.S. Nitrous Oxide Emissions from Waste Management, 1990-2003

Estimated 2003 Emissions (Thousand Metric Tons Nitrous Oxide)	20
Change Compared to 2002 (Thousand Metric Tons Nitrous Oxide)	*
Change from 2002 *(Percent)*	*0.9%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	4
Change from 1990 *(Percent)*	*23.7%*

*Less than 0.5 thousand metric tons.

Nitrous oxide emissions from waste management are estimated at 20 thousand metric tons (or 6.0 million metric tons carbon dioxide equivalent) for 2003, 1.9 percent of all U.S. anthropogenic nitrous oxide emissions (Table 24). During 2003, emissions from human sewage in wastewater were responsible for 96.1 percent of the estimated emissions from this source, and the remainder was associated with waste combustion. Estimated emissions from waste management increased by 0.9 percent between 2002 and 2003 and by 23.7 percent between 1990 and 2003. Because of the lack of reliable data and an effective estimation method, no estimate of emissions from industrial wastewater was calculated, leaving estimated emissions from waste management lower than they otherwise would be had a viable estimation method been available.

Human Sewage in Wastewater

In 2003, nitrous oxide emissions from wastewater were 19 thousand metric tons (or 5.8 million metric tons carbon dioxide equivalent), a 0.8-percent increase from 2002 levels and a 24.7-percent increase from the 1990 level (Table 24). Estimates of nitrous oxide emissions from human waste are scaled to population size and per capita protein intake. U.S. population has grown by 16.6 percent since 1990. U.S. per capita protein intake rose steadily between 1990 and 1999, before declining slightly in 2000, 2001, and 2002. Today, U.S. per capita protein intake is 7.0 percent above 1990 levels. Data on protein intake are taken from the United Nations Food and Agriculture Organization (FAO).[73]

Nitrous oxide is emitted from wastewater that contains nitrogen-based organic materials, such as those found in human or animal waste. Two natural processes—

---

[73] Food and Agriculture Organization of the United Nations, statistical databases, web site http://apps.fao.org.

nitrification and denitrification—combine to produce nitrous oxide. Nitrification, an aerobic process, converts ammonia into nitrate; denitrification, an anaerobic process, converts nitrate to nitrous oxide. Factors that influence the amount of nitrous oxide generated from wastewater include temperature, acidity, biochemical oxygen demand (BOD),[74] and nitrogen concentration.

Waste Combustion

In 2003, estimated nitrous oxide emissions from waste combustion were 1 thousand metric tons, up 3.2 percent from 2002 levels and 2.5 percent above 1990 levels. Data on the amount of waste generated in the United States in 2003 were not available in time for this report; therefore, EIA scaled the 2003 estimates for waste combustion to the growth in U.S. gross domestic product. The share of waste burned is estimated to have been unchanged from 2002 to 2003, and the total volume of waste generated is estimated to have increased by 3.2 percent. The total volume of waste generated in the United States increased by 53.1 percent between 1990 and 2003; however, the share of waste burned in 2003 was just 7.7 percent, compared with 11.5 percent in 1990.[75]

Industrial Sources

U.S. Nitrous Oxide Emissions from Industrial Sources, 1990-2003

Estimated 2003 Emissions (Thousand Metric Tons Nitrous Oxide)	45
Change Compared to 2002 (Thousand Metric Tons Nitrous Oxide)	-6
Change from 2002 *(Percent)*	*-11.8%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	-51
Change from 1990 *(Percent)*	*-53.0%*

Emissions of nitrous oxide from industrial sources were 45 thousand metric tons (or 13.4 million metric tons carbon dioxide equivalent) in 2003, a decrease of 6 thousand metric tons or 1.8 million metric tons carbon dioxide equivalent (11.8 percent) from 2002 and a decrease of 51 thousand metric tons or 15.1 million metric tons carbon dioxide equivalent (53.0 percent) since 1990. Nitrous oxide is emitted as a byproduct of certain chemical production processes. Table 29 provides estimates of emissions from the production of adipic acid and nitric acid, the two principal known sources.

Adipic Acid Production

Emissions from adipic acid production fell from 13 thousand metric tons of nitrous oxide (or 3.9 million metric tons carbon dioxide equivalent) in 2002 to 10 thousand metric tons (or 3.0 million metric tons carbon dioxide equivalent) in 2003—a decrease of 22.9 percent. As discussed below, emissions from this source have been in the range of 12 to 13 thousand metric tons of nitrous oxide per year since 1998.

Adipic acid is a fine white powder that is used primarily in the manufacture of nylon fibers and plastics, such as carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizer for polyvinyl chloride and polyurethane resins, lubricants, insecticides, and dyes. In the United States, three companies, which operate a total of four plants, manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid. Nitrous oxide is an intrinsic byproduct of this chemical reaction. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.[76] Between 1990 and 1996, emissions from adipic acid manufacture grew by 23.2 percent, reaching 70 thousand metric tons of nitrous oxide (or 20.7 million metric tons carbon dioxide equivalent) before dropping sharply to 27 thousand metric tons of nitrous oxide (or 7.8 million metric tons carbon dioxide equivalent) in 1997 (Table 29).

Beginning in 1996, two of the four plants that manufacture adipic acid controlled emissions by thermally decomposing the nitrous oxide. This technique eliminates 98 percent of potential nitrous oxide emissions from the process.[77] During the first quarter of 1997, a third plant installed emissions controls, increasing the share of adipic acid production employing emissions abatement controls from 74.1 percent in 1996 to 91.6 percent in 1997. In 1998, with emissions controls in place for the full year, 97.4 percent of emissions from U.S. adipic acid production were controlled.[78] Estimated emissions of nitrous oxide from uncontrolled adipic acid production decreased from 22 thousand metric tons in 1997 to 5 thousand metric tons in 2003, and 2003 emissions of nitrous oxide from controlled plants remained relatively

---

[74] Biochemical oxygen demand is a measure of the organic content within the wastewater that is subject to decomposition.

[75] "Nationwide Survey: The State of Garbage in America," *Biocycle* (January 2004), p. 31. Waste streams were estimated for 2003 by scaling to economic growth, and the share of waste combusted was held constant at the 2002 level.

[76] M.H. Thiemens and W.C. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 1991).

[77] Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

[78] R.A. Reimer, R.A. Parrett, and C.S. Slaten, "Abatement of N_2O Emissions Produced in Adipic Acid," in *Proceedings of the Fifth International Workshop on Nitrous Oxide Emissions* (Tsukuba, Japan, July 1992).

constant at 5 thousand metric tons. With the share of adipic acid production employing abatement controls now at nearly 100 percent, future changes in nitrous oxide emissions from this source are expected to result primarily from changes in plant production levels in response to market demand.

Nitric Acid Production

The 6.4 million metric tons of nitric acid manufactured in 2003[79] resulted in estimated emissions of 35 thousand metric tons of nitrous oxide, equivalent to 10.4 million metric tons of carbon dioxide (Table 29). This estimate was 7.9 percent lower than 2002 levels and 11.2 percent lower than 1990 levels. The emissions factor used to estimate nitrous oxide emissions from the production of nitric acid was based on measurements at a single DuPont plant, which indicated an emissions factor of 2 to 9 grams of nitrous oxide emitted per kilogram of nitric acid manufactured, suggesting a significant range of uncertainty. Nitric acid, a primary ingredient in fertilizers, usually is manufactured by oxidizing ammonia (NH_3) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation.

---

[79] U.S. Department of Commerce, Bureau of Census, *Current Industrial Reports: Fertilizer Materials and Related Products, Fourth Quarter 2003*, MQ325B(03)-4 (Washington, DC, March 2004), Table 1.

Table 24. Estimated U.S. Emissions of Nitrous Oxide, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Nitrous Oxide										
Energy										
Mobile Combustion	139	175	179	176	182	182	182	177	177	178
Stationary Combustion	45	47	49	49	48	49	50	49	49	50
Total	**183**	**222**	**227**	**225**	**230**	**231**	**232**	**226**	**226**	**228**
Agriculture										
Nitrogen Fertilization of Soils	604	601	587	604	616	613	601	598	586	581
Crop Residue Burning	2	2	2	2	2	2	2	2	2	2
Solid Waste of Domesticated Animals	209	222	220	216	212	211	209	208	207	205
Total	**814**	**825**	**809**	**822**	**830**	**825**	**811**	**807**	**795**	**788**
Waste Management										
Waste Combustion	1	1	1	1	1	1	1	1	1	1
Human Sewage in Wastewater	16	17	17	17	18	18	19	19	19	19
Total	**16**	**18**	**18**	**18**	**18**	**19**	**20**	**20**	**20**	**20**
Industrial Processes	**96**	**111**	**116**	**74**	**58**	**57**	**56**	**47**	**51**	**45**
Total	**1,110**	**1,175**	**1,170**	**1,138**	**1,137**	**1,132**	**1,119**	**1,100**	**1,092**	**1,082**
Million Metric Tons Carbon Dioxide Equivalent										
Energy										
Mobile Combustion	41.1	51.9	52.9	52.1	53.8	54.0	53.8	52.5	52.3	52.7
Stationary Combustion	13.2	13.8	14.4	14.5	14.3	14.5	14.9	14.4	14.6	14.8
Total	**54.2**	**65.7**	**67.3**	**66.6**	**68.2**	**68.5**	**68.7**	**66.9**	**66.8**	**67.5**
Agriculture										
Nitrogen Fertilization of Soils	178.6	178.0	173.9	178.9	182.2	181.4	177.7	176.9	173.5	172.1
Crop Residue Burning	0.5	0.5	0.5	0.5	0.6	0.5	0.6	0.6	0.5	0.5
Solid Waste of Domesticated Animals	61.9	65.6	65.1	63.8	62.9	62.4	61.8	61.4	61.2	60.7
Total	**241.0**	**244.1**	**239.5**	**243.2**	**245.7**	**244.3**	**240.1**	**238.9**	**235.2**	**233.3**
Waste Management										
Waste Combustion	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Human Sewage in Wastewater	4.6	5.0	5.1	5.1	5.2	5.4	5.6	5.6	5.7	5.8
Total	**4.8**	**5.3**	**5.4**	**5.4**	**5.4**	**5.6**	**5.8**	**5.9**	**5.9**	**6.0**
Industrial Processes	**28.6**	**32.9**	**34.3**	**21.8**	**17.2**	**16.8**	**16.6**	**14.0**	**15.2**	**13.4**
Total	**328.7**	**347.9**	**346.5**	**337.0**	**336.4**	**335.2**	**331.2**	**325.6**	**323.2**	**320.2**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.81-4.94, web site www.ipcc.ch/pub/guide.htm; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenter PublicationsGHGEmissionsUSEmissionsInventory2004.html.

Table 25. U.S. Nitrous Oxide Emissions from Mobile Combustion, 1990 and 1995-2003

Item	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Nitrous Oxide										
Motor Vehicles										
Passenger Cars	85	100	100	98	102	102	100	97	96	96
Buses	*	*	*	*	*	*	*	*	*	*
Motorcycles	*	*	*	*	*	*	*	*	*	*
Light-Duty Trucks	35	56	58	58	59	60	59	59	60	61
Other Trucks	6	7	7	8	8	8	8	8	8	8
Total	**127**	**163**	**166**	**164**	**170**	**170**	**168**	**165**	**164**	**166**
Other Mobile Sources	**12**	**12**	**13**	**12**	**12**	**13**	**13**	**13**	**12**	**12**
Total	**139**	**175**	**179**	**176**	**182**	**182**	**182**	**177**	**177**	**178**
Million Metric Tons Carbon Dioxide Equivalent										
Motor Vehicles										
Passenger Cars	25.2	29.5	29.7	28.9	30.1	30.1	29.7	28.8	28.4	28.4
Buses	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	*	*	*	*	*	*	*	*	*	*
Light-Duty Trucks	10.4	16.5	17.1	17.2	17.6	17.6	17.6	17.4	17.8	18.2
Other Trucks	1.7	2.1	2.2	2.3	2.3	2.4	2.4	2.5	2.3	2.3
Total	**37.4**	**48.2**	**49.1**	**48.5**	**50.2**	**50.3**	**49.9**	**48.8**	**48.6**	**49.0**
Other Mobile Sources	**3.6**	**3.6**	**3.7**	**3.6**	**3.6**	**3.7**	**3.9**	**3.7**	**3.7**	**3.7**
Total	**41.1**	**51.9**	**52.9**	**52.1**	**53.8**	**54.0**	**53.8**	**52.5**	**52.3**	**52.7**

*Less than 500 metric tons nitrous oxide or less than 50,000 metric tons carbon dioxide equivalent.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: Calculations based on vehicle miles traveled from U.S. Department of Transportation, *Federal Highway Statistics* (various years), Table VM-1, and current year preliminary estimates calculated using growth rates from EIA, *Short-Term Energy Outlook* (various years). Other Mobile Sources calculations based on Oak Ridge National Laboratory, *Transportation Energy Data Book*; EIA, *Fuel Oil and Kerosene Sales*, *State Energy Data Report*, and *Petroleum Supply Annual* (various years). Passenger car and light-duty truck emissions coefficients from U.S. Environmental Protection Agency, Office of Air and Radiation, *Emissions of Nitrous Oxide From Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996*, EPA-420-R-98-009 (Washington DC, August 1998). Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.64-1.68, web site www.ipcc.ch/pub/guide.htm.

Table 26. U.S. Nitrous Oxide Emissions from Stationary Combustion, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
	Thousand Metric Tons Nitrous Oxide									
Residential										
Coal	*	*	*	*	*	*	*	*	*	*
Fuel Oil[a]	1	1	1	1	1	1	1	1	1	1
Natural Gas	*	*	1	*	*	*	*	*	*	1
Wood	2	2	2	2	2	2	2	1	1	1
Total	**4**	**4**	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Commercial										
Coal	*	*	*	*	*	*	*	*	*	*
Fuel Oil[a]	1	*	*	*	*	*	*	*	*	*
Natural Gas	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*
Total	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Industrial										
Coal	4	3	3	3	3	3	3	3	3	3
Fuel Oil[a]	5	5	5	6	5	6	6	6	6	6
Natural Gas	1	1	1	1	1	1	1	1	1	1
Wood	6	7	7	7	6	6	6	6	6	6
Total	**10**	**10**	**10**	**10**	**10**	**10**	**9**	**10**	**9**	**9**
Electric Power										
Coal	23	25	26	27	27	27	28	28	28	29
Fuel Oil[a]	1	*	*	1	1	1	1	1	1	1
Natural Gas	*	*	*	*	*	*	1	1	1	*
Wood	1	*	1	1	1	1	1	*	1	1
Total	**24**	**26**	**27**	**28**	**29**	**29**	**30**	**30**	**30**	**31**
Total All Sectors										
Coal	**27**	**28**	**30**	**30**	**30**	**30**	**32**	**31**	**31**	**32**
Fuel Oil[a]	**7**	**7**	**7**	**7**	**7**	**8**	**8**	**8**	**8**	**8**
Natural Gas	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Wood	**9**	**10**	**10**	**9**	**9**	**9**	**9**	**8**	**8**	**8**
Total	**45**	**47**	**49**	**49**	**48**	**49**	**50**	**49**	**49**	**50**

[a] Fuel oil use in the residential sector consists of distillate fuel only. In the other sectors it includes both distillate and residual fuel oil.
*Less than 500 metric tons nitrous oxide.
P = preliminary data. See notes and sources at end of table.

Table 26. U.S. Nitrous Oxide Emissions from Stationary Combustion, 1990 and 1995-2003 (Continued)

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
	Thousand Metric Tons Carbon Dioxide Equivalent									
Residential										
Coal	11	7	7	7	5	6	5	5	5	5
Fuel Oil[a]	251	247	266	255	235	263	279	275	265	269
Natural Gas	129	142	153	145	133	138	146	140	143	149
Wood	677	694	693	504	451	482	504	431	365	418
Total	**1,067**	**1,090**	**1,119**	**912**	**824**	**889**	**934**	**851**	**777**	**841**
Commercial										
Coal	54	49	51	54	38	43	38	40	38	39
Fuel Oil[a]	170	131	134	126	118	118	134	135	122	124
Natural Gas	77	88	92	94	88	89	93	89	91	92
Wood	45	54	58	57	56	61	62	47	49	49
Total	**346**	**322**	**335**	**330**	**300**	**311**	**326**	**310**	**299**	**304**
Industrial										
Coal	1,131	1,020	995	977	914	893	906	929	873	896
Fuel Oil[a]	1,478	1,538	1,617	1,659	1,628	1,678	1,629	1,652	1,638	1,660
Natural Gas	242	274	283	283	279	268	271	248	254	238
Wood	1,680	1,924	1,961	2,017	1,867	1,887	1,906	1,681	1,784	1,775
Total	**2,851**	**2,832**	**2,895**	**2,920**	**2,820**	**2,839**	**2,802**	**2,830**	**2,764**	**2,794**
Electric Power										
Coal	6,770	7,278	7,680	7,878	8,008	8,034	8,426	8,205	8,342	8,539
Fuel Oil[a]	228	135	146	166	233	216	204	229	216	214
Natural Gas	94	123	110	118	133	140	151	153	164	143
Wood	150	146	161	160	160	161	156	147	175	188
Total	**7,242**	**7,682**	**8,097**	**8,321**	**8,534**	**8,551**	**8,937**	**8,733**	**8,897**	**9,084**
Total All Sectors										
Coal	**7,965**	**8,354**	**8,733**	**8,916**	**8,965**	**8,976**	**9,375**	**9,179**	**9,257**	**9,479**
Fuel Oil[a]	**2,128**	**2,051**	**2,163**	**2,205**	**2,214**	**2,275**	**2,243**	**2,291**	**2,240**	**2,268**
Natural Gas	**541**	**627**	**638**	**640**	**633**	**634**	**660**	**630**	**652**	**622**
Wood	**2,552**	**2,818**	**2,873**	**2,738**	**2,534**	**2,591**	**2,628**	**2,350**	**2,372**	**2,430**
Total	**13,187**	**13,850**	**14,406**	**14,499**	**14,345**	**14,476**	**14,906**	**14,405**	**14,521**	**14,799**

[a] Fuel oil use in the residential sector consists of distillate fuel only. In the other sectors it includes both distillate and residual fuel oil.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.50, web site www.ipcc.ch/pub/guide.htm. Energy consumption data from Energy Information Administration, *State Energy Data Report 1998*, DOE/EIA-0214(98) (Washington, DC, September 2003); and *Monthly Energy Review*, DOE/EIA-0035(2003/08) (Washington, DC, August 2003).

Table 27. U.S. Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils, 1990 and 1995-2003
(Thousand Metric Tons Nitrous Oxide)

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Nitrous Oxide										
Direct Emissions										
Nitrogen Fertilizers	179	173	159	159	161	161	154	150	154	155
Animal Manure	4	5	4	4	4	4	4	4	4	4
Crop Residues	94	94	106	114	117	113	116	116	111	109
Soil Mineralization	10	10	10	10	10	11	11	11	11	11
Biological Fixation in Crops	171	179	178	187	194	193	191	195	182	176
Sewage Sludge	1	1	1	1	1	1	1	1	2	2
Total Direct Emissions	**459**	**461**	**459**	**475**	**486**	**482**	**476**	**476**	**461**	**456**
Indirect Emissions										
Soil Leaching	123	119	109	110	110	111	106	103	106	107
Atmospheric Deposition	22	21	20	20	20	20	19	18	19	19
Total Indirect Emissions	**144**	**140**	**129**	**129**	**130**	**130**	**125**	**122**	**125**	**126**
Total	**604**	**601**	**587**	**604**	**616**	**613**	**601**	**598**	**586**	**581**
Million Metric Tons Carbon Dioxide Equivalent										
Direct Emissions										
Nitrogen Fertilizers	53.1	51.2	47.1	47.2	47.5	47.7	45.6	44.4	45.6	46.0
Animal Manure	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Crop Residues	27.9	27.8	31.4	33.8	34.5	33.5	34.4	34.4	32.7	32.4
Soil Mineralization	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Biological Fixation in Crops	50.7	53.1	52.8	55.2	57.3	57.2	56.4	57.6	53.8	52.0
Sewage Sludge	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5
Total Direct Emissions	**135.9**	**136.5**	**135.7**	**140.6**	**143.8**	**142.8**	**140.8**	**140.9**	**136.6**	**134.8**
Indirect Emissions										
Soil Leaching	36.3	35.2	32.4	32.4	32.6	32.8	31.3	30.6	31.4	31.6
Atmospheric Deposition	6.5	6.3	5.8	5.8	5.8	5.8	5.6	5.5	5.6	5.6
Total Indirect Emissions	**42.8**	**41.4**	**38.2**	**38.2**	**38.5**	**38.6**	**36.9**	**36.0**	**37.0**	**37.3**
Total	**178.6**	**178.0**	**173.9**	**178.9**	**182.2**	**181.4**	**177.7**	**176.9**	**173.5**	**172.1**

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.89-4.107, web site www.ipcc.ch/pub/guide.htm. Total nitrogen content of U.S. commercial fertilizer consumption—1988-1994, Tennessee Valley Authority; 1995-2002, Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, DC, various years). Manure application based on cattle population data provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, web sites www.usda.gov/nass/pubs/histdata.htm and www.nass.usda.gov/ipedb/. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 6-8. Manure production and waste management systems used from L.M. Safley, M.E. Casada et al., *Global Methane Emissions From Livestock and Poultry Manure* (Washington, DC, February 1992), and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

Table 28. U.S. Nitrous Oxide Emissions from Solid Waste of Domesticated Animals, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Nitrous Oxide										
Cattle	194	206	205	200	197	195	194	192	192	190
Swine	5	5	5	6	6	6	5	6	6	6
Poultry	3	4	4	4	4	4	4	4	4	4
Sheep	3	3	3	2	2	2	2	2	2	2
Goats	1	1	1	1	1	1	1	1	1	1
Horses	2	2	2	2	2	2	2	2	2	2
Total	**209**	**222**	**220**	**216**	**212**	**211**	**209**	**208**	**207**	**205**
Million Metric Tons Carbon Dioxide Equivalent										
Cattle	57.5	61.1	60.6	59.2	58.3	57.9	57.4	56.9	56.7	56.3
Swine	1.5	1.6	1.5	1.7	1.7	1.6	1.6	1.6	1.6	1.7
Poultry	0.9	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Sheep	1.0	0.8	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6
Goats	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Horses	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Total	**61.9**	**65.6**	**65.1**	**63.8**	**62.9**	**62.4**	**61.8**	**61.4**	**61.2**	**60.7**

P = preliminary data.

Note: Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Nitrogen content of waste by species, manure management systems, and emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.89-4.107, web site www.ipcc.ch/pub/guide.htm. Population data for horses and goats extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture* (1982, 1987, 1992, and 1997). All other animal populations from U.S. Department of Agriculture, National Agricultural Statistics Service, web sites www.usda.gov/nass/pubs/histdata.htm and www.nass.usda.gov/ipedb/. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 6-8. Cattle sizes adjusted by annual slaughter weight from U.S. Department of Agriculture, National Agricultural Statistics Service.

Table 29. U.S. Nitrous Oxide Emissions from Industrial Sources, 1990 and 1995-2003

Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Thousand Metric Tons Nitrous Oxide										
Adipic Acid										
Controlled Sources	3	4	4	5	5	5	5	5	5	5
Uncontrolled Sources	54	63	66	22	7	7	7	7	8	5
Total	57	67	70	27	12	12	13	12	13	10
Nitric Acid	40	44	46	47	46	45	43	35	38	35
Total Known Industrial Sources	**96**	**111**	**116**	**74**	**58**	**57**	**56**	**47**	**51**	**45**
Million Metric Tons Carbon Dioxide Equivalent										
Adipic Acid										
Controlled Sources	1.0	1.1	1.1	1.4	1.5	1.5	1.6	1.4	1.6	1.6
Uncontrolled Sources	15.9	18.7	19.6	6.4	2.0	2.1	2.1	2.1	2.3	1.4
Total	16.8	19.8	20.7	7.8	3.5	3.6	3.7	3.5	3.9	3.0
Nitric Acid	11.7	13.1	13.6	13.9	13.7	13.2	12.9	10.4	11.3	10.4
Total Known Industrial Sources	**28.6**	**32.9**	**34.3**	**21.8**	**17.2**	**16.8**	**16.6**	**14.0**	**15.2**	**13.4**

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0573(2002) (Washington, DC, October 2003). Totals may not equal sum of components due to independent rounding.

Sources: Data sources and methods documented in Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0638(2002) (Washington, DC, January 2004), and *Documentation for Emissions of Greenhouse Gases in the United States 2003*, DOE/EIA-0638(2003) (to be published).

5. Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

Overview

Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2003

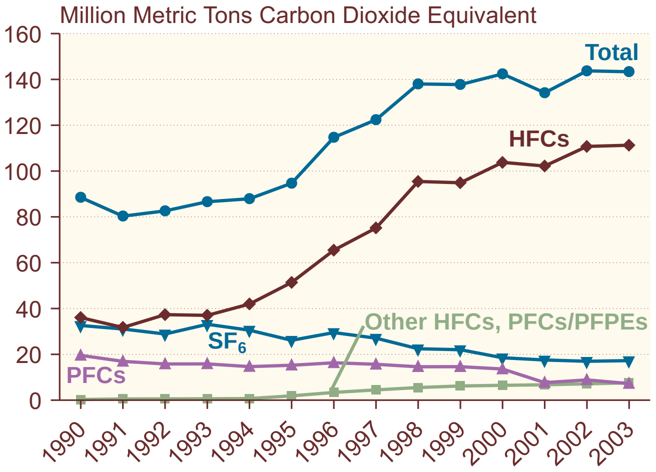
Estimated 2003 Emissions (Million Metric Tons Carbon Dioxide Equivalent)	143.4
Change Compared to 2002 (Million Metric Tons Carbon Dioxide Equivalent)	-0.4
Change from 2002 *(Percent)*	*-0.3%*
Change Compared to 1990 (Million Metric Tons Carbon Dioxide Equivalent)	54.8
Change from 1990 *(Percent)*	*62.0%*

In addition to the three principal greenhouse gases (carbon dioxide, methane, and nitrous oxide), there are other gases that account for 2.1 percent of total U.S. greenhouse gas emissions when weighted by their 100-year global warming potentials (GWP).[80] The U.S. Environmental Protection Agency (EPA) estimates total emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) in 2003 at 143.4 million metric tons carbon dioxide equivalent—a 0.3-percent decrease from 2002 emissions, but a 62.0-percent increase over 1990 emissions. Table 30 summarizes U.S. emissions of HFCs, PFCs, and SF_6 from 1990 to 2003, and Table 31 shows the corresponding emissions in metric tons carbon dioxide equivalent.

In summary, revised EPA data for 1990-2002 and new estimates for 2003 show that emissions of HFCs have risen significantly from their 1990 level; annual emissions of PFCs declined overall from 1990 through 2000 and then dropped more significantly since 2000; and SF_6 emissions have declined overall, falling to about one-half their 1990 level by 2002 (Figure 4). In the case of HFCs, the overall increase in emissions reflects the use of HFCs as replacements for CFCs (chlorofluorocarbons), halons, and other ozone-depleting chemicals that are being phased out under the Montreal Protocol because they damage the Earth's stratospheric ozone layer. The upward trend in HFC emissions is expected to continue in the next decade as HCFCs (hydrochlorofluorocarbons) used as interim substitutes for CFCs are also phased out under the provisions of the Copenhagen Amendments to the Montreal Protocol. PFC emissions from the aluminum industry have been falling since 1990; however, the decrease is partially offset by increases in PFC emissions from the semiconductor industry. Emissions of SF_6 have declined overall in the magnesium and utility sectors since 1990, despite an increase in use in the semiconductor industry.

The small quantities of HFCs, PFCs, and SF_6 that are emitted have disproportionate effects on overall emissions because of their large GWPs. PFCs and SF_6 have particularly high GWPs because of their stability, strong infrared absorption in the atmosphere, and long atmospheric lifetimes.[81] SF_6 is the most potent of the greenhouse gases, with a GWP of 22,200. PFCs, with

Figure 4. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2003



Source: Estimates presented in this chapter.

---

[80] Preliminary data estimates received by EIA from the U.S. Environmental Protection Agency (EPA), Office of Air and Radiation, September 2004. Note that EIA calculates emissions in carbon dioxide equivalent units using the GWP values published by the Intergovernmental Panel on Climate Change (IPCC) in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report.

[81] See discussion of relative forcing effects of gases in Chapter 1.

atmospheric lifetimes in the thousands of years, have GWPs in the range of 7,000 to 9,000. HFC-23 is the most potent greenhouse gas of the HFCs, with a GWP of 12,000, while other HFCs have GWPs in the range of 100 to 10,000.[82]

The emissions estimates in Table 30 are taken from data supplied by the EPA's Office of Air and Radiation.[83] The estimates in Table 31 are based on data provided by the EPA's Office of Air and Radiation in units of native gas (thousand metric tons), which were converted to carbon dioxide equivalent units by the Energy Information Administration (EIA), using GWP values from the IPCC's 2001 Third Assessment Report. The 2003 preliminary estimates were developed by the EPA and provided to EIA. They include some revisions to the historical emissions estimates, based on recent runs of the EPA's Vintaging Model (see boxes on pages 65 and 66). The revisions are reflected in the emissions estimates presented in this chapter.

Hydrofluorocarbons (HFCs)

U.S. Emissions of Hydrofluorocarbons, 1990-2003

Estimated 2003 Emissions (Million Metric Tons Carbon Dioxide Equivalent)	111.3
Change Compared to 2002 (Million Metric Tons Carbon Dioxide Equivalent)	0.5
Change from 2002 *(Percent)*	*0.5%*
Change Compared to 1990 (Million Metric Tons Carbon Dioxide Equivalent)	75.2
Change from 1990 *(Percent)*	*208.6%*

Since 1990, HFC emissions have accounted for a growing share (77.6 percent in 2003) of total carbon dioxide equivalent emissions of HFCs, PFCs, and SF_6 combined. The EPA estimates U.S. emissions of all HFCs in 2003 at 111.3 million metric tons carbon dioxide equivalent, a 0.5-percent increase from 2002 emissions and a 208.6-percent increase from 1990.[84] By far the largest portion of HFC emissions, 88.5 percent, is attributed to their use as replacements for ozone-depleting substances, which have grown from trace amounts in 1990 to 98.4 million metric tons carbon dioxide equivalent in 2003.

HFCs are compounds containing carbon, hydrogen, and fluorine. Although they do not destroy stratospheric ozone, they are powerful greenhouse gases. HFCs are used in many applications, such as solvents, domestic and commercial refrigerants, firefighting agents, propellants for pharmaceutical and industrial aerosols, foam-blowing agents, and in blends for air conditioning refrigerants.

The market for HFCs is expanding as CFCs and other ozone-depleting substances are being phased out under the Montreal Protocol and the Clean Air Act. HFCs have been introduced into the market to fill the void in many key applications. For example, HFCs are used in fire protection applications to replace Halon 1301 and Halon 1211, which are no longer being produced in the United States.[85] HCFCs, now interim replacements for CFCs, will also be phased out. For example, HCFC-141b and HCFC-142b, which are used as blowing agents in insulation foams, will be replaced by HFCs for some uses.[86]

Trifluoromethane (HFC-23)

The EPA estimates 2003 emissions of HFC-23 at 1,080 metric tons of gas.[87] Annual emissions have fluctuated since 1990, showing an overall decline of 64.0 percent by 2003. Although emissions of HFC-23 are relatively small, its high GWP (12,000)[88] gives it a substantial potential climatic effect. Nearly all HFC-23 emissions (97.6 percent) are created as a byproduct in the production of chlorodifluoromethane (HCFC-22) and generally are vented to the atmosphere. In some cases the HFC-23 is captured for use in a limited number of applications. While production of HCFC-22 peaked in 2000, emissions of HFC-23 from this source have declined since 1998,

---

[82] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

[83] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004.

[84] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004. Note that EIA calculates emissions in carbon dioxide equivalent units using the GWP values published by the IPCC in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report.

[85] European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/others/firefighting/main_appli/main.htm.

[86] European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/insulation/main_appli/main.htm.

[87] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004.

[88] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

EPA Revises Emissions Estimation Methodology

The primary source for the emission estimates presented in this chapter is data obtained from the U.S. Environmental Protection Agency (EPA), Office of Air and Radiation, which also prepares an annual inventory of greenhouse gas emissions.[a] The data supporting the EPA inventory include emissions estimates through 2003, incorporating a number of revisions to the estimates of HFC, PFC, and SF_6 emissions for 2002 and earlier years. Those changes are reflected in the estimates presented in this chapter.

The changes to the historical emission estimates are the result of revisions to the data and estimation methodologies used by the EPA:

- *Electrical Transmission and Distribution.* The changes in calculations of emissions from electricity transmission and distribution include both a revised methodology and updated activity data for 1990 through 1998. The revised methodology accounts for the quantity of SF_6 that is recaptured and/or released from operating electrical equipment, rather than assuming all SF_6 was released at the time of its initial installation into the equipment. The methodology assumes that only 22.5 percent of the SF_6 is emitted at the time of its installation and the remaining 77.5 percent is emitted over a 30-year period. The activity data were updated in two ways: first, with the results of a survey of SF_6 manufacturers conducted in 2002 by the RAND Corporation;[b] and second, with revised data received from participants in the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems, which led to updated regression equations and extrapolations to non-reporting partners. These revisions resulted in a decrease in estimated SF_6 emissions from electric power systems of 9.0 percent for 1990, 18.2 percent for 1998, and 3.3 percent for 2001; and an increase in estimated emissions of 1.4 percent in 2000.
- *Magnesium Production and Processing.* The emissions estimates in this report were revised to reflect new historical data supplied by participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. This change resulted in a decrease of about 0.5 percent in estimated SF_6 emissions for 2001.
- *Semiconductor Manufacture.* The EPA updated activity data provided by participants in EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry, as well as its PFC Emissions Vintaging Model (PEVM), which estimates emissions from entities that do not participate in the partnership program. The EPA also revised its methodology for estimating the historical distribution of emissions among HFCs, PFCs, and SF_6, by incorporating market information on sales volumes that was obtained in surveys. These updates resulted in an average decrease of 9 percent in estimates of emissions from semiconductor manufacture for 1995 through 2001.
- *Substitution of Ozone-Depleting Substances.* The EPA updated assumptions for its Vintaging Model pertaining to market trends in chemicals and chemical substitutes. These changes resulted in an average annual increase of 9.1 percent in HFC and PFC emissions for the period 1990 through 2001.
- *Aluminum Production.* In cooperation with the EPA's Voluntary Aluminum Industrial Partnership program, participants provided additional smelter-specific information on aluminum production and emission factors. The new information resulted in a decrease in PFC emissions of 1.0 percent for 1990 through 1994, 4.0 percent for 2001; and an increase of 12.0 percent for 2000.

[a] The information presented in this text box was obtained from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-004 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[b] K.D. Smythe, RAND Corporation, RAND Environmental Science and Policy Center, "Production and Distribution of SF_6 by End-Use Application," International Conference on SF_6 and the Environment: Emission Reduction Strategies (San Diego, CA, November 21-22, 2002).

because the emission rate of HFC-23 (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has decreased significantly. Production of HCFC-22 has also fallen significantly between 2000 and 2002, resulting in further reductions in emissions.[89]

HCFC-22 is used as a component of blowing agents for polyurethane foams and extruded polystyrene foams, and in the refrigerant market for stationary refrigeration and air conditioning (including chillers, room and household (central) air conditioners, and

---

[89] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-004 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

The EPA Vintaging Model: Estimation Methods and Uncertainty

The U.S. Environmental Protection Agency (EPA) uses a detailed Vintaging Model for equipment and products containing ozone-depleting substances (ODS) and ODS substitutes to estimate actual versus potential emissions of various ODS substitutes, including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). The model estimates the quantities of equipment and products sold each year that contain ODS and ODS substitutes, and the amounts of chemicals required for their manufacture and/or maintenance over time. Emissions from more than 40 different end uses are estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as it leaks over time.

For most products (refrigerators, air conditioners, fire extinguishers, etc.), emissions calculations are split into two categories: emissions during equipment lifetime, which arise from annual leakage and service losses plus emissions from manufacture; and disposal emissions, which occur when the equipment is discarded. By aggregating the data over different end uses, the model produces estimates of annual use and emissions of each compound.[a]

The EPA is consistently making improvements to the model to use more accurate data from the industries and to reduce uncertainty. The level of detail incorporated in the EPA Vintaging Model is higher than that of the default methodology used by the Intergovernmental Panel on Climate Change, although there still is some uncertainty about some of the model inputs, such as equipment characteristics and sales figures.

[a] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-004 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

dehumidifiers). The EPA administers a voluntary program with HCFC-22 producers to reduce HFC-23 emissions, which has helped to offset the rising demand for HCFC-22 in the short term. In the long term, domestic production of HCFC-22 for non-feedstock uses will be phased out by 2020 under the U.S. Clean Air Act, pursuant to U.S. agreements under the Copenhagen Amendments to the Montreal Protocol. However, its production for use as a feedstock in the production of other chemicals (fluorinated polymers) will be allowed to continue indefinitely and is anticipated to grow.[90]

Tetrafluoroethane (HFC-134a)

According to EPA estimates, emissions of HFC-134a, which has a GWP of 1,300,[91] were 46,559 metric tons in 2003.[92] HFC-134a accounts for the largest share of all HFC emissions (54.4 percent in terms of carbon dioxide equivalent), and the single largest share of any one gas for all HFC, PFC, and SF_6 emissions combined (42.2 percent). The 2003 estimate is 6.3 percent higher than that for 2002.

Since 1994, HFC-134a has been the transportation industry standard for replacing CFCs in air conditioners for passenger cars, trucks, trains, and buses, because it is nonflammable and has low toxicity. It is also used for domestic refrigeration and freezing, as a propellant for industrial and pharmaceutical aerosols, as a solvent, and as a blowing agent for extruded polystyrene foams.

HFC-134a is also used in refrigerant blends (e.g., R-404A) in most new commercial refrigeration equipment built in the United States and in commercial chillers, but leakage from these sources is much less than from automotive air conditioners. Leakage occurs primarily during the servicing of the units rather than during normal operation. Short-term uses of HFC-134a, on the other hand, are becoming an important source of emissions. Such uses include aerosols and open-cell foam blowing, which are denoted as short-term uses because most of the HFC-134a used will be emitted to the atmosphere within a short period of time.

HFCs make attractive solvents because of their nonflammability, thermal and chemical stability, excellent dielectric properties, high material compatibility, low surface tension and viscosity, and high liquid density. HFC-134a, in particular, is used in special extraction processes to produce important natural active pharmaceuticals, such as TAXOL® for breast cancer treatment,

---

[90] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-004 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[91] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

[92] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004.

nutraceuticals, flavors, and fragrances.[93] According to the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), worldwide sales of HFC-134a jumped more than fourfold between 1992 and 1993, doubled again in 1994, and continued growing steadily to 159,319 metric tons of gas in 2002.[94]

Other HFCs

Other HFCs with considerable radiative forcing potential include HFC-125, HFC-143a, and HFC-236fa, with 100-year GWPs of 3,400, 4,300, and 9,400, respectively.[95] The EPA estimates emissions of HFC-125 (pentafluoroethane) at 213 metric tons of gas in 1992, increasing to 5,247 metric tons in 2003.[96] The estimate for 2003 is 9.8 percent higher than the estimate for 2002. HFC-125 is used in the blend R-410A, which is designed to replace HCFC-22 as the refrigerant of choice for stationary commercial refrigeration and air conditioning applications, as well as in the blends R-404A and R-507A. Some manufacturers have already introduced air conditioners that use R-410A, but as yet the product has captured only a small percentage of the market. As the phase-out of HCFC-22 begins to gain momentum, producers expect a rapid increase in the demand for R-410A.[97] HFC-125 can also be used as a firefighting agent.

The EPA estimates 1993 emissions of HFC-143a (trifluoroethane) at 29 metric tons of gas, increasing to 3,834 metric tons in 2003.[98] The estimate for 2003 is 19.7 percent higher than the estimate for 2002. HFC-143a is a halocarbon used in blends for commercial refrigeration and air conditioning, such as R-404A and R-507A. HFC-143a, like other HFCs, is used as a substitute because it contains neither chlorine nor bromine and will not emit ozone-depleting halogen radicals into the stratosphere. Like other halocarbons, HFC-143a does make a positive contribution to atmospheric warming; however, the GWPs of R-404A and R-507A are lower than those of the gases it replaces, such as CFC-12 with a GWP of 10,600.

The EPA estimates 1997 emissions of HFC-236fa (hexafluoropropane) at 9 metric tons of gas, increasing to 369 metric tons in 2003.[99] The estimate for 2003 is 8.1 percent higher than the estimate for 2002. HFC-236fa is also used as a refrigerant, in particular by the U.S. Navy for shipboard applications.[100] In another application, HFC-236fa is used as a firefighting agent.

There is a group of other HFCs and PFCs/PFPEs for which the EPA withholds individual emissions data, because the data are considered confidential and could compromise business practices. This group includes HFC-152a, HFC-227ea, HFC-245fa, and HFC-4310mee, with 100-year GWPs of 120, 3,500, 950, and 1,500, respectively.[101] The EPA estimates total emissions of this group of "other HFCs" at 7.6 million metric tons carbon dioxide equivalent in 2003, representing 5.3 percent of all emissions of HFCs, PFCs, and SF_6 reported.[102] Emissions of these HFCs are small but growing rapidly, as they continue to find applications as substitutes for CFCs and HCFCs. Emissions of "other HFCs" increased by 5.9 percent in 2003 compared with 2002.

Other HFCs and HFC blends are also likely to gain market share as a result of the phaseout of CFCs and HCFCs, because no single product is suited for all applications. For example, each potential replacement product has an optimal operating temperature range; hence, the refrigerant best suited for use in ice cream freezers will differ from the best choice for milk coolers.[103]

In addition to replacing HCFC-22 in stationary air conditioning and refrigeration applications, other HFCs are expected to gain new markets as foam blowing agents. CFCs have already been phased out of this market, having been replaced by HCFCs (primarily HCFC-141b). Among the potential replacements, HFC-245fa (pentafluoropropane) appears to be the strongest contender.[104]

---

[93] European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/solvents/main_appli/main.htm.

[94] Alternative Fluorocarbons Environmental Acceptability Study, Production, Sales and Atmospheric Release, web site www.afeas.org/prodsales_download.html.

[95] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

[96] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004.

[97] J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

[98] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004.

[99] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004.

[100] E-mail correspondence with the Office of Policy, U.S. Department of Energy, October 18, 2000.

[101] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

[102] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004. Note that EIA calculates emissions in carbon dioxide equivalent units using the GWP values published by the IPCC in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report.

[103] C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

[104] C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

Perfluorocarbons (PFCs)

U.S. Emissions of Perfluorocarbons, 1990-2003

Estimated 2003 Emissions (Million Metric Tons Carbon Dioxide Equivalent)	7.3
Change Compared to 2002 (Million Metric Tons Carbon Dioxide Equivalent)	-1.6
Change from 2002 *(Percent)*	*-18.0%*
Change Compared to 1990 (Million Metric Tons Carbon Dioxide Equivalent)	-12.3
Change from 1990 *(Percent)*	*-62.9%*

The EPA estimates 2003 emissions of PFCs at 7.3 million metric tons carbon dioxide equivalent, accounting for 5.1 percent of all emissions of HFCs, PFCs, and SF_6 combined. The estimate for 2003 is 18.0 percent lower than the estimate for 2002 and 62.9 percent lower than 1990 emissions (Table 31).[105] The overall decrease is the result of improvements in the aluminum industry, which creates PFCs as byproducts, as well as decreases in domestic aluminum production; a small increase in PFC emissions is seen in industrial applications, such as in semiconductor manufacturing.

PFCs are compounds composed of carbon and fluorine that have relatively high GWPs (5,700 for perfluoromethane [CF_4] and 11,900 for perfluoroethane [C_2F_6]).[106] PFCs are also characterized by long atmospheric lifetimes (up to 50,000 years); hence, unlike most HFCs, they are essentially permanent additions to the atmosphere.

The principal quantifiable source of PFCs is as a byproduct of aluminum smelting created during periods of process inefficiency and disruption. The amount created depends on the frequency and duration of the events. The EPA estimates U.S. emissions from aluminum production at 504 metric tons of perfluoromethane and 56 metric tons of perfluoroethane in 2003.[107] Reductions in primary aluminum production and efficiency improvements to reduce anode effects leading to process inefficiency have contributed to reductions in emissions of perfluoromethane and perfluoroethane from this source by 79.6 percent and 77.0 percent, respectively, since 1990.

Aluminum smelting companies that participate in EPA's Voluntary Aluminum Industry Partnership (VAIP) program have achieved efficiency improvements through voluntary actions. Reductions in primary aluminum production have also played a role in reducing PFC emissions. According to data from the U.S. Geological Survey, domestic primary aluminum production decreased significantly between the years 1998 and 2001 and remained steady in 2002. The decline in production resulted from cutbacks in smelter production, which in turn were caused by increased energy costs in various parts of the country.[108]

Another source of PFC emissions is semiconductor manufacturing. For 2003, the EPA estimates emissions of perfluoromethane and perfluoroethane from semiconductor manufacturing at 162 metric tons of perfluoromethane and 228 metric tons of perfluoroethane, respectively.[109] Both estimates reflect the rapid growth of the semiconductor industry in the 1990s, which resulted in increases of 40.6 percent and 42.6 percent in emissions of perfluoromethane and perfluoroethane, respectively, since 1990. Perfluoromethane and perfluoroethane are used as plasma etchants and cleaning agents in semiconductor manufacturing; some of the gas used in those processes does not react with the materials and, unless abated, is emitted to the atmosphere. A variety of other perfluorinated compounds are used in the semiconductor industry, including perfluoropropane (C_3F_8, with a GWP of 8,600), perfluorobutane (C_4F_{10}, GWP 8,600), perfluorohexane (C_6F_{14}, GWP 9,000), and nitrogen trifluoride (NF_3).[110] Although continued expansion of the worldwide semiconductor market may lead to increased PFC use and emissions, emissions of PFCs from this source have been falling since their peak

---

[105] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004. Note that EIA calculates emissions in carbon dioxide equivalent units using the GWP values published by the IPCC in 2001 in its Third Assessment Report, whereas the EPA uses the GWP values from the IPCC's 1996 Second Assessment Report.

[106] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

[107] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004.

[108] U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries 2003,* web site http://minerals.usgs.gov/minerals/pubs/mcs/2003/mcs2003.pdf.

[109] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004.

[110] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

in 1999 as a result of drops in semiconductor production (and silicon consumption) and voluntary industry efforts to curb emissions through new methods, such as process optimization.[111]

Sulfur Hexafluoride (SF_6)

U.S. Emissions of Sulfur Hexafluoride, 1990-2003

Estimated 2003 Emissions (Million Metric Tons Carbon Dioxide Equivalent)	17.3
Change Compared to 2002 (Million Metric Tons Carbon Dioxide Equivalent)	0.3
Change from 2002 *(Percent)*	*1.6%*
Change Compared to 1990 (Million Metric Tons Carbon Dioxide Equivalent)	-15.4
Change from 1990 *(Percent)*	*-47.1%*

The EPA estimates 2003 emissions of SF_6 at 777 metric tons of gas, accounting for 12.0 percent of all HFC, PFC, and SF_6 emissions combined in 2003.[112] The estimate for 2003 is 47.1 percent lower than the estimate for 1990. The decrease is the result of industry efforts to reduce emissions from electrical power systems, as well as the rising cost of SF_6. In contrast, emissions of SF_6 from uses in the semiconductor manufacturing industry have increased overall by 62.0 percent since 1990.

SF_6 is used primarily in electrical applications, in which it is an excellent dielectric gas for high-voltage applications, because it is chemically inert, gaseous at low temperatures, nonflammable, nontoxic, and noncorrosive.[113] In electrical transmission and distribution systems, SF_6 acts as an insulator and arc interrupter for circuit breakers, switch gear, and other electrical equipment; however, it can escape through seals, especially in older equipment. Emissions also occur during equipment installation, servicing, and disposal.[114]

Other applications that produce SF_6 emissions include magnesium metal casting processes that employ SF_6 to replace toxic and corrosive materials, such as salt fluxes and sulfur dioxide (SO_2). Another use of SF_6 is as a cover gas during magnesium production and processing to prevent excessive oxidation of molten magnesium in the presence of air, although emissions from this source have declined due to a decrease in the quantity of magnesium die casting, process optimizations by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry, and the closure of primary magnesium processing facilities in the United States in 2001.[115] Pre-treating aluminum melt with SF_6 (or an inert gas mixture) prevents porosity and therefore weakening of the metal. It also removes oxides and solid impurities. In addition, mixtures of SF_6 and O_2 are used as feed gases for plasma etching of semiconductor devices.[116] Because of its extremely low atmospheric concentration, SF_6 is also useful as an atmospheric tracer gas for a variety of experimental purposes. Other minor applications include leak detection, loud speakers, lasers, and as a cover gas or fluxing and degassing agent for specialized casting operations in the aluminum industry.[117]

---

[111] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-004 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[112] Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2004. In compiling its estimates, the EPA receives data from participants in the SF_6 Emission Reduction Partnership for Electric Power Systems and the SF_6 Emission Reduction Partnership for the Magnesium Industry.

[113] European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?chfamilies/SF6/prod_main/prod.htm.

[114] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-004 (Washington, DC, April 2004),web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[115] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-004 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[116] European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/electri_appli/main_appli/main.htm.

[117] Historically, emissions of SF_6 from the aluminum industry have been omitted from global estimates, because any emissions are expected to be insignificant. The EPA does not estimate emissions from this source due to uncertainties about the quantities used and the amounts destroyed in the applications.

Table 30. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990 and 1995-2003

(Thousand Metric Tons of Gas)

Gas	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Hydrofluorocarbons										
HFC-23	3.0	2.3	2.7	2.6	3.5	2.6	2.6	1.7	1.7	1.1
HFC-125	0.0	1.3	1.9	2.5	3.1	3.6	4.0	4.4	4.8	5.2
HFC-134a	0.0	13.9	18.9	24.1	28.2	32.5	36.9	40.5	43.8	46.6
HFC-143a	0.0	0.2	0.5	0.9	1.4	1.7	2.2	2.6	3.2	3.8
HFC-236fa	0.0	0.0	0.0	*	0.1	0.1	0.2	0.3	0.3	0.4
Perfluorocarbons										
CF_4	2.6	1.8	1.9	1.8	1.5	1.5	1.5	0.7	0.9	0.7
C_2F_6	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.3	0.3	0.3
PFCs/PFPEs	W	W	W	W	W	W	W	W	W	W
Other HFCs, PFCs/PFPEs	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Sulfur Hexafluoride	**1.5**	**1.2**	**1.3**	**1.2**	**1.0**	**1.0**	**0.8**	**0.8**	**0.8**	**0.8**

*Less than 50 metric tons of gas.

P = preliminary data. M = mixture of gases. W = withheld to avoid disclosure of confidential data.

Notes: Other HFCs, PFCs/PFPEs include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, and a variety of PFCs and perfluoropolyethers (PFPEs). They are grouped together to protect confidential data. Totals may not equal sum of components due to independent rounding.

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, September 2004).

Table 31. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990 and 1995-2003

(Million Metric Tons Carbon Dioxide Equivalent)

Gas	1990	1995	1996	1997	1998	1999	2000	2001	2002	P2003
Hydrofluorocarbons										
HFC-23	36.1	28.0	32.3	31.2	41.7	31.7	30.9	20.6	20.6	13.0
HFC-125	0.0	4.4	6.3	8.6	10.7	12.1	13.6	14.9	16.2	17.8
HFC-134a	0.0	18.0	24.5	31.4	36.7	42.2	48.0	52.7	56.9	60.5
HFC-143a	0.0	0.9	2.3	4.0	5.9	7.5	9.3	11.4	13.8	16.5
HFC-236fa	0.0	0.0	0.0	0.1	0.6	1.3	2.0	2.6	3.2	3.5
Total HFCs	**36.1**	**51.4**	**65.5**	**75.1**	**95.5**	**94.9**	**103.8**	**102.2**	**110.7**	**111.3**
Perfluorocarbons										
CF_4	14.7	10.3	11.0	10.0	8.7	8.7	8.6	4.3	5.1	3.9
C_2F_6	4.8	4.9	5.3	5.6	5.9	6.0	5.0	3.4	3.8	3.4
Total PFCs	**19.6**	**15.3**	**16.3**	**15.7**	**14.6**	**14.6**	**13.6**	**7.7**	**8.9**	**7.3**
Other HFCs, PFCs/PFPEs	**0.3**	**1.9**	**3.4**	**4.5**	**5.5**	**6.2**	**6.5**	**6.7**	**7.1**	**7.6**
Sulfur Hexafluoride	**32.6**	**26.1**	**29.5**	**27.1**	**22.4**	**22.0**	**18.5**	**17.5**	**17.0**	**17.3**
Total Emissions	**88.5**	**94.7**	**114.7**	**122.4**	**138.0**	**137.8**	**142.4**	**134.2**	**143.7**	**143.4**

P = preliminary data.

Notes: Other HFCs, PFCs/PFPEs include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, and a variety of PFCs and perfluoropolyethers (PFPEs). They are grouped together to protect confidential data. Totals may not equal sum of components due to independent rounding.

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, September 2004).

6. Land Use Issues

Overview

Land use and forestry issues are important to national and global inventories of greenhouse gases in two ways:

- Vegetation can "sequester" or remove carbon dioxide from the atmosphere and store it for potentially long periods in above- and below-ground biomass, as well as in soils. Soils, trees, crops, and other plants may make significant contributions to reducing net greenhouse gas emissions by serving as carbon "sinks."
- Humans can alter the biosphere through changes in land use and forest management practices and, in effect, alter the quantities of atmospheric and terrestrial carbon stocks, as well as the natural carbon flux among biomass, soils, and the atmosphere.

Land use issues are of particular interest to the United States because U.S. forests and soils annually sequester large amounts of carbon dioxide. Much of the forest land in the United States was originally cleared for agriculture, lumber, or fuel in the hundred years prior to 1920. Since then, however, much of the agricultural and pasture land has reverted to forest land, increasing its ability to sequester atmospheric carbon dioxide.

The amount of carbon being sequestered annually is uncertain, in part because of an absence of data and difficulties in measuring sequestration. Moreover, in addition to technical uncertainties, there are also policy and accounting questions about the aspects of the biological carbon cycle that would be included in national inventories as anthropogenic emissions and removals.

The revised guidelines for national emissions inventories published in 1997 by the Intergovernmental Panel on Climate Change (IPCC) stipulate the inclusion of carbon sequestration through land use and forestry in national greenhouse gas inventories as an offset to gross greenhouse gas emissions from other sources.[118] The U.S. Environmental Protection Agency (EPA),[119] based on data generated by the U.S. Department of Agriculture, estimates annual U.S. carbon sequestration for the year 2002 at 690.7 million metric tons carbon dioxide equivalent, a decline of approximately 27.9 percent from the 957.9 million metric tons carbon dioxide equivalent sequestered in 1990 (Table 32). In 1990 land use change and forestry practices represented an offset of 15.7 percent of total U.S. anthropogenic carbon dioxide emissions, but by 2002 that amount had declined to 10.0 percent.[120]

Table 32. Net Carbon Dioxide Sequestration from U.S. Land Use Change and Forestry, 1990 and 1996-2002
(Million Metric Tons Carbon Dioxide Equivalent)

Component	1990	1996	1997	1998	1999	2000	2001	2002
Forests	846.6[a]	964.1[a]	730.1[b]	617.8[b]	588.4[b]	602.3[b]	600.2[b]	600.8[b]
Urban Trees	58.7[a]	58.7[a]	58.7[a]	58.7[a]	58.7[a]	58.7[a]	58.7[a]	58.7[a]
Agricultural Soils	26.5[a]	19.0[a]	19.3[b]	16.9[b]	17.3[b]	19.0[b]	20.7[b]	21.2[b]
Landfilled Yard Trimmings and Food Scraps	26.0[a]	13.4[a]	12.9[b]	12.4[b]	11.3[b]	10.1[b]	10.2[b]	10.1[b]
Total	**957.9[a]**	**1,055.2[a]**	**821.0[b]**	**705.8[b]**	**675.8[b]**	**690.2[b]**	**689.7[b]**	**690.7[b]**

[a] Estimate based on historical data.

[b] Estimate based on a combination of historical data and projections.

Note: Totals may not equal sum of components due to independent rounding.

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenter PublicationsGHGEmissions USEmissionsInventory2004.html.

---

[118] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Vol. 3 (Paris, France, 1997), web site www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[119] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions USEmissionsInventory2004.html.

[120] EIA does not include sequestration from land-use change and forestry as part of its annual emissions inventory.

Land Use Change and Forestry Carbon Sequestration

The EPA's estimates for carbon sequestration from land use change and forestry in 2002 include four main components: (1) changes in forest carbon stocks (600.8 million metric tons carbon dioxide equivalent or 87.0 percent of the total), (2) changes in agricultural soil carbon stocks (21.2 million metric tons carbon dioxide equivalent or 3.1 percent of the total), (3) changes in carbon stocks in urban trees (58.7 million metric tons carbon dioxide equivalent or 8.5 percent of the total), and (4) changes in carbon stocks in landfilled yard trimmings and food scraps (10.1 million metric tons carbon dioxide equivalent or 1.5 percent of the total).[121]

IPCC Good Practice Guidance for Land Use, Land Use Change, and Forestry (LULUCF)

International guidelines—the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)*—were adopted 8 years ago to support accounting for the storage and emission of greenhouse gases from various sources. The guidelines were developed before the adoption of the Kyoto Protocol and thus do not fully represent the new requirements for accounting for carbon fluxes resulting from LULUCF activities.

To address a variety of limitations of the *IPCC Guidelines*, the Parties to the UNFCCC in 1998 called for the IPCC to produce Good Practice Guidance to the *IPCC Guidelines*. The first volume of the *Good Practice Guidance* was completed in 2000 and adopted by the Sixth Conference of the Parties to the UNFCCC (COP-6) in May 2000. For several reasons, however, the first volume did not cover LULUCF activities. At the time that the *Good Practices Guidance* was being developed, the IPCC was also preparing a Special Report on LULUCF, and simultaneous work on the two documents carried the risk of delivering inconsistencies. Further, significant negotiations on LULUCF activities were underway in the UNFCCC international climate change negotiations, and the IPCC believed it would be best to develop the guidance for LULUCF after completion of the negotiations.

The IPCC was requested to develop Good Practice Guidance for LULUCF under decision 11/CP.7, agreed to at COP-7 in Marrakech in November 2001. As part of this process, a wide range of countries nominated expert authors to be involved in the development of LULUCF guidance. Three meetings of expert authors were held during 2002 in order to prepare a first draft of the *Good Practice Guidance* for LULUCF, which was released for review in December 2002. Submission of comments on the draft document was completed at the end of January 2003, with more than 6,000 comments received from governments and experts. The expert author teams considered the comments during meetings held in early April 2003, and a second draft document was issued.

The second draft of the *Good Practice Guidance* for LULUCF was released in May 2003 for review by experts and governments. Submission of comments—over 4,000 were received—on the second draft document was completed at the end of June 2003. In response, the IPCC expert author teams revised the second draft and provided a final draft to governments in October 2003 for final comment.[a, b] The report was adopted by the IPCC Plenary at its 21st session, held in Vienna in November 2003.[c]

The *Good Practice Guidance* for LULUCF provides methods and guidance for estimating, measuring, monitoring, and reporting on carbon stock changes and greenhouse gas emissions from LULUCF activities under the Kyoto Protocol. It provides guidance related to specific aspects of the LULUCF sector, including consistent representation of land areas, sampling for area estimates, estimating emissions and removals, and verification. The report assists countries in preparing inventories for the land use, land-use change and forestry sector, and is consistent with the available good practice guidance for other sectors. It represents another step in the IPCC's ongoing program of inventory development, and will support future revisions of the *IPCC Guidelines* themselves.

[a] The Cooperative Research Centre for Greenhouse Accounting, "Good Practice for Land Use, Land-Use Change, and Forestry," web site www.greenhouse.crc.org.au/goodpractice/.

[b] G.-J. Nabuurs and N.H. Ravindranath, "Task 1, Chapter 3: Good Practice Guidance for National GHG Inventory for LULUCF Sector." Presentation at the IPCC-NGGIP Side Event at SB-18 (Bonn, Germany, June 6, 2003).

[c] Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme (IPCC-NGGIP), "Good Practice Guidance for Land Use, Land-Use Change and Forestry" (2003), web site www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.htm.

---

[121] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

The EPA's estimates for carbon sequestration in forests are based on carbon stock estimates developed by the U.S. Forest Service, U.S. Department of Agriculture (USDA), employing methodologies that are consistent with the *Revised 1996 IPCC Guidelines*. The USDA estimates of carbon stocks in urban trees were based on field measurements in ten U.S. cities and data on national urban tree cover, again employing a methodology consistent with the *Revised 1996 IPCC Guidelines*. Estimates for sequestration in agricultural soils were based on changes in carbon stocks in mineral and organic soils resulting from agricultural land use and land management, as well as emissions of carbon dioxide resulting from the use of crushed limestone and dolomite on soils. Methodologies drawn from the IPCC guidelines were used to derive all components of changes in agricultural soil carbon stocks. The EPA estimates for carbon stocks in landfilled yard trimmings and food scraps are based on the EPA's own method of examining life-cycle greenhouse gas emissions and sinks associated with solid waste management.[122]

The EPA's carbon flux estimates, with the exception of those from wood products, urban trees, and liming, are based on periodic surveys of U.S. forest land and soils, conducted on a less frequent basis. Carbon fluxes from forests (except wood products) and from agricultural soils (except liming) are collected over 5- or 10-year intervals and averaged annually for years between surveys. Each State is surveyed independently and at varying times, thus the estimates for carbon fluxes from forest carbon stocks differ at the national level from year to year. Forest soils, which are surveyed on a regional scale, have fluxes over multi-year periods, with large discontinuities in-between intervals. Agricultural soils exhibit a pattern similar to that of forest soils. The most current national forest and land-use surveys were completed for the year 1999, thus carbon flux estimates from forests and agricultural soils are derived in part from modeled projections for future years. Data on carbon fluxes from urban trees, collected over the period from 1990 through 1999, were applied to the entire time series.[123]

Inventory of Woody Residuals in the United States

The U.S. Forest Service (USFS) conducts analyses to estimate the quantity of woody residuals in the United States. The USFS estimates both the types and amounts of woody residuals generated, as well as the portion of those tonnages that are available for recovery.[a] The data from the USFS analyses are useful to wood recycling enterprises, because they help to identify sources for processing and markets for services that help foresters clear and process downed woody debris that poses a significant fire threat.

The major sources of solid waste wood generated in the United States that are analyzed by the USFS are municipal solid waste (MSW), construction and demolition debris, woody forest residues, and primary timber processing mill residues. Determining the amounts recoverable involves estimating total waste generated, less amounts currently recovered, combusted, or considered unusable. The total amounts of recoverable wood from these sources in 2002 were as follows: (1) 8.7 million tons from MSW, (2) 29.2 million tons from construction and demolition debris,[b] and (3) 86 million tons from woody forest residues and primary timber processing mill residues.[c]

Woody forest residues include logging residues, which represent the largest proportion of solid waste wood generated in the United States that is available for recovery. Currently, however, this material remains in the forest, contributing to "down woody material" (the portion of trees that have fallen and remain on the forest floor or in forest streams). Advances are being made in the collection, processing, and utilization of recoverable solid wood waste, but there still are some technical and economic obstacles to improved utilization.

[a] D. McKeever, "Taking Inventory of Woody Residuals," *BioCycle*, Vol. 44, No. 7 (July 2003), pp. 31-35.

[b] D. McKeever and R. Falk, "Recovering Wood for Reuse and Recycling: A United States Perspective," in C. Gallis, Editor, *European COST E31 Conference: Management of Recovered Wood Recycling, Bioenergy and Other Options* (Thessaloniki, Greece, April 22-24, 2004), pp. 29-40.

[c] D. McKeever and R. Falk, "Woody Residues and Solid Waste Wood Available for Recovery in the United States, 2002," in C. Gallis, Editor, *European COST E31 Conference: Management of Recovered Wood Recycling, Bioenergy and Other Options* (Thessaloniki, Greece, April 22-24, 2004), pp. 307-316.

---

[122] U.S. Environmental Protection Agency, *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*, 2nd Edition, EPA-530-R-02-006 (Washington, DC, May 2002), web site www.epa.gov/epaoswer/non-hw/muncpl/ghg/ghg.htm.

[123] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

Changes in Forest Carbon Stocks

In the United States, the most significant pressures on the amount of carbon sequestered through forest lands are land management activities and the continuing effects of past changes in land use. These activities directly affect carbon flux by shifting the amount of carbon accumulated in forest ecosystems.[124] Land management activities affect both the stocks of carbon that can be stored in land-based carbon sinks, such as forests and soils, and the flows, or fluxes, of carbon between land-based sinks and the atmosphere.

Forests are multifaceted ecosystems with numerous interrelated components, each of which stores carbon. These components include five forest carbon pools and two wood products carbon pools:

- Forest carbon pools:
  - Trees (living trees, standing dead trees, roots, stems, branches, and foliage)
  - Understory vegetation (shrubs and bushes, roots, stems, branches, and foliage)
  - Forest floor (fine woody debris, tree litter, and humus)
  - Down dead wood (logging residue and other dead wood on the ground, stumps, and roots of stumps)
  - Organic material in soil
- Wood products carbon pools:
  - Harvested wood products in use
  - Harvested wood products in landfills.

As a result of natural biological processes occurring in forests, as well as anthropogenic activities, carbon is constantly cycling through these components and between the forest and the atmosphere. The net change in overall forest carbon may not always be equal to the net flux between forests and the atmosphere, because timber harvests may not necessarily result in an instant return of carbon to the atmosphere. Timber harvesting transfers carbon from one of the five "forest carbon pools" to one of the two "wood products carbon pools." Once carbon is transferred to a product pool, it is emitted over time as carbon dioxide as the product combusts or decays. Emission rates vary significantly, depending on the type of product pool that houses the carbon.[125]

In the United States, enhanced forest management, regeneration of formerly cleared forest areas, and timber harvesting have resulted in the annual sequestration of carbon throughout the past decade. Since the 1920s, deforestation for agricultural purposes has become a nearly defunct practice. More recently, managed growth practices have become common in eastern forests, greatly increasing their biomass density over the past 50 years. In the 1970s and 1980s, federally sponsored tree planting and soil conservation programs were embraced. These programs resulted in the reforestation of formerly harvested lands, improvement in timber management activities, soil erosion abatement, and the conversion of cropland to forests. Forest harvests have also affected carbon sequestration. The majority of harvested timber in the United States is used in wood products. The bulk of the discarded wood products are landfilled, thus large quantities of the harvested carbon are relocated to long-term storage pools rather than to

USDA Agriculture and Forestry Greenhouse Gas Inventory

The U.S. Department of Agriculture (USDA) Global Change Program Office published its first national greenhouse gas inventory in March 2004. The *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001* (USDA GHG Inventory) provides an assessment of greenhouse gas emissions and sinks in the nation's agriculture and forests.[a] The publication details emissions and sinks estimates for livestock, cropland and forests, as well as energy consumption in livestock and cropland agriculture. These emissions estimates are provided at State, regional and national levels, and are categorized by land ownership and management practices whenever possible. The estimates in the USDA GHG Inventory are consistent with those published last year by the EPA in its *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*.[b]

[a] U.S. Department of Agriculture, Global Change Program Office, Office of the Chief Economist, *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001*, Technical Bulletin No. 1907 (March 2004), web site www.usda.gov/oce/gcpo/ghginventory.html.

[b] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), web site http://yosemite.epa. gov/ oar/ globalwarming. nsf/ content/ Resource Center PublicationsGHGEmissionsUSEmissionsInventory2003.html.

---

[124] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions USEmissionsInventory2004.html.

[125] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions USEmissionsInventory2004.html.

the atmosphere. The size of wood product landfills has increased over the past century.[126]

According to the EPA (Table 33), carbon sequestration by forests and harvested wood products totaled 600.8 million metric tons carbon dioxide equivalent in 2002. Between 1990 and 2002, U.S. forest and harvested wood components accounted for an average annual net sequestration of 736 million metric tons carbon dioxide equivalent, resulting from domestic forest growth and increases in forested land area; however, there was a decrease of approximately 28 percent in annual sequestration over the same period.[127]

The overall decline in forest carbon sequestration was driven largely by a 39.3-percent reduction in the rate of sequestration in the forest carbon pool (636.6 million metric tons carbon dioxide equivalent in 1990 versus 386.4 million metric tons in 2002). The reduction in the forest carbon pool sequestration rate can be attributed primarily to a 74.1-percent decline in the estimated rate of sequestration in forest soils. Forest soil carbon sequestration fell from an annual average of 212.7 million metric tons carbon dioxide equivalent during the period 1990-1996 to an annual average of 55 million metric tons during the period 1997-2002.

The net forest carbon flux has varied significantly from year to year, most notably from 1996 to 1997 and from 1997 to 1998 (Table 33). The U.S. Forest Service reports there are different reasons for these shifts, and those reasons encompass both substantive differences in the source of carbon stocks and the methodology utilized to determine the levels of sequestration for each year. The shift downward from 1996 to 1997 resulted primarily from changes in soil carbon stocks. However, the EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002* utilized databases containing data on changes in forest area—and thus soil carbon—only for the years 1987, 1992, and 1997. Data for the missing years were interpolated. There was a large shift, however, in forest area—and soil carbon—between 1987 and 1992 and again between 1992 and 1997. Although forest area increased between 1992 and 1997, it increased at a lower rate than between 1987 and 1992, resulting in a shift downward in soil carbon stocks and total sequestration quantities. The shift downward between 1997 and 1998 is attributed primarily to changes in the carbon sequestration level of trees.[128]

Table 33. Net Carbon Dioxide Sequestration in U.S. Forests, 1990 and 1996-2002
(Million Metric Tons Carbon Dioxide Equivalent)

Description	1990[b]	1996[b]	1997[a]	1998[b]	1999[b]	2000[b]	2001[b]	2002[b]
Forest Carbon Stocks	**636.6**	**756.5**	**517.4**	**411.7**	**373.8**	**391.5**	**386.4**	**386.4**
Trees	354.2	464.6	401.0	307.5	275.0	289.9	285.5	285.5
Understory	-0.8	3.1	1.7	0.5	-2.2	-2.5	-2.2	-2.2
Forest Floor	38.1	12.7	-2.7	-11.0	-16.2	-17.2	-16.5	-16.5
Down Dead Wood	32.5	63.5	62.4	59.7	62.2	66.3	64.6	64.6
Forest Soils	212.7	212.7	55.0	55.0	55.0	55.0	55.0	55.0
Harvested Wood Carbon Stocks	**210.1**	**207.6**	**212.7**	**206.1**	**214.7**	**210.8**	**213.8**	**214.4**
Wood Products	47.6	56.1	57.7	51.9	61.5	58.7	59.0	59.2
Landfilled Wood	162.4	151.5	155.0	154.2	153.1	152.1	154.8	155.3
Total	**846.6**	**964.1**	**730.1**	**617.8**	**588.4**	**602.3**	**600.2**	**600.8**

[a] Estimates based on historical data.

[b] Estimates based on a combination of historical data and projections.

Notes: The sums of the annual net stock changes in this table (shown in the "Total" row) represent estimates of the actual net flux between the total forest carbon pool and the atmosphere. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys and models. Totals may not equal sum of components due to independent rounding.

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenter PublicationsGHGEmissions USEmissionsInventory2004.html.

---

[126] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions USEmissionsInventory2004.html.

[127] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), p. 208, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHG Emissions USEmissionsInventory2004.html.

[128] According to an August 31, 2004, personal communication with Linda Heath, Project Leader, U.S. Department of Agriculture, Forest Service, projections were used to estimate values for the years 1998 through 2002. After publication of EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, it was discovered that the data provided for the years 1987, 1992, and 1997 had been updated, and those revisions were not reflected in the EPA publication. To avoid this situation in the future, the U.S Forest Service will utilize existing data in the U.S. Forest Service Forest Inventory and Analysis Program and will not make projections.

Wood products carbon stocks experienced a slight increase in overall annual sequestration levels between 1990 and 2002, reflecting accumulation of carbon in harvested wood pools.[129] There were small variations from year to year, but the trend in net sequestration amounts has generally been upward, from 210.1 million metric tons carbon dioxide equivalent in 1990 to 214.4 million metric tons carbon dioxide equivalent in 2002 (Table 33). This reflects an increase in both harvesting for wood products and in the amount of wood contained in wood product landfills.

The EPA employs methodology consistent with the *Revised 1996 IPCC Guidelines* to estimate the net sequestration resulting from harvested wood. The IPCC provides two alternative approaches to account for carbon emissions from harvested wood. These are: (1) assume that all harvested wood replaces wood products that decay in the inventory year, thus the amount of wood harvested annually equates to annual emissions from harvests; or (2) account for the variable rate of decay of harvested wood depending on its disposition (e.g., product pool, landfill, and combustion). The estimates used by EPA in its inventory, and reported in this chapter, result from using the second approach, employing estimates of carbon stored in wood products and landfilled wood.[130] EPA also employs the "production approach"; that is, carbon stored in imported wood products is not counted, but carbon stored in exports is counted, even when logs are processed in other countries.[131]

EPA estimates of carbon stocks in wood products and landfilled wood from 1910 onward are based on historical data and data derived from models utilized by the USDA Forest Service. These models (the forest sector modeling system) include an area change model, a timber market model, a pulp and paper model, and an inventory model. Estimates were derived using data on annual wood and paper production, and by tracking the disposition of carbon in harvested wood for each year from 1910 through 2002. Estimates include the change in carbon stocks in wood products and landfilled wood, and carbon emissions to the atmosphere both with and without energy recovery. Carbon in exported wood was counted as if it remained in the United States, and carbon in imported wood was not counted.[132]

EPA estimates of carbon stored in harvested wood products are currently being revised. Updated estimates will use more detailed wood products production and use data and improved parameters on disposition and decay of products. Estimation methods may also change as a result of discussions to be held by the UNFCCC in August 2004 regarding accounting for changes in harvested wood products (see box on page 77). Preliminary results suggest that estimates of carbon stored in harvested wood may in fact be lower than the estimates included in the EPA Inventory[133] and detailed in this chapter.

Changes in Urban Tree Carbon Stocks

Urban forests make up a considerable portion of the total tree canopy cover in the United States. Urban areas, which cover 3.5 percent of the continental United States, are estimated to contain about 3.8 billion trees, accounting for approximately 3 percent of total tree cover in the United States. The EPA's carbon sequestration estimates for urban trees are derived from estimates by Nowak and Crane,[134] based on data collected throughout the 1990s and applied to the entire time series in this report. Net carbon dioxide flux from urban trees is estimated at 58.7 million metric tons carbon dioxide equivalent annually from 1990 through 2002 (Table 32).[135]

---

[129] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002,* EPA-430-R-04-003 (Washington, DC, April 2004), p. 208, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[130] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001,* EPA-430-R-03-004 (Washington, DC, April 2003), p. 6-6, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html.

[131] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), p. 210, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[132] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002,* EPA-430-R-04-003 (Washington, DC, April 2004), p. 211, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[133] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002,* EPA-430-R-04-003 (Washington, DC, April 2004), p. 214, web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[134] D.J. Nowak and D.E. Crane, "Carbon Storage and Sequestration by Urban Trees in the United States," *Environmental Pollution,* Vol. 116, No. 3 (2001), pp. 381-389.

[135] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002,* EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

Accounting for Harvested Wood Products in Future Greenhouse Gas Inventories

Harvested wood products (HWP) are defined as "goods manufactured or processed from wood, including lumber and panels for end uses such as housing and furniture, and paper and paperboard for uses such as packaging, printing and writing, and sanitary applications."[a] HWP are an important part of the overall carbon cycle and are thus integral to any greenhouse gas (GHG) accounting system or inventory.

Preparation of the IPCC 2006 Guidelines for national greenhouse gas inventories under the UNFCCC—including methods for estimating and reporting of HWP—is underway. The issue of accounting for HWP, however, is a complex one, and involves the consideration of factors such as international trade (import-export) of wood products, timing of emissions accounting, determining whether emissions include those from existing wood product pools or solely from harvesting, and establishing how complex or simplistic the accounting approach should be so as not to create barriers to participation.[b] The choice of what accounting approach is to be used for HWP by the IPCC in its 2006 Guidelines remains to be determined. Three individual accounting approaches (i.e., stock-change approach, production approach, and atmospheric-flow approach) for reporting HWP in the national greenhouse gas inventories under the UNFCCC have been developed and debated. These three approaches were discussed at a UNFCCC-sponsored workshop held in Norway on August 30 through September 2, 2004, and are detailed below. Final guidance could be adopted late in 2004 based on the decisions made at this workshop.[c]

The first approach under consideration for HWP is the *stock-change approach*. This approach accounts for changes in carbon stock in forests in the country in which the wood is grown, deemed the producing country. Changes in the products pool are accounted for in the country where the products are used, deemed the consuming country. These stock changes are counted within national boundaries, where and when they occur.[d] Under this approach, the HWP stock change in a country may be estimated considering either transfers into and out of the HWP pool, or the difference between HWP carbon stocks at two different set points in time.

The next alternative—the *atmospheric flow approach*—accounts for emissions or sequestration of carbon to and/or from the atmosphere within national boundaries, both where and when emissions and sequestration occur. The producing country accounts for sequestration of carbon attributed to forest growth, while the consuming country accounts for emissions of carbon to the atmosphere from oxidation of HWP.[e] Under this approach, it is the net CO_2 flow from the pools to the atmosphere that would be reported as the equivalent emission, and the net flow in the opposite direction as the equivalent amount of carbon sequestration.[f]

The third approach for accounting for HWP is the *production approach*. While this approach also reports changes in carbon stock, it is the producing country that reports the stock changes in HWP regardless of the location of the stock (i.e., whether within country boundaries or exported).[g] This approach thus accounts for domestically produced stocks only; that is, stock changes are counted when, but not where, they occur if wood products are exported or traded.[h]

An additional method—the *simple decay approach*—was proposed by one Annex I country and is effectively a method falling under the production approach. This method assumes that HWP remain a part of the forest in which they were produced until decomposed.[i] This approach is therefore similar to the production approach in that it also estimates the stock changes in HWP when, but not where, they occur if wood products are exported or traded. Both sequestration of carbon from the atmosphere due to forest growth and emissions resulting from harvesting are accounted for in the producing country.[j]

[a] "United States Submission on the Views Related to Carbon Accounting and Wood Products," in United Nations Framework Convention on Climate Change, *Issues Relating to Harvested Wood Products*, Paper No. 7 (May 10, 2004), pp. 42-43, web site http://unfccc.int/resource/docs/2004/sbsta/misc09.pdf.

[b] M. Ward, "Harvested Wood Products, A Beginning Guide to Key Issues," Senior Counsel to the Government of New Zealand (July 2004).

[c] K. Pingoud et al., "Approaches for Inclusion of Harvested Wood Products in Future GHG Inventories Under the UNFCCC, and their Consistency with the Overall UNFCCC Inventory Reporting Framework," *IEA Bioenergy* (July 13, 2004).

[d] M. Ward (July 2004).

[e] M. Ward (July 2004).

[f] K. Pingoud et al. (July 13, 2004).

[g] K. Pingoud, et al. (July 13, 2004).

[h] M. Ward (July 2004).

[i] K. Pingoud et al. (July 13, 2004).

[j] M. Ward (July 2004).

Changes in Agricultural Soil Carbon Stocks

The amount of organic carbon in soils depends on the balance between addition of organic material and loss of carbon through decomposition. The quantity and quality of organic matter within soils, as well as decomposition rates, are determined by the interaction of climate, soil properties, and land use. Agricultural practices—including clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, and flooding—can alter organic matter inputs and decomposition, causing a net flux of carbon to or from soils. The IPCC methodology, which is used by the EPA to estimate the net flux from agricultural soils (Table 34), is divided into three categories of land use and land management activities: (1) agricultural land use and land management activities on mineral soils;[136] (2) agricultural land use and land management activities on organic soils;[137] and (3) liming of soils. Of the three activities, the use and management of mineral soils is estimated to be the most significant contributor to total flux from 1990 through 2002. Sequestration in mineral soils in 2002 was estimated to be 64.7 million metric tons carbon dioxide equivalent, while emissions from organic soils and liming were estimated at 34.7 and 8.8 million metric tons carbon dioxide equivalent, respectively. In net, these activities resulted in 21.2 million metric tons carbon dioxide equivalent sequestered through agricultural soils in 2002.[138]

Changes in Landfilled Yard Trimming and Food Scrap Carbon Stocks

Carbon stored in landfilled yard trimmings can remain sequestered indefinitely. In the United States, yard trimmings (grass clippings, leaves, and branches) and food scraps make up a considerable portion of the municipal waste stream, and significant amounts of the yard trimmings and food scraps collected are discarded in landfills. Both the amount of yard trimmings and food scraps collected annually and the percentage that is landfilled have declined over the past decade. Net carbon dioxide sequestration from landfilled yard trimmings and food scraps has declined accordingly, from 26.0 million metric tons carbon dioxide equivalent in 1990 to 10.1 million metric tons carbon dioxide equivalent in 2002 (Table 35). Since 1990, programs limiting disposal of yard trimmings have led to an increase in backyard composting and the use of mulching mowers. The number of municipal composting facilities has also risen, further reducing the amount of trimmings that are discarded in landfills. The EPA's methodology for estimating carbon storage relies on a life-cycle analysis of greenhouse gas emissions and sinks associated with solid waste management.[139]

Table 34. Net Carbon Dioxide Sequestration in U.S. Agricultural Soils, 1990 and 1996-2002
(Million Metric Tons Carbon Dioxide Equivalent)

Description	1990	1996	1997	1998	1999	2000	2001	2002
Mineral Soils	70.3[a]	62.7[a]	62.8[a]	61.2[b]	61.1[b]	62.5[b]	64.4[b]	64.7[b]
Organic Soils	-34.3[a]	-34.7[a]	-34.7[a]	-34.7[b]	-34.7[b]	-34.7[b]	-34.7[b]	-34.7[b]
Liming of Soils	-9.5[a]	-8.9[a]	-8.7[a]	-9.6[a]	-9.1[a]	-8.8[a]	-9.0[a]	-8.8[b]
Total	**26.5[a]**	**19.0[a]**	**19.3[a]**	**16.9[b]**	**17.3[b]**	**19.0[b]**	**20.7[b]**	**21.2[b]**

[a] Estimates based on historical data.

[b] Estimates based on a combination of historical data and projections.

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenter PublicationsGHGEmissions USEmissionsInventory2004.html.

---

[136] Mineral soils are soils consisting predominantly of, and having their properties determined predominantly by, mineral matter. They usually contain less than 200 grams of organic carbon per kilogram of soil (less than 120 to 180 grams per kilogram if saturated with water) but may contain an organic surface layer up to 30 centimeters thick.

[137] Organic soils are soils that, when saturated with water, have 174 grams or more of organic carbon per kilogram of soil if the mineral fraction has 500 grams per kilogram or more of clay, or 116 grams per kilogram organic carbon if the mineral fraction has no clay, or has proportional intermediate contents. If the soil is never saturated with water, organic soils have 203 grams per kilogram or more organic carbon.

[138] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions USEmissionsInventory2004.html.

[139] U.S. Environmental Protection Agency, *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*, 2nd Edition, EPA530-R-02-006 (Washington, DC, May 2002), web site www.epa.gov/epaoswer/non-hw/muncpl/ghg/ghg.htm.

Land Use and International Climate Change Negotiations

In past international negotiations on climate change, the United States and many other countries have maintained that the inclusion of LULUCF activities in a binding agreement that limits greenhouse gas emissions is of the utmost importance; however, issues of whether and how terrestrial carbon sequestration could be accepted for meeting various commitments and targets have remained subjects of complex and difficult international negotiations on climate change.

Many of the countries involved in climate change negotiations have agreed that implementation of LULUCF activities under an international climate change agreement may be complicated by a lack of clear definitions for words such as "reforestation" and "forest." Further, implementation may be hindered by the lack of effective accounting rules. According to researchers at the Pew Center on Global Climate Change,[140] implementation of LULUCF provisions in an international climate change agreement raises many issues for such activities and/or projects, such as:

- What is a direct human-induced activity?
- What is a forest and what is reforestation?
- How will the issues of uncertainty and verifiability be addressed?
- How will the issues of (non) permanence and leakage be addressed?
- Which activities beyond afforestation, reforestation and deforestation (ARD), if any, should be included, and what accounting rules should apply?
- Which carbon pools and which greenhouse gases should be considered?

Uncertainties related to data issues have also slowed international negotiations on climate change.

The Ninth Session of the Conference of the Parties to the UN Framework Convention on Climate Change (COP-9) occurred in Milan, Italy, in December 2003. The parties at this meeting agreed on some of the rules for carbon sequestration projects under the Clean Development Mechanism (CDM), but the issue on how to treat the non-permanence of carbon sinks projects is still widely debated. Policymakers at COP-9 decided to limit the duration of credits generated from carbon sequestration projects, and also addressed the topics of additionality, leakage, uncertainties, and socioeconomic and environmental impacts.[141]

Land Use Data Issues

Uncertainties in the EPA estimates of U.S. carbon sequestration include sampling and measurement errors inherent to forest carbon estimates. The forest surveys engage a statistical sample that represents the expansive variety of growth conditions over large territories. Although more current inventories are conducted annually in each State, much of the existing data may have been collected over more than one year in any

Table 35. Net Carbon Dioxide Sequestration from Landfilled Yard Trimmings and Food Scraps, 1990 and 1996-2002
(Million Metric Tons Carbon Dioxide Equivalent)

Description	1990	1996	1997	1998	1999	2000	2001	2002
Yard Trimmings	**23.2**	**11.3**	**10.4**	**9.6**	**8.4**	**7.2**	**7.4**	**7.4**
Grass	2.5	1.0	0.9	0.8	0.7	0.6	0.7	0.7
Leaves	11.2	5.9	5.4	5.1	4.5	4.0	4.0	4.0
Branches	9.6	4.4	4.0	3.7	3.2	2.6	2.7	2.7
Food Scraps	**2.8**	**2.1**	**2.5**	**2.8**	**2.9**	**2.9**	**2.8**	**2.7**
Total	**26.0**	**13.4**	**12.9**	**12.4**	**11.3**	**10.1**	**10.2**	**10.1**

Note: Totals may not equal sum of components due to independent rounding.

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenter PublicationsGHGEmissions USEmissionsInventory2004.html.

---

[140] G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. 5, web site www.pewclimate.org/docUploads/land_use.pdf.

[141] Pew Center on Global Climate Change, "Ninth Session of the Conference of the Parties to the UN Framework Convention on Climate Change" (Milan, Italy, December 1-12, 2003), web site www.pewclimate.org/what_s_being_done/in_the_world/cop_9_milan.cfm.

Global Forest Resources Assessment 2000

The Food and Agriculture Organization of the United Nations (FAO) is the main intergovernmental source of data on global forests. FAO's global forest assessments date back to 1948, with the most recent assessment—*Global Forest Resources Assessment 2000*—published in 2001. The 2000 assessment was the first to include a uniform definition of forests for all regions of the world—that is, areas with at least 10 percent of canopy cover (excluding stands of trees primarily used for agricultural production). Using this new definition, FAO estimated the world's forested area in 2000 at 3.9 billion hectares. This assessment indicated, however, that the world's forests experienced average net annual losses of 9.4 million hectares per year during the 1990 to 2000 period. This net figure results from annual losses of 14.6 million hectares due to deforestation, and annual gains of 5.2 million hectares due to reforestation, afforestation, and natural expansion of forests. Net losses were 12.3 million hectares annually for tropical forests, while non-tropical forests experienced average annual gains of 2.9 million hectares per year.[a]

The FAO *Global Forest Resources Assessment 2000* draws its forest data for the United States from U.S. Forest Service periodic forest inventories, which cover all forest land in the United States for more than 70 years. The national forest inventory measures samples on a 5- to 10-year cycle with an accuracy of ±1 percent per million hectares for forest area estimates. The FAO Assessment for 2000 cites total U.S. forest area at 226 million hectares. The change in U.S. forest area from 1990 to 2000 was 0.4 million hectares per year.[b]

A revised assessment is currently being prepared and will be published in 2005. *Global Forest Resources Assessment 2005* will involve more sophisticated datasets that result from satellite remote sensing.[c] EIA intends to include data on U.S. forests from the *Global Forest Resources Assessment 2005*, if available, in next year's report.

[a] Food and Agriculture Organization of the United Nations, *Global Forest Resources Assessment 2000*, "Executive Summary," web site www.fao.org/DOCREP/004/Y1997E/y1997e05.htm#bm05.

[b] Food and Agriculture Organization of the United Nations, *Global Forest Resources Assessment 2000*, Chapter 34, "North America, Excluding Mexico," web site www.fao.org/DOCREP/004/Y1997E/y1997e13.htm#bm39.

[c] T. Parris, "Global Forest Assessments," *Environment*, Vol. 45, No. 10 (2003), p. 3.

given State. Thus, there may be uncertainty about the year associated with the forest survey data. In addition, the existing forest survey data do not include forest stocks in Alaska, Hawaii, and the U.S. territories (although net carbon fluxes from these stocks are anticipated to be insignificant).[142]

Additional uncertainty results from the derivations of carbon sequestration estimates for forest floor, understory vegetation, and soil from models based on forest ecosystem studies. To extrapolate results of these studies to the forest land in question, an assumption was made that the studies effectively described regional or national averages. This assumption may result in bias from applying data from studies that improperly represent average forest conditions, from modeling errors, and/or from errors in converting estimates from one reporting unit to another.[143]

Aside from the land use data issues and uncertainties discussed above, which are specific to the methodologies used for the EPA estimates, there is concern about larger and more general uncertainty surrounding estimates of terrestrial carbon sequestration. It is anticipated to be difficult, as well as expensive, to determine carbon stock changes over shorter time periods, such as the 5-year periods suggested during international climate change negotiations. This concern is especially problematic if the carbon stocks are large and the stock changes are comparatively small.[144] Several countries involved in the negotiations have maintained that the accounting of terrestrial carbon stock changes over a 5-year commitment period fails to account for the differing dynamics of carbon stocks and fluxes over time.

In addition to concerns about uncertainty, permanence, and leakage, a recent scientific study published in the

---

[142] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[143] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002*, EPA-430-R-04-003 (Washington, DC, April 2004), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

[144] G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. 31, web site www.pewclimate.org/docUploads/land_use.pdf.

science journal *Nature* has raised questions about carbon sequestration through terrestrial sinks. The authors of the study, Dr. John Lichter and Dr. William Schlesinger, concluded that while forests do sequester carbon dioxide from the air and store it in the soil, the majority of the sequestered carbon is ultimately released back into the atmosphere as carbon dioxide when organic soil material decomposes. They maintain that their findings highlight the uncertainty of the role of soils as long-term carbon storage pools and assert that considerable long-term net carbon sequestration in forest soils may be unlikely.[145] Many scientists agree that much work remains to be done on the science surrounding terrestrial carbon sequestration; however, a number of the countries involved in international climate change negotiations assert that the potential for terrestrial carbon sequestration should be embraced, or at the very least, not discounted or overlooked.

Research by CarboEurope, a European program that has pioneered research into the carbon budget, reveals that soils in forests release more carbon than their trees will absorb in the first 10 years. Forest soils and the organic matter within them generally contain three to four times as much carbon as does vegetation on the ground. CarboEurope's researchers contend that, when ground is cleared for forest planting, rotting organic matter in the soil releases a surge of carbon dioxide into the air that will exceed the amount of carbon dioxide absorbed by growing trees for at least the first 10 years of forest growth; only later will the uptake of carbon by the trees begin to offset the release of carbon dioxide from the soil. In fact, their research indicates that some new forests planted on wet, peaty soils may never absorb as much carbon as they release.[146]

Thus, while there are methods available for estimating the amount of carbon sequestered through U.S. forests and soils, many uncertainties remain in the accounting methodology and overall conceptual feasibility of carbon sequestration both nationally and globally. For this reason, caution should be employed when accounting for the amount of carbon sequestered through land use and forestry practices, or when making decisions about the amount of sequestered carbon to be treated as an offset to national carbon dioxide emissions.

---

[145] W.H. Schlesinger and J. Lichter, "Limited Carbon Storage in Soil and Litter of Experimental Forest Plots Under Increased Atmospheric CO_2," *Nature,* Vol. 411 (2001), pp. 466-469.

[146] F. Pearce, "Tree Farms Won't Halt Climate Change," *New Scientist,* Print Edition (October 28, 2002), web site www.newscientist.com/news/news.jsp?id=ns99992958.

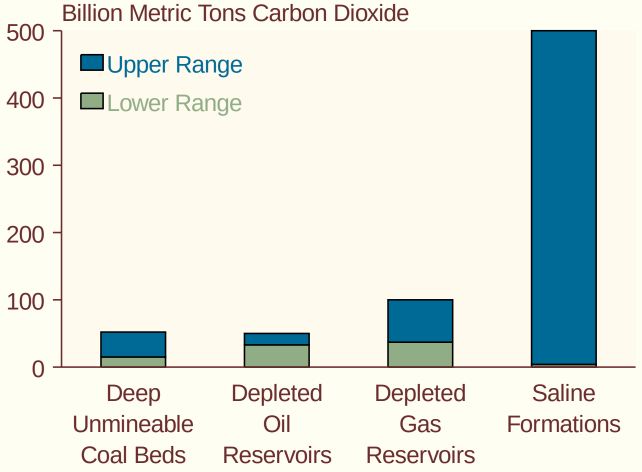
Carbon Dioxide Capture and Geologic Storage

The capture and permanent storage of carbon dioxide in geologic formations has gained increasing attention as an option for sequestering carbon dioxide emissions from industrial processes and coal-fired power generation. As part of the February 2002 introduction of the Global Climate Change Initiative, President Bush announced that the U.S. Government will develop policies to encourage geologic sequestration, which the Initiative describes as "critical to long-term emission reductions." Federal support for sequestration technologies include \$20 million for seven regional partnerships spanning 40 States to test potential capture technologies and storage reservoirs, creation of the Carbon Sequestration Leadership Forum to encourage multilateral carbon sequestration projects, and the Integrated Sequestration and Hydrogen Research Initiative, FutureGen, which is a \$1 billion government/industry partnership to design a "nearly emission-free" coal-fired plant to produce electricity and hydrogen.

The increased attention to geologic sequestration stems from the significant potential to store anthropogenic carbon dioxide in underground geologic formations. In the United States alone, geologic formations, such as depleted oil and gas reservoirs, deep unmineable coalbeds, and deep saline formations, may have the potential to store 140 to 670 billion metric tons of captured carbon dioxide.[a] These underground formations, which can be found all over the world, have the potential structure and porosity necessary for permanent sequestration, in that they already have stored crude oil, natural gas, brine, and naturally occurring carbon dioxide for millions of years. The two figures in this box show the estimated capacity range of each domestic geologic storage option in the United States and potential locations for geologic storage.

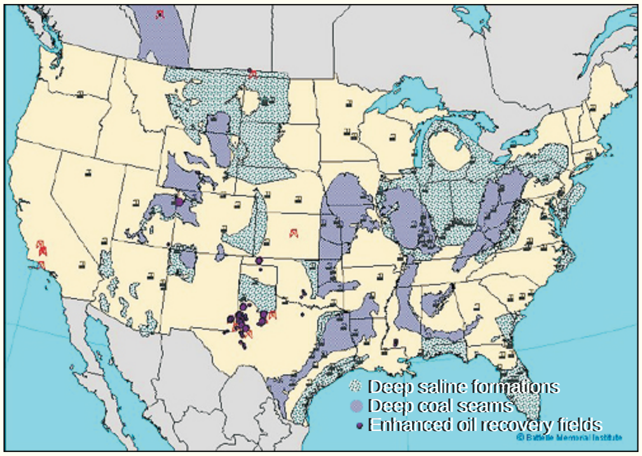
(continued on page 83)

Estimates of U.S. Geologic Storage Potential



Sources: Maximum and minimum estimates derived from: D.A. Beecy, V.A. Kuuskraa, and C. Schmidt, "A Perspective on the Potential Role of Geologic Options in a National Carbon Management Strategy," *Journal of Energy & Environmental Research*, Vol. 2, No. 1 (February 2002), pp. 47-53, web site www.netl.doe.gov/publications/journals/vol2/Papers/47-53.pdf; C.W. Byrer, "Sequestration of Carbon Dioxide in Geologic Formations." Presentation at COAL-SEQ 1 Forum (Houston, TX, March 14, 2002), web site www.coal-seq.com/Proceedings/CharlesByrer-CO2-Presentation.pdf; and CO_2 Capture and Storage Working Group, NCCTI Energy Technologies Group, Office of Fossil Energy, U.S. Department of Energy, *CO_2 Capture and Storage in Geologic Formations*, Revised Draft (Washington, DC, January 8, 2002), web site www.netl.doe.gov/coalpower/sequestration/pubs/CS-NCCTIwhitepaper.pdf.

Potential Geologic Storage Locations in the United States



Source: U.S. Department of Energy, Pacific Northwest National Laboratory.

[a] CO_2 Capture and Storage Working Group, NCCTI Energy Technologies Group, Office of Fossil Energy, U.S. Department of Energy, *CO_2 Capture and Storage in Geologic Formations*, Revised Draft (Washington, DC, January 8, 2002), web site www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/CS-NCCTIwhitepaper.pdf.

Carbon Dioxide Capture and Geologic Storage (Continued)

The geologic storage process involves the separation and capture of carbon dioxide from an anthropogenic source, such as a power plant or industrial facility; compression and transport of the carbon dioxide to the storage reservoir; and injection of the carbon dioxide into a geologic reservoir. As shown in the table below, geologic carbon dioxide storage projects can be divided into two categories. The first category consists of *value-added* capture and storage projects, in which captured carbon dioxide is reused for chemical or other industrial processes or to enhance resource recovery, such as enhanced oil, gas, and coalbed methane production. For this type of project, some of the cost of

(continued on page 84)

Summary of Carbon Dioxide Capture and Geologic Storage Options

Capture and Separation of Waste Carbon Dioxide from Power Production and Industrial Processes	Transportation	Storage	
		Resource Recovery and Reuse	Other Geologic Storage
• Chemical absorption with liquid amine solution • Oxygen-fired combustion • Pre-combustion decarbonization (e.g., through gasification)	• Carbon dioxide pipeline • Shipping • Trucking[a]	• Enhanced oil, gas, and coalbed methane recovery • Food processing and carbonation, and synthesis of chemicals	• Deep saline formations • Deep, unmineable coal seams • Depleted oil and gas reservoirs • Shales
Sample Applications			
A new 600-megawatt IGCC plant could capture up to 90 percent of carbon dioxide emissions. Additional energy expenditures would reduce the total captured carbon dioxide to 85 percent of what would be emitted without the project.[b]	A 300-kilometer pipeline transports carbon dioxide from a North Dakota gasification plant to the Weyburn oil field in Saskatchewan.	Carbon dioxide is injected under pressure into a geologic formation to enhance fuel extraction. More than 70 enhanced oil recovery (EOR) projects worldwide, mostly in U.S., 10 percent of which rely on waste carbon dioxide.[c]	Since 1996, Statoil has avoided Norway's carbon tax by sequestering carbon dioxide in a sandstone aquifer below the North Sea. About 1 million metric tons of carbon is stored a year, equivalent to 3 percent of Norway's total annual carbon dioxide emissions.
Estimated Cost of Carbon Dioxide Emissions Avoided (Dollars per Metric Ton)			
Power Plant Technology[d]	**Transportation Options[e]**	**Resource Recovery Options[e]**	**Other Storage Options[e]**
IGCC: 19.5 Ultra-supercritical PC: 42.4 NGCC: 60.4 High-purity CO_2 industrial sources: 10[h]	100 km via pipeline: 1-3 500 km via tanker: 2 Trucking: NA	NA[f]	Sample storage sites:[g] 4-19

IGCC = integrated gasification combined cycle; NA = not available; NGCC = natural gas combined cycle; PC = pulverized coal.

[a] A.F.B. Wildenborg and L.G.H. van der Meer, "The Use of Oil, Gas and Coal Fields as CO_2 Sinks." Paper presented at IPCC Workshop on Carbon Capture and Storage (Regina, Canada, November 18-21, 2002), web site www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/pdfs/ipcc_geological_storage2.pdf.

[b] Science Applications International Corporation, calculations based on data from K. Thambimuthu, J. Davison, and M. Gupta, "CO_2 Capture and Reuse." Paper presented at IPCC Workshop on Carbon Capture and Storage (Regina, Canada, November 18-21, 2002), web site http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/pdfs/ipcc_co2cap_reuse.pdf.

[c] U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, *Carbon Sequestration Technology Roadmap and Program Plan* (Washington, DC, March 12, 2003), web site www.fe.doe.gov/programs/sequestration/publications/programplans/2003/sequestration_roadmap03-13-03.pdf.

[d] Electric Power Research Institute, *Updated Cost and Performance Estimates for Fossil Fuel Power Plants with CO_2 Removal*, Interim report (Palo Alto, CA, December 2002), web site www.netl.doe.gov/coalpower/gasification/pubs/pdf/1004483.pdf.

[e] International Energy Agency (IEA), *Solutions for the 21st Century: Zero Emissions Technologies for Fossil Fuels* (Paris, France, May 2002), web site www.iea.org/impagr/zets/strategy/strategic_layout.pdf.

[f] No estimates are available on the added cost benefits of resource enhancement and the impact on total injection and storage cost.

[g] Due to the wide variation in storage types and site parameters, cost estimates for carbon dioxide storage are based on site-specific data and are not distinguished by storage type.

[h] International Energy Agency (IEA), Greenhouse Gas Research and Development Programme, *Opportunities for Early Application of CO_2 Sequestration Technologies*, Report PH4/10 (Cheltenham, UK, September 2002).

Source: National Energy Technology Laboratory, *Greenhouse Gas Accounting Issues for Carbon Capture and Geologic Storage Projects* (Pittsburgh, PA, February 2003), p. 2.

Carbon Dioxide Capture and Geologic Storage (Continued)

carbon dioxide storage is mitigated by the potential revenue expected from the sale of recovered oil or natural gas. In addition, the technologies for value-added storage are already mature. About 10 percent of the carbon dioxide-based enhanced oil recovery operations in the United States use waste carbon dioxide from industrial processes rather than naturally occurring carbon dioxide extracted directly from the ground. The typical storage rate is 2,000 standard cubic feet of carbon dioxide per barrel of oil recovered.[b]

The second category includes storage projects undertaken *specifically* to reduce carbon dioxide emissions, without the incentive of other value-added benefits. So far, one such large-scale geologic sequestration project has been implemented. In 1996, prompted by the Norwegian tax on carbon dioxide, the oil company Statoil began taking unwanted carbon dioxide from the Sleipner West field in the Norwegian North Sea and storing it 1,000 meters beneath the seabed in a saline aquifer reservoir. Since 1996, about 1 million metric tons of carbon dioxide per year has been injected into the Utsira saline aquifer, an amount roughly equal to one-third of the carbon dioxide output of a 300-megawatt coal-fired power plant.

The main challenge to geologic storage of carbon dioxide is not the technical feasibility of injection and storage, but the economics of capturing carbon dioxide from a point source. Carbon dioxide is never produced in a pure form and must therefore be separated from other products of combustion, making it more economical and practical to collect carbon dioxide from large point sources or power plants. The cost of capturing carbon dioxide is competitive in cases where the waste carbon dioxide stream is relatively pure, such as from natural gas processing or fertilizer and methanol production. Capture from stationary power plants is more costly, however, particularly from natural-gas-fired plants where the carbon dioxide content of the flue gas is lower. A number of commercial technologies to capture carbon dioxide have been developed, but they are energy-intensive and reduce the power plant's net output while increasing cost and contributing to atmospheric emissions. The estimated "energy penalty" of installing capture technology at a power plant ranges from 14 to 40 percent, depending on the type of combustion technology used.[c]

As shown in the table on page 83, the cost of capturing carbon dioxide from integrated gasification combined cycle (IGCC), advanced pulverized coal (PC), natural gas combined cycle (NGCC) power plants, and high-purity carbon dioxide sources ranges from $10 to $60 per metric ton of carbon dioxide emissions avoided. Capturing and sequestering 90 percent of the carbon dioxide from a new power plant in the United States is estimated to add $0.02 per kilowatt-hour to the cost of electricity, with 75 to 80 percent of the added cost attributable to the capture and combustion process.[d] Because capture technology must be an integral part of plant design, installing capture technology at existing facilities would be even more expensive.

EIA's national inventory does not consider carbon dioxide injected into oil, natural gas, or other geologic reservoirs as an emission but, instead, requires the reporting of carbon dioxide vented and flared during the production and processing of oil and gas. For active operations using enhanced oil recovery techniques, however, no estimate of carbon dioxide emissions is included in the annual inventory, because most of the carbon dioxide recovered with the oil is recycled and reinjected, and because currently there is no sound basis for estimating the quantity of carbon dioxide leaked from such operations.

[b] U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, *Carbon Sequestration Technology Roadmap and Program Plan—2004* (Washington, DC, April 2004), web site www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/SequestrationRoadmap4-29-04.pdf.

[c] International Energy Agency (IEA), *Solutions for the 21st Century: Zero Emissions Technologies for Fossil Fuels* (Paris, France, May 2002), web site www.iea.org/dbtw-wpd/textbase/papers/2003/strategic_layout.pdf.

[d] J. David, *Economic Evaluation of Leading Technology Options for Sequestration of Carbon Dioxide*. M.S. Thesis (Cambridge, MA: Massachusetts Institute of Technology, May 2000), web site http://sequestration.mit.edu/pdf/JeremyDavid_thesis.pdf.

References

Abrahamson, D. "Aluminum and Global Warming." *Nature* 356. April 1992.

Air Transportation Association. *Monthly Fuel Cost and Consumption.* Various years. Web site www.air-transport.org/public/industry/16.asp.

Alternative Fluorocarbons Environmental Acceptability Study. *Atmospheric Chlorine: CFCs and Alternative Fluorocarbons*. Web site www.afeas.org/atmospheric_chlorine.html.

Alternative Fluorocarbons Environmental Acceptability Study. *Production, Sales and Atmospheric Release of Fluorocarbons Through 1998*. Web site www.afeas.org/prodsales_download.html

American Automobile Manufacturers Association. *AAMA Vehicle Facts and Figures, 1996*. Detroit, MI.

American Chemical Council. *U.S. Chemical Industry Statistical Handbook*. Washington, DC, various years.

American Chemical Council. *Guide to the Business of Chemistry*. Washington, DC, various years.

American Gas Association. *Gas Engineers Handbook: Fuel Gas Engineering Practices*. New York, NY: Industrial Press, 1974.

American Gas Association. *Gas Facts*. Annual Statistical Report. Washington, DC, various years.

American Iron and Steel Institute. *Iron and Steel Annual Statistical Report*. Washington, DC, various years.

American Petroleum Institute. *Basic Petroleum Data Book*. Washington, DC, various years.

American Petroleum Institute. *Sales of Natural Gas Liquids and Liquefied Refinery Gases*. Washington, DC, various years.

American Society for Testing and Materials. *ASTM and Other Specifications for Petroleum Products and Lubricants*. Philadelphia, PA, 1985.

American Society of Agricultural Engineers. *Manure Production and Characteristics Standards*. St. Joseph, MI, 1988.

"Analysis of Adipic Acid Market." *Chemical Market Reporter*. June 15, 1998.

"Annual Report on Top 50 Industrial Chemicals." *Chemical and Engineering News*. April or June issue, various years.

"Annual Survey of State Agencies." *World Oil*. February issue, various years.

Association of American Plant Food Control Officials. *Commercial Fertilizers*. Washington, DC, various years.

Augenstein, D. "The Greenhouse Effect and U.S. Landfill Methane." *Global Environmental Change*. December 1992.

Australian Greenhouse Office, *Greenhouse Sinks and the Kyoto Protocol: An Issues Paper*, Commonwealth of Australia, 2000. Web site www.greenhouse.gov.au/pubs/internationalsinks.

Baldwin, R.L., Thornley, J.H.M., and Beever, D.E. "Metabolism of the Lactating Cow: Digestive Elements of a Mechanistic Model." *Journal of Dairy Research* 54. 1987.

Barnard, G. "Use of Agricultural Residues as Fuel." *Bioenergy and the Environment*. Ed. J. Pasztor and L. Kristoferson. Boulder, CO: Westview Press, 1990.

Bartlett, K., and Harriss, R.C. "Review and Assessment of Methane Emissions from Wetlands." *Chemosphere* 26, Nos. 1-4. 1993.

Berdowski, J.J.M., Beck, L., Piccot, S., Olivier, G.J., and Veldt, C. "Working Group Report: Methane Emissions from Fuel Combustion and Industrial Processes." *Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*. Ed. A.R. van Amstel. RIVM Report no. 481507003. Bilthoven, The Netherlands, 1993.

Bingemer, H.G., and Crutzen, P.J. "The Production of Methane From Solid Wastes." *Journal of Geophysical Research* 92, D2. February 20, 1987.

Biocycle Magazine. "Nationwide Survey: The State of Garbage in America." Annual Survey, various years. Web site www.biocycle.net.

Birdsey, R.A. *Carbon Storage and Accumulation in United States Forest Ecosystems*. U.S. Forest Service General Technical Report WO-59. Washington, DC, 1992.

Birdsey, R.A. "Changes in Forest Carbon Storage from Increasing Forest Area and Timber Growth." *Forests and Global Change, Vol 1: Opportunities for Increasing Forest Cover*. Ed. R.N. Sampson and D. Hair. Washington, DC: American Forests, 1992.

Birdsey, R.A., and L.S. Heath, "Carbon Changes in U.S. Forests." *Productivity of America's Forests and Climate Change*. Ed. L.A. Joyce. Fort Collins, CO: USDA Forest Service. General Technical Report RM-GTR-271, 1995.

Blaxter, K.L., and Clapperton, J.L. "Prediction of the Amount of Methane Produced by Ruminants." *British Journal of Nutrition* 19. 1965.

Bodanzky, D. "Prologue to the Climate Convention." *Negotiating Climate Change: The Inside Story of the Rio Convention*. Ed. I. Minter and J.A. Leonard. Cambridge, UK: Cambridge University Press, 1994.

Boden, T.A., Kaiser, D., Stepanski, R.J., and Stoss, F.W. *Trends '93: A Compendium of Data on Global Change*. ORNL/CDIAC-65. Oak Ridge, TN: Oak Ridge National Laboratory, September 1994.

Boden, T.A., Stepanski, R.J., and Stoss, F.W. *Trends '91: A Compendium of Data on Global Change*. ORNL/CDIAC-46. Oak Ridge, TN: Oak Ridge National Laboratory, December 1991.

Bogner, J.E. "Anaerobic Burial of Refuse in Landfills: Increased Atmospheric Methane and Implications for Increased Carbon Storage." *Ecological Bulletins* 42. 1992.

Boswell, C. "Hydrofluorocarbons Build with Transition Away from CFCs." *Chemical Market Reporter*. September 13, 1999.

Bouwman, A.F. "Exchange of Greenhouse Gases Between Terrestrial Ecosystems and Atmosphere." *Soils and the Greenhouse Effect*. Ed. A.F. Bouwman. New York, NY: John Wiley and Sons, 1990.

Bremner, J.M., and Blackmer, A.M. "Nitrous Oxide: Emissions From Soil During Nitrification of Fertilizer Nitrogen." *Science* 199. 1978.

Brown, P. "Climate Fear As Carbon Levels Soar," *The Guardian*. October 12, 2004. Web site www.guardian.co.uk/international/story/0,,1324276,00.html.

Burdick, D.L., and Leffler, W.L. *Petrochemicals in Nontechnical Language*. Oklahoma City, OK: Pennwell Publishing Company, 1990.

Cicerone, R.J., and Shetter, J.D. "Sources of Atmospheric Methane: Measurements in Rice Paddies and Discussion." *Journal of Geophysical Research* 86, C8. August 1981.

Cicerone, R.J., Shetter, J.D., and Delwiche, C.C. "Seasonal Variation of Methane Flux from a California Rice Paddy." *Journal of Geophysical Research* 88. December 1983.

Clean Air Act Amendments of 1990. P.L. 101-549, Nov. 15, 1990. Title VI, "Stratospheric Ozone Protection," 10489AT2849-2872.

Clinton, W.J., and Gore, A. *The President's Climate Change Action Plan*. Washington, DC, October 1994.

Cooperative Research Centre for Greenhouse Accounting. "Good Practice for Land Use, Land-Use Change, and Forestry." Web site www.greenhouse.crc.org.au/goodpractice/.

Cost, N.D., Howard, J., Mead, B., McWilliams, W.H., Smith, W.B., Van Hooser, D.D., and Wharton, E.H. *The Biomass Resource of the United States*. USDA Forest Service General Technical Report WO-57. Washington, DC, 1990.

Crutzen, P.J., Aselmann, I., and Seiler, W. "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans." *Tellus* 38B. 1986.

Cubbage, F.C. "Federal Land Conversion Programs." *Forests and Global Change* 1. 1992.

Dahl, T. *Wetlands Losses in the United States: 1780's to 1980's*. Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service, 1990.

Dale, C., et al. "First Oxygenated Gasoline Season Shakes Out Differently Than Expected." *Oil and Gas Journal.* October 25, 1993.

Darley, E. *Emission Factors from Burning Agricultural Wastes Collected in California*. Final Report, CAL/ARB Project 4-011. Riverside, CA: University of California, 1977.

Daugherty, A. *Major Uses of Land in the United States: 1987*. Agricultural Economic Report No. 643. Washington, DC: U.S. Department of Agriculture, Economic Research Service, 1991.

Daugherty, A. *Major Uses of Land in the United States: 1992*. Agricultural Economic Report No. 723. Washington, DC: U.S. Department of Agriculture, Economic Research Service, September 1995.

David, J. *Economic Evaluation of Leading Technology Options for Sequestration of Carbon Dioxide*. M.S. Thesis. Cambridge, MA: Massachusetts Institute of Technology, May 2000. Web site http://sequestration.mit.edu/pdf/JeremyDavid_thesis.pdf.

De Soete, G.G. "Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control." *International IPCC Workshop Proceedings: Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control*. Ed. A.R. van Amstel. Bilthoven, Netherlands: RIVM, 1993.

Defense Logistics Agency, Defense Fuel Supply Center, Office of the Comptroller. *Fact Book Annual Report*. Alexandria, VA, various years.

DeLuchi, M. *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity*. Vol. 2. ANL/ESD/TM-22. Chicago, IL: Argonne National Laboratory, November 1993.

Douglas, H. *Handbook of Mineral Economics*. San Francisco, CA: Hugh Douglas and Company, 1983.

Drexel University Project Team. *Energy Analysis of 108 Industrial Processes*. Lilburn, GA: The Fairmont Press, 1996.

"DuPont Set To Expand Markets for Ozone-Safe HFC-152a Product." *Ozone Depletion Online Today*. June 9, 1995.

Duxbury, J.M., and McConnaughey. P.K. "Effect of Fertilizer Source on Denitrification and Nitrous Oxide Emission in a Maize Field." *Soil Sci. Soc. Am. J.* 50. 1986.

E.H. Pechan and Associates, Inc. *The Emission Reduction and Cost Analysis Model for* NO_X *ERCAM-*NO_X. Report prepared for the U.S. Environmental Protection Agency, Ozone/CO Programs Branch. Research Triangle Park, NC, May 1994.

Eberle, A.C. "An Engineering Estimate of the Incremental Change in Methane Emissions with Increasing Throughput in a Natural Gas System." Presented at the 1994 International Workshop on Environmental and Economic Impacts of Natural Gas Losses, March 22 and 23, Prague, The Czech Republic.

EcoSecurities, Ltd. "'Sinks' and Climate Change. Comment on Recent Reporting on Last Week's *Nature* Journal. EcoSecurities Press Release. Web site www.ecosecurities.com/ 200about_us/ 223press_releases/ 223press_release_sinks_climate.html. June 2001.

Electric Power Research Institute. *Updated Cost and Performance Estimates for Fossil Fuel Plants with* CO_2 *Removal*. Interim Report. Palo Alto, CA, December 2002. Web site www.netl.doe.gov/coalpower/gasification/pubs/1004483.pdf.

Energy Information Administration. *Annual Energy Outlook*. DOE/EIA-0383. Washington, DC, various years. Web site www.eia.doe.gov/oiaf/aeo/.

Energy Information Administration. *Annual Energy Review*. DOE/EIA-0384. Washington, DC, various years. Web site www.eia.doe.gov/emeu/aer/.

Energy Information Administration. *Btu Tax on Finished Petroleum Products.* Unpublished draft report. Washington, DC, April 1993.

Energy Information Administration. *Coal Industry Annual*. DOE/EIA-0584. Washington, DC, various years.

Energy Information Administration. *Coal Production*. DOE/EIA-0118. Washington, DC, various years.

Energy Information Administration. *Coal Quarterly*. DOE/EIA-0121. Washington, DC, various years.

Energy Information Administration. *Cost and Quality of Fuels for Electric Utility Plants*. DOE/EIA-0191. Washington, DC, various years.

Energy Information Administration. *Documentation for Emissions of Greenhouse Gases in the United States 2002*. DOE/EIA-0638 (2002). Washington, DC, 2004.

Energy Information Administration. *Electric Power Annual*. DOE/EIA-0348. Washington, DC, various years.

Energy Information Administration. *Emissions of Greenhouse Gases in the United States*. DOE/EIA- 0573. Washington, DC, various years.

Energy Information Administration. Form EIA-767, "Steam Electric Plant Operation and Design Report." Unpublished survey data. Washington, DC, various years.

Energy Information Administration. *Fuel Oil and Kerosene Sales*. DOE/EIA-0535. Washington, DC, various years.

Energy Information Administration. *Household Vehicles Energy Consumption*. DOE/EIA-0464. Washington, DC, various years.

Energy Information Administration. *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity*. SR/OIAF/98-03. Washington, DC, October 1998. Web site www.eia.doe.gov/oiaf/kyoto/kyotorpt.html.

Energy Information Administration. *International Energy Annual*. DOE/EIA-0121. Washington, DC, various years. Web site www.eia.doe.gov/emeu/iea/.

Energy Information Administration. *International Energy Outlook*. DOE/EIA-0484. Washington, DC, various years.

Energy Information Administration. *Manufacturing Energy Consumption Survey*. DOE/EIA-0512. Washington, DC, various years. Web site www.eia.doe.gov/emeu/mecs/.

Energy Information Administration. *Monthly Energy Review*. DOE/EIA-0035. Washington, DC, various issues. Web site www.eia.doe.gov/emeu/mer/.

Energy Information Administration. *Natural Gas Annual*. DOE/EIA-0131. Washington, DC, various years.

Energy Information Administration. *Natural Gas Monthly*. DOE/EIA-0130. Washington, DC, various issues.

Energy Information Administration. *Petroleum Supply Annual*. DOE/EIA-0340. Washington, DC, various years.

Energy Information Administration. *Petroleum Supply Monthly*. DOE/EIA-0109. Washington, DC, various years.

Energy Information Administration. *Renewable Energy Annual*. DOE/EIA-0603. Washington, DC, various years. Web site www.eia.doe.gov/cneaf/solar.renewables/page/rea_data/rea_sum.html.

Energy Information Administration. *Short-Term Energy Outlook*. DOE/EIA-0202. Washington, DC, various issues.

Energy Information Administration. *State Energy Data Report: Consumption Estimates*. DOE/EIA-0214. Washington, DC, various years.

Energy Information Administration. *U.S. Coal Supply and Demand: 2000 Review*. Washington, DC, 2001. Web site www.eia.doe.gov/cneaf/coal/page/special/feature.html.

Energy Information Administration. *U.S. Coal Supply and Demand: 2003 Review*. Washington, DC, 2004. Web site www.eia.doe.gov/cneaf/coal/page/special/feature.html.

Energy Information Administration. *U.S. Electric Utility Demand Side Management 1994*. DOE/EIA-0589(94). Washington, DC, December 1995.

"Environmental Protection Drives Emissions Reduction Effort." *Electronic Design*. December 1, 1997.

"EPA Launches PFC Reduction Program." *Chemical Week*. July 31, 1996.

European Fluorocarbon Technical Committee. "Fluorocarbons and Sulphur Hexafluoride: Products and Main Applications. Web site www.fluorocarbons.org/frame.htm?chfamilies/SF6/prod_main/prod.htm.

"Fluorocarbon Outlook Turns Bullish." *Chemical Market Reporter*. May 25, 1998.

Food and Agriculture Organization of the United Nations. *Food Balance Sheets*. Various years. Web site http://apps.fao.org/.

Food and Agriculture Organization of the United Nations. *Global Forest Resources Assessment 2000*. Web site www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/004/Y1997E/Y1997E00.HTM.

Franklin Associates, Ltd. *Characterization of Municipal Solid Waste in the United States: Annual Updates*. Prepared for U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, various years.

Freedonia Group, Inc. *Carbon Dioxide*. Business Research Report B286. Cleveland, OH, November 1991.

Freedonia Group Inc. *Carbon Dioxide*. Industry Study 564. Cleveland, OH, February 1994.

Gas Technology Institute. *Chemical Composition of Discovered and Undiscovered Natural Gas in the United States—1993 Update*. GRI-93/0456. December 1993.

Gas Technology Institute. *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*. GRI-92/0123. March 1992.

Goodger, E.M. *Hydrocarbon Fuels: Production, Properties and Performance of Liquids and Gases*. New York, NY: John Wiley & Sons, 1975.

Greeley, W. (U.S. Forest Service). "The Relation of Geography to Timber Supply." *Economic Geography* 1. 1925.

Griffin, R. "CO_2 Release from Cement Production 1950-1985." Ed. G. Marland et al. Oak Ridge, TN, Oak Ridge National Laboratory, 1987.

Grubb, M.J. "On Coefficients for Determining Greenhouse Gas Emissions from Fossil Fuel Production and Consumption." London, UK: Royal Institute of International Affairs, Energy and Environmental Programme, 1989.

Guerra, C.R., Kelton, K., and Nielsen, D.C. "Natural Gas Supplementation with Refinery Gases and Hydrogen." *New Fuels and Advances in Combustion Technologies*. Chicago, IL: Institute of Gas Technology, 1979.

Guthrie, V.B., Ed. *Petroleum Products Handbook*. New York, NY: McGraw-Hill, 1960.

Hadaller, O.J., and Momenthy, A.M. "Conventional Jet Fuels." *The Characteristics of Future Fuels*. Part 1. Seattle, WA: Boeing Corp., September 1990.

Harrison, M.R., and Cowgill, R.M. *Tier 2 Summary of Methane Emissions from the Natural Gas Industry*. Draft Final Report Prepared for the Gas Research Institute and the U.S. Environmental Protection Agency. Washington, DC, January 1996.

Hashimoto, A.G., Varel, V.H., and Chen, Y.R. "Ultimate Methane Yield From Beef Cattle Manure: Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." *Agricultural Wastes* 3. 1981.

Heath, L.S., Birdsey, R.A., and Row, C. "Carbon Pools and Flux in U.S. Forest Products." *The Role of Forest Ecosystems and Forest Resource Management in the Global Carbon Cycle*. NATO ASI Series. Germany: Springer-Verlag, 1995.

"HFC-134a Prices Rise As Market Tightens." *Chemical Market Reporter*. March 15, 1999.

Hill, D.T. "Methane Productivity of the Major Animal Types." *Transactions of the ASAE* 27. 1984.

Holzappfel-Pschorn, A., and Seiler, W. "Methane Emission During a Cultivation Period from an Italian Rice Paddy." *Journal of Geophysical Research* 91. October 1986.

Hong, B.D., and Slatick, E.R. "Carbon Dioxide Emission Factors for Coal." Energy Information Administration. *Quarterly Coal Report*, January-March 1994. Washington, DC, 1994.

Houghton, R.A., et al. "The Flux of Carbon from Terrestrial Ecosystems to the Atmosphere in 1980 Due to Changes in Land Use: Geographic Distribution of the Global Flux." *Tellus* 39. 1987.

Hunt, J.M. *Petroleum Geochemistry and Geology*. San Francisco, CA: W.H. Freeman, 1979.

Intergovernmental Panel on Climate Change. *Climate Change: The IPCC Scientific Assessment*. Cambridge, UK: Cambridge University Press, 1990. Web site www.ipcc.ch/pub/reports.htm.

Intergovernmental Panel on Climate Change. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Cambridge, UK: Cambridge University Press, 1992. Web site www.ipcc.ch/pub/reports.htm.

Intergovernmental Panel on Climate Change. *Climate Change 1994: Radiative Forcing of Climate Change*. Cambridge, UK: Cambridge University Press, 1995. Web site www.ipcc.ch/pub/reports.htm.

Intergovernmental Panel on Climate Change. *Climate Change 1995: The Science of Climate Change*. Cambridge, UK: Cambridge University Press, 1996. Web site www.ipcc.ch/pub/reports.htm.

Intergovernmental Panel on Climate Change. *Climate Change 2001: The Scientific Basis*. Cambridge, UK: Cambridge University Press, 2001. Web site www.ipcc.ch/pub/reports.htm.

Intergovernmental Panel on Climate Change. *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. Hayama, Kanagawa, Japan: 2003. Web site www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.htm.

Intergovernmental Panel on Climate Change. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. J. Penman, D. Kruger, et al., Editors. Tokyo, Japan: Institute for Global Environmental Strategies, 2000. Web site www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm.

Intergovernmental Panel on Climate Change. *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Vols. 1-4. (Paris, France, 1997). Web site www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Intergovernmental Panel on Climate Change. *Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control*. Proceedings, Research for Man and Environment. Bilthoven, Netherlands, February 1993.

Intergovernmental Panel on Climate Change, Summary for Policymakers: Land Use, Land-Use Change, and Forestry (May 2000). Web site: www.ipcc.ch/pub/srlulucf-e.pdf.

International Energy Agency. *Opportunities for Early Application of* CO_2 *Sequestration Technologies*. Report PH4/10. Cheltenham, UK: September 2002.

International Energy Agency. *Solutions for the 21st Century: Zero Emissions Technologies for Fossil Fuels*. Working Document. Paris, France: May 2002. Web site www.iea.org/dbtw-wpd/textbase/papers/2003/strategic_layout.pdf.

Jaques, A., Neitzert, F., and Boileau, P. *Trends in Canada's Greenhouse Gas Emissions (1990-1995)* Ottawa, Canada: Environment Canada, October 1997.

Keeling, C.D., and Whorf, T.P. "Atmospheric CO_2 Records From Sites in the SIO Air Sampling Network." 1993.

Kirchgessner, D., Cowgill, R.M., Harrison, M., and Campbell, L.M. "Methods for Estimating Methane Emissions from the Domestic Natural Gas Industry." Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Air Pollution Prevention Division, June 1995.

Kirchgessner, D.A., Piccot, S.D., and Chadha, A. "Estimation of Methane Emissions from A Surface Coal Mine Using Open-Path FTIR Spectroscopy and Modeling Techniques." *Chemosphere*. Special Methane Edition. 1993.

Kolshus, H. *Carbon Sequestration in Sinks: An Overview of Potential and Costs*. CICERO Working Paper 2001: 11. Oslo, Norway, November 2001.

Kostick, D. "Soda Ash, Sodium Bicarbonate, and Sodium Sulfate." *Mineral Facts and Problems*. 1985 ed. Washington, DC, 1985.

Kostick, D. "Sodium Compounds." *Minerals Yearbook, 1987*. Washington, DC, 1987.

Kramlich, J.C., and Linak, W.P. "Nitrous Oxide Behavior in the Atmosphere, and in Combustion and Industrial Systems." *Progress in Energy and Combustion Science* 20. 1994.

Landau, C.W., and Bolich, P.K. "Methane Emissions from Louisiana First and Ratoon Crop." *Soil Science* 156. 1993.

Leutwyler, K. "No Global Warming?" *Scientific American*. February 1994.

Li, C., Frolking, S., and Harriss, R. "Modeling Carbon Biogeochemistry in Agricultural Soils." *Global Biogeochemical Cycles* 8. September 1994.

Liss, W.E., et al. *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*. GRI-92/0123. Chicago, IL: Gas Research Institute, October 1992.

MacKinnon, M. "Canada's Stance on Pollution Debunked." *The Globe and Mail*. June 5, 2001.

Mann, L.K. "Changes in Soil Carbon Storage After Cultivation." *Soil Science* 142. November 1986.

Mannsville Chemical Corporation. "Adipic Acid." *Chemical Products Synopsis*. Asbury Park, NJ, June 1990.

ManTech Environmental Technology, Inc. *Impact of Conservation Tillage on Soil and Atmospheric Carbon in the Contiguous United States*. PB92-113448. Prepared for the Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency. September 1991.

Marland, G., and Pippin, A. "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy* 14. 1990.

Marland, G., and Rotty, R. "Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982." *Tellus* 36B. 1984.

Marland, G., and Schlamadinger, B. *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol*. Arlington, VA: Pew Center on Global Climate Change, June 2000. Web site www.pewclimate.org/docUploads/land_use.pdf.

Marland, G., et al. *Estimates of CO_2 Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data*. Oak Ridge, TN: Oak Ridge National Laboratory, 1989.

Martel, C.R., and Angelo, L.C. "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels." *Current Research in Petroleum Fuels*. Vol. I. New York, NY: MSS Information Corporation, 1977.

Matthews, E., and Fung, I. "Methane Emissions From Natural Wetlands: Global Distribution, Area, and Environmental Characteristics." *Global Biogeochemical Cycles* 1. March 1987.

Matthews, E., Fung, I., and Lerner, J. "Methane Emission From Rice Cultivation: Geographic and Seasonal Distribution of Cultivated Areas and Emissions." *Global Biogeochemical Cycles* 5. March 1991.

McKeever, D. "Taking Inventory of Woody Residuals." *BioCycle* 44. July 2003.

McKeever, D., and Falk, R. "Recovering Wood for Reuse and Recycling: A United States Perspective." In C. Gallis, Editor. *European COST E31 Conference: Management of Recovered Wood Recycling, Bioenergy, and Other Options*. Thessaloniki, Greece: April 2004.

McKeever, D., and Falk, R. "Woody Residues and Solid Waste Wood Available for Recovery in the United States, 2002." In C. Gallis, Editor. *European COST E31 Conference: Management of Recovered Wood Recycling, Bioenergy, and Other Options*. Thessaloniki, Greece: April 2004.

Moore, T.R. and Knowles, R. "The Influence of Water Table Level on Methane and Carbon Dioxide Emissions From Peatland Soils." *Canadian Journal of Soil Science* 69. 1989.

Mosier, A. "Nitrous Oxide Emissions from Agricultural Soils." Paper presented at RIVM International Workshop on Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control. Amersfoort, The Netherlands: February 3-5, 1993.

Mosier, A., et al. "Methane and Nitrous Oxide Fluxes in Native, Fertilized, and Cultivated Grasslands." *Nature* 350. 1991.

Mosier, A., and Schimel, D. "Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide." *Chemistry & Industry* 2. December 1991.

Mosier, A., Parton, W.J., and Hutchinson, G.L. "Modelling Nitrous Oxide Evolution from Cropped and Native Soils." *Ecology Bulletin* 35. 1983.

Mynenei, R., et al. "Forests Storing 700 Million Tons of Carbon per Year." *UniSci Daily University Science News*. December 12, 2001.

Nabuurs, G.J., and N.H. Ravindranath. "Task 1, Chapter 3: Good Practice Guidence for National GHG Inventory for LULUCF Sector." Presentation at the IPCC-NGGIP Event at SB-18. Bonn, Germeny, June 6, 2003.

Nagy, B., and Columbo, U., eds. *Fundamental Aspects of Petroleum Chemistry*. New York, NY: Elsevier Publishing, 1967.

National Energy Technology Laboratory. *Greenhouse Gas Accounting Issues for Carbon Capture and Geologic Storage Projects*. Pittsburgh, PA, February 2003.

National Institute of Petroleum and Energy Research. *Motor Gasoline*, Summer Edition; and *Motor Gasoline*, Winter Edition. Various years.

National Research Council. *Rethinking the Ozone Problem in Urban and Regional Air Pollution.* Washington, DC: National Academy Press, 1991.

Neue, H.H., and Scharpenseel, H.W. *Gaseous Products of Decomposition of Organic Matter and Rice*. Los Banos, Philippines, 1984.

Nowak, D.J., and Crane, D.E. "Carbon and Sequestration by Urban Trees in the United States." *Environmental Pollution* 116. 2001.

Oak Ridge National Laboratory. *Transportation Energy Data Book*. Oak Ridge, TN, various years. Web site www-cta.ornl.gov/publications/tedb.html.

Oil & Gas Journal. "Pipeline Economics" (special issue). Various years.

Oil & Gas Journal. "Worldwide Gas Processing" (special issue). Various years.

Oil & Gas Journal. "Worldwide Refining" (special issue). Various years.

Organization for Economic Cooperation and Development. *Estimation of Greenhouse Gas Emissions and Sinks*. Final Report. Paris, France, August 1991.

Pacey, J. "Methane Recovery from Landfills." Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium. U.S. Environmental Protection Agency, Washington, DC, June 27-29, 1995.

Pacey, J., Thorneloe, S.A., and Dorne, M. "Methane Recovery from Landfills and an Overview of EPA's Research Program for Landfill Gas Utilization." Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium, U.S. Environmental Protection Agency. Washington, DC, June 27-29, 1995.

Parris, T. "Global Forest Assessments." *Environment* 45. 2003. p. 3.

Parson, E.A., and Greene, O. "The Complex Chemistry of the International Ozone Agreements." *Environment* 37. March 1995.

Pearce, F. "Tree Farms Won't Halt Climate Change." *New Scientist*. Print Edition. October 28, 2002. Web site www.newscientist.com/news/news.jsp?id=ns99992958.

Pew Center on Global Climate Change. *Ninth Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change*. Milan, Italy, December 1-12, 2003. Web site www.pewclimate.org/what_s_being_done/in_the_world/cop_9_milan.cfm.

"PFCs Can Be Recycled with New Technology." American Institute of Chemical Engineers. Press Release. March 12, 1997.

Piccot, S.D., Masemore, S.S., Ringler, E., and Kirchgessner, D.A. "Developing Improved Methane Emission Estimates for Coal Mining Operations." Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium, U.S. Environmental Protection Agency. Washington, DC, June 27-29, 1995.

Pingoud, P., et al. "Approaches for Inclusion of Harvested Wood Products in Future GHG Inventories Under the UNFCCC, and Their Consistency with the Overall UNFCCC Reporting Framework." *IEA Bioenergy*. July 13, 2004.

Powell, D.S., Faulkner, J.L., Darr, D.R., Zhu, Z., and MacCleery, D.W. *Forest Resources of the United States, 1992*. USDA Forest Service General Technical Report RM-234. Washington, DC, September 1993.

Prather, M., et al. "Other Trace Gases and Atmospheric Chemistry." Intergovernmental Panel on Climate Change. *Climate Change 1994: Radiative Forcing of Climate Change*. Cambridge, UK: Cambridge University Press, 1995.

Radian Corporation. *Global Emissions of Methane from Petroleum Sources*. Report prepared for the American Petroleum Institute. Research Triangle Park, NC, February 1992.

Radian Corporation. *Nitrous Oxide Emissions from Adipic Acid Manufacturing*. Report prepared for U.S. Environmental Protection Agency, Office of Research and Development. Rochester, NY, January 1992.

Railroad Commission of Texas. *Annual Summaries of Texas Natural Gas*. Various years.

Ravishankara, A.R., Turnipseed, A.A., Jensen, N.R., Barone, S., Mills, M., Howard, C.J., and Solomon, S. "Do Hydrocarbons Destroy Stratospheric Ozone?" *Science* 263. 1994.

Reimer, R.A., Parrett, R.A., and Slaten, C.S., "Abatement of N_2O Emissions Produced in Adipic Acid." *Proceedings of the 5th International Workshop on Nitrous Oxide Emissions*. Tsukuba, Japan, July 1992.

Rhodes, A.K. "U.S. Refiners Scramble To Meet Reformulated Gasoline Mandate." *Oil and Gas Journal*. January 27, 1992.

Ringen, S., Lanum, J., and Miknis, F.P. "Calculating Heating Values from Elemental Compositions of Fossil Fuels." *Fuel* 58. January 1979.

Rose, J.W., and Cooper, J.R. *Technical Data on Fuel*. London, UK: The British National Committee, World Energy Conference, 1977.

Safley, L.M., Casada, M.E., Woodbury, J., and Roos, K.F. *Global Methane Emissions from Livestock and Poultry Manure*. EPA/400/1-91/048. Washington, DC: U.S. Environmental Protection Agency, Office of Air and Radiation, February 1992.

Salthouse, R. *Making Clean Gasoline*. Logistics Management Institute, September 1992.

Sampson, R.N., and Winnett, S.M. "Trees, Forests, and Carbon." *Forests and Global Change*, Vol. 1. Washington, DC, 1992.

Sass, R.L., Fisher, F.M., and Harcombe, P.A. "Methane Production and Emission in a Texas Rice Field." *Global Biogeochemical Cycles* 4. March 1990.

Sass, R.L., Fisher, F.M., Lewis, S., Jund, M., and Turner, F. "Methane Emissions from Rice Fields: Effect of Soil Properties." *Global Biogeochemical Cycles* 8. 1994.

Sass, R.L., Fisher, F.M., and Wang, Y.B. "Methane Emissions from Rice Fields: The Effect of Floodwater Management." *Global Biogeochemical Cycles* 6. 1992.

Schiff, D. and Sciannamea, M. "Greenlook." *Electronic Design*. December 15, 1997.

Schlesinger, W.H. "Changes in Soil Carbon Storage and Associated Properties with Disturbance and Recovery." *The Changing Carbon Cycle: A Global Analysis*. Ed. J. Trabalka and D. Riechle. New York, NY: Springer-Verlag, 1986.

Schlesinger, W.H., and Lichter, J. "Limited Carbon Storage in Soil and Litter of Experimental Forest Plots Under Increased Atmospheric CO_2." *Nature* 411. 2001.

Schmidt, P.F. *Fuel Oil Manual.* New York, NY: Industrial Press, 1969.

Schutz, H., Seiler, W., and Conrad, R. "Processes Involved in Formation and Emissions of Methane in Rice Paddies." *Biogeochemistry* 7. 1989.

Science Applications International Corporation. *Analysis of the Relationship Between the Heat and Carbon Content of U.S. Coals: Final Task Report*. Report prepared for Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels. Washington, DC, 1992.

Seager, T.P. and Theis, T.L. "A Thermodynamic Basis for Evaluating Environmental Policy Trade-offs." *Clean Technology and Environmental Policy* 4. 2002.

Searls, J.P. "Sodium Compounds," *Minerals Yearbook, 1984*. Washington, DC: U.S. Bureau of Mines, 1984.

Seiler, W., and Crutzen, P. "Estimates of Gross and Net Fluxes of Carbon Between the Biosphere and the Atmosphere from Biomass Burning." *Climatic Change* 2. 1980.

Shine, K.P., Fouquart, Y., Ramaswamy, V., Solomon, S., and Srinivasan, J. "Radiative Forcing." *Climate Change 1994: Radiative Forcing of Climate Change*. Cambridge, UK: Cambridge University Press, 1995.

Smythe, K.D. "Production and Distribution of SF_6 by End-Use Application." International Conference on SF_6 and the Environment: Emission Reduction Strategies. San Diego, CA. November 21-22, 2002.

Spicer, C.W., Holdren, M.W., Smith, D.L., Hughes, D.P., and Smith, M.D. "Chemical Composition of Exhaust from Aircraft Turbine Engines." *Journal of Engineering for Gas Turbines and Power* 114. January 1992.

Steudler, P.A., et al. "Influence of Nitrogen Fertilization on Methane Uptake in Temperate Forest Soils." *Nature* 341. September 28, 1989.

Stevens, W.R. III. *Abatement of Nitrous Oxide Emissions Produced in the Adipic Acid Industry*. White House Conference on Global Climate Change, Nitrous Oxide Workshop. Wilmington, DE: Mimeo, The DuPont Company, June 11, 1993.

Strehler, A., and Stutzle, W. "Biomass Residues." *Biomass: Regenerable Energy*. Ed. D.O. Hall and R.P. Overend. Chichester, UK: John Wiley and Sons, 1987.

Sturges, W.T., et al. "A Potent Greenhouse Gas Identified in the Atmosphere: SF_5CF_3." *Science* 289. July 28, 2000.

Takeshita, M., and Soud, H. *FGD Performance and Experience on Coal-fired Plants*. London, UK: IEA Coal Research, July 1993.

Tennessee Valley Authority. *Commercial Fertilizers*. Washington, DC, 1995-2002.

Thiemens, M., and Trogler, W. "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide." *Science* 251. February 22, 1991.

Thorneloe, S.A. “Landfill Gas Recovery/Utilization—Options and Economics.” Paper presented at the Sixteenth Annual Conference by the Institute of Gas Technology on Energy from Biomass and Wastes, Orlando, FL, March 5, 1992.

Thorneloe, S.A., Doorn, M.R.J., Stefanski, L.A., Barlaz, M.A., Peer, R.L., and Epperson, D.L. “Estimate of Methane Emissions from U.S. Landfills.” Prepared for U.S. Environmental Protection Agency, Office of Research and Development. April 1994.

Trevits, M.A., Finfinger, G.L., and LaScola, J.C. “Evaluation of U.S. Coal Mine Emissions.” Society for Mining, Metallurgy and Exploration, *Proceedings of the Fifth U.S. Mine Ventilation Symposium*. Littlejohn, 1991.

Turner, D.P., Lee, J.L., Koerper, G.J., and Barker, J.R., Eds. *The Forest Sector Carbon Budget of the United States: Carbon Pools and Flux under Alternative Policy Options*. EPA/600/3-93/093. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development, May 1993.

U.S. Department of Agriculture, Crop Reporting Board, Statistical Reporting Service. *Commercial Fertilizers*. SpCr 7. Washington, DC, various years.

U.S. Department of Agriculture, Forest Service. *AVHRR Forest Type Map, 1993 RPA Program, Forest Inventory and Analysis*. Starkville, MS, December 1992. Modified for printing by Pacific Meridian Resources, Emeryville, CA, 1996.

U.S. Department of Agriculture, Global Change Program Office. *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001*. Technical Bulletin No. 1907. March 2004. Web site www.usda.gov/oce/gcpo/ghginventory.html.

U.S. Department of Agriculture, National Agricultural Statistics Service. *Agricultural Statistics*. Washington, DC, various years. Web site www.usda.gov/nass/.

U.S. Department of Agriculture, National Agricultural Statistics Service, Agricultural Statistics Board. *Cattle, February Issue*. Washington, DC, various years. Web site www.usda.gov/nass/.

U.S. Department of, Agriculture, National Agricultural Statistics Service. *Census of Agriculture, United States Summary and State Data. Vol. 1, Geographic Area Series, Part 51*. Washington, DC, 1982, 1987, 1992, and 1997. Web site www.nass.usda.gov/census/.

U.S. Department of Agriculture, National Agricultural Statistics Service, Agricultural Statistics Board. *Chickens and Eggs, February issue*. Washington, DC, various years. Web site www.usda.gov/nass/.

U.S. Department of Agriculture, National Agricultural Statistics Service, Agricultural Statistics Board. *Crop Production*. Washington, DC, various years. Web site www.usda.gov/nass/.

U.S. Department of Agriculture, National Agricultural Statistics Service. *NASS On-Line Database*. Web site www.nass.usda.gov:81.

U.S. Department of Agriculture, National Agricultural Statistics Service, Agricultural Statistics Board. *Poultry—Production and Value Summary* (annual). Washington, DC, various years. Web site www.usda.gov/nass/.

U.S. Department of Agriculture, National Agricultural Statistics Service, Agricultural Statistics Board. *Rice Stocks*. Washington, DC, various years. Web site www.usda.gov/nass/.

U.S. Department of Agriculture, National Agricultural Statistics Service, Agricultural Statistics Board. *Sheep and Goats, February issue*. Washington, DC, various years. Web site www.usda.gov/nass/.

U.S. Department of Agriculture, Soil Conservation Service (now the National Resources Conservation Service). *1991 Update of National Resources Inventory Wetlands Data for Non-Federal Rural Lands*. Washington, DC, not dated.

U.S. Department of Agriculture, Soil Conservation Service (now the National Resources Conservation Service). *Summary Report: 1992 National Resources Inventory*. Washington, DC, July 1994.

U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division. *Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries*. Unpublished, various years.

U.S. Department of Commerce, Bureau of the Census. *1990 Census of Population and Housing. Population and Housing Unit Counts, United States*. CPH-2-1. Washington, DC, 1993.

U.S. Department of Commerce, Bureau of the Census. *Census of Manufacturers, 1992*. Washington, DC, 1995.

U.S. Department of Commerce, Bureau of the Census. *Census of Mineral Industries, 1992*. Washington, DC, 1995.

U.S. Department of Commerce, Bureau of the Census. *Current Industrial Reports: Industrial Gases*. Washington, DC, various years.

U.S. Department of Commerce, Bureau of the Census. *Current Industrial Reports: Quarterly and Annual Report on Fertilizer Materials*. MQ28B and MA28B. Washington, DC, various years.

U.S. Department of Commerce, Bureau of the Census. *United States Census*. Washington, DC, various years.

U.S. Department of Commerce, Bureau of Economic Analysis. *Real Gross Domestic Product and Related Measures*. Washington, DC, various years. Web site www.bea.gov.

U.S. Department of Commerce, National Bureau of Standards. *Thermal Properties of Petroleum Products*. Miscellaneous Publication No. 97. Washington, DC, 1929.

U.S. Department of Energy. *An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions*. DOE/NBB-0088P. Washington, DC, April 1990.

U.S. Department of Energy. *Atmospheric Carbon Dioxide and the Global Carbon Cycle*. DOE/ER-0239. Ed. J.R. Trabalka. Washington, DC, 1985.

U.S. Department of Energy. *Carbon Sequestration Technology Roadmap and Program Plan 2004*. Washington, DC, April 2004. Web site www.netl.doe.gov/coal/CarbonSequestration/pubs/SequestrationRoadmap4-29-04. pdf.

U.S. Department of Energy. *Carbon Sequestration Technology Roadmap and Program Plan 2004*. Washington, DC, March 2003. Web site www.fe.doe.gov/programs/sequestration/publications/programplans/2003/sequestration_roadmap03-13-03.pdf

U.S. Department of Energy. *CO_2 Capture and Storage in Geologic Formations*. Revised Draft. Washington, DC, January 2002. Web site www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/CS-NCCTIwhitepaper.pdf.

U.S. Department of Energy. *Compliance Assessment of the Portsmouth Gaseous Diffusion Plant*. DOE/EH-0144. Washington, DC, April 1990.

U.S. Department of Energy. *Energy Technology Characterizations Handbook: Environmental Pollution and Control Factors*, Third Edition. DOE/EP-0093. Washington, DC, March 1983.

U.S. Department of Energy. *The Climate Change Action Plan: Technical Supplement*. DOE/PO-0011. Washington, DC, March 1994.

U.S. Department of Energy and U.S. Environmental Protection Agency. *Report to the President on Carbon Dioxide Emissions From the Generation of Electric Power in the United States*. Washington, DC, 1999.

U.S. Department of State. *Climate Action Plan*. Publication 10496. Washington, DC, July 1997.

U.S. Department of State. *National Action Plan for Global Climate Change*. Publication 10026. Washington, DC, December 1992.

U.S. Department of the Interior, U.S. Geological Survey. *U.S. Coal Quality Database, Version 2.0*. Web site http://energy. er. usgs. gov/ products/ databases/ CoalQual/intro.htm.

U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Aluminum Annual Report*. Washington, DC, various years.

U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Cement Annual Report*. Washington, DC, various years.

U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Copper Annual Report*. Washington, DC, various years.

U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Crushed Stone Annual Report*. Washington, DC, various years.

U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Minerals Commodity Summaries*. Reston, VA, various years. Web site http://minerals.usgs.gov/minerals/pubs/commodity/.

U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Minerals Yearbook*. Washington, DC, various years.

U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Soda Ash Annual Report*. Washington, DC, various years.

U.S. Department of Transportation, Federal Highway Administration. *Highway Statistics*. Washington, DC, various years.

U.S. Environmental Protection Agency. *Cost Methodology Report for Beef and Dairy Animal Feeding Operations*. EPA-821-R-01-019. Washington, DC, January 2001.

U.S. Environmental Protection Agency. *Emissions of Nitrous Oxide From Highway Mobile Sources*. EPA-420-R-98-009. Washington, DC, August 1998.

U.S. Environmental Protection Agency. *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*. Washington, DC, September 1994.

U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Washington, DC, various years. Most recent report at web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.

U.S. Environmental Protection Agency. *Land Use, Land Use Change, and Forestry* (2000). Web site www.epa.gov.

U.S. Environmental Protection Agency. *Methane Emissions from Abandoned Coal Mines in the United States: Emission inventory and 1990-2002 Emission Estimates*. Washington, DC, 2004. Web site www.epa.gov/cmop/pdf/amm_final_report.pdf.

U.S. Environmental Protection Agency. *Regional Interim Emission Inventories, 1987-1991.* Volume I, "Development Methodologies." EPA-454-R-93-021a. Research Triangle Park, NC, May 1993.

U.S. Environmental Protection Agency. *Solid Waste Management and Greenhouse Gases: A Life-Style Assessment of Emissions and Sinks*. 2nd Edition. EPA-530-R-02-006. Washington, DC, May 2002. Web site www.epa.gov/epaoswer/non-hw/muncpl/ghg/ghg.htm.

U.S. Environmental Protection Agency, Environmental Research Laboratory. *The Impact of Conservation Tillage Use on Soil and Atmospheric Carbon in the Contiguous United States*. EPA/600/3-91/056. Corvallis, OR, November 1991.

U.S. Environmental Protection Agency, Office of Air and Radiation. *Anthropogenic Methane Emissions in the United States: Estimates for 1990. Report to Congress.* Ed. Kathleen Hogan. Washington, DC, April 1993.

U.S. Environmental Protection Agency, Office of Air and Radiation. *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gases and Sinks, 1990-1996s*. EPA-420-R-98-009. Washington, DC, August 1998.

U.S. Environmental Protection Agency, Office of Air and Radiation. *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*. EPA 430-R-97-020. Washington, DC, September 1997.

U.S. Environmental Protection Agency, Office of Air and Radiation. *Methane Emissions from Coal Mining—Issues and Opportunities for Reduction*. EPA/400/9-90/008. Washington, DC, September 1990.

U.S. Environmental Protection Agency, Office of Air and Radiation. *Estimates of Methane Emissions from the U.S. Oil Industry*. Draft Report. Washington, DC, 2001.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *Compilation of Air Pollutant Emission Factors*. AP-42, Fifth Edition. Vol. I: Stationary Point and Area Sources. Research Triangle Park, NC, September 1995. Web site www.epa.gov/ttn/chief/index.html.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *Compilation of Air Pollutant Emission Factors*. AP-42, Supplement D. Research Triangle Park, NC, September 1995. Web site www.epa.gov/ttn/chief/index.html.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Pollutant Emission Estimates 1980-1991*. EPA-454/R-92-013. Research Triangle Park, NC, October 1992.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Pollutant Emission Trends*. Research Triangle Park, NC, various years. Web site www.epa.gov/ttn/chief/trends/.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Pollutant Emission Trends Summaries, 1990-1999*. Research Triangle Park, NC, June 2001. Web site www.epa.gov/ttn/chief/trends/index.html.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Quality and Emissions Trends Report*. Research Triangle Park, NC, various years. Web site www.epa.gov/airtrends/.

U.S. Environmental Protection Agency, Office of Mobile Sources. *User's Guide to MOBILE 5: Mobile Source Emissions Model*. Ann Arbor, MI, 1993.

U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation. *International Anthropogenic Methane Emissions: Estimates for 1990*. EPA 230-R-93-010. Washington, DC, January 1994.

U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation. *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Washington, DC, various years. Web site www.epa. gov.

U.S. Environmental Protection Agency, Office of Research and Development. *The Forest Sector Carbon Budget of the United States: Carbon Pools and Flux Under Alternative Policy Options*. EPA-600-3-93-093. Washington, DC, May 1993.

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. *Characterization of Municipal Solid Waste in the United States: 1996 Update*. EPA-530-S-96-001. Washington, DC, May 1997.

U.S. Environmental Protection Agency, Office of Water. *Cost Methodology Report for Beef and Dairy Animal Feeding Operations*. EPA-821-R-01-019. Washington, DC, January 2001.

U.S. Global Change Research Program, *Forest Responses to Changes in Atmospheric Composition and Climate*, 2000. Web site www.usgcrp.gov/usgcrp/960610SM.html.

United Nations. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. FCCC/CP/1997/L.7/Add.1. 1997. Web site www.unfccc.de/resource/docs/convkp/kpeng.pdf.

United Nations. *Report of the Intergovernmental Negotiating Committee for a Framework on Convention on Climate Change on the Work of the Second Part of Its Fifth Session. Held at New York from 30 April to 9 May 1992*. UN Document A/AC.237/18, Part II. May 15, 1992.

United Nations Environment Program. *Report of the Conference of the Parties on its First Session. Held at Berlin from 28 March to 7 April 1995. Addendum, Part Two: Action Taken by the Conference of the Parties at its First Session*. FCCC/CP/1995/7/Add.1. June 1995.

United Nations Framework Convention on Climate Change. *Review of the Implementation of the Convention and of Decisions of the First Session of the Conference of the Parties: Ministerial Declaration*. FCCC/CP/1996/L.17. July 1996.

United Nations Framework Convention on Climate Change. *Issues Relating to Harvested Wood Products*. Paper No. 7. "United States Submissions on the Views Related to Carbon Accounting and Wood Practice. May 2004. Web site http://unfccc.int/resource/docs/2004/sbsta/misc09.pdf.

University of Florida, Institute of Food and Agricultural Sciences, Cooperative Extension Service. "Florida's 2000 Rice Variety Census" and "An Overview of the Florida Rice Industry." Web site http://edis.ifas.ufl.edu.

Waddle, K.L., Oswald, D., Daniel, D., Powell, L.,and Douglas, S. *Forest Statistics of the United States, 1987*. USDA Forest Service Resource Bulletin PNW-RB-168. Portland, OR: Pacific Northwest Research Station, 1989.

Ward, M. "Harvested Wood Products—A Beginning Guide to Key Issues. July 2004. Available by e-mail from murray.ward@paradise.net.nz.

Ward's Communications, Inc. *Ward's Automotive Report*. Southfield, MI, various years.

Ward's Communications, Inc. *Ward's Automotive Yearbook*. Southfield, MI, 1999.

Wassmann, R., Papen, H., and Rennenberg, H. "Methane Emissions from Rice Paddies and Possible Mitigation Strategies." *Chemosphere* 26. 1993.

White House, Office of the President. "President Bush Announces Clear Skies & Global Climate Change Initiatives." Web site www.whitehouse.gov/infocus/environment/.

Wildenborg, A.F.B., and van der Meer, L.G.H. "The Use of Oil, Gas and Coal Fields as CO2 Sinks." Intergovernmental Panel on Climate Change Workshop on Carbon Capture and Storage. Regina, Canada. November 18-21, 2003. Web site www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/pdfs/ipcc_geological_storage2.pdf

World Oil Magazine. "Total U.S. Oil Wells." February issue, various years.

World Resources Institute, *Forest and Land-Use Change Carbon Sequestration Projects*, 2000. Web site www.wri.org/climate/sequester.html.

World Semiconductor Council. "Position Paper Regarding PFC Emissions Reduction Goal." Press Release, April 26, 1999. Web site www.semiconductorcouncil.org/news/pfc.html.

Wuebbles, D.J., and Edmonds, J. *Primer on Greenhouse Gases*. Chelsea, MI: Lewis Publishers, 1991.

Related Links

Australian Greenhouse Office.
www.greenhouse.gov.au

Carbon Dioxide Information Analysis Center.
http://cdiac.esd.ornl.gov

Centre for the Analysis and Dissemination of Demonstrated Energy Technologies.
www.caddet-ee.org

Center for Renewable Energy and Sustainable Technology.
http://solstice.crest.org

Climate Ark.
www.climateark.org

Energy Information Administration.
www.eia.doe.gov

Energy Information Administration, Greenhouse Gas Emissions and Climate Change Publications.
www.eia.doe.gov/environment.html

Global Change Data & Information System.
http://globalchange.gov

Global Environment Facility.
www.gefweb.org

Global Climate Change from the Government of Canada.
www.climatechange.gc.ca

Intergovernmental Panel on Climate Change.
www.ipcc.ch

International Energy Agency.
www.iea.org

International Institute for Sustainable Development.
www.iisd.org

National Institute for Global Environment Change.
http://nigec.ucdavis.edu

Natural Resources Defense Council, Global Warming.
www.nrdc.org/globalWarming

Organization for Economic Cooperation and Development.
www.oecd.org/env/

Pew Center on Climate Change.
www.pewclimate.org

Resources for the Future.
www.rff.org

Weathervane, Digital Forum on Global Climate Policy.
www.weathervane.rff.org

Union of Concerned Scientists.
www.ucsusa.org

United Nations Development Programme.
www.undp.org

United Nations Environment Programme.
www.unep.ch

United Nations Environment Programme,
Ozone Secretariat (Montreal Protocol).
www.unep.ch/ozone/home.htm

United Nations Food and Agriculture Program.
www.fao.org

United Nations Framework Convention on Climate Change.
www.unfccc.de

U.S. Agency for International Development.
www.usaid.gov

U.S. Department of Agriculture, Global Change Program Office.
www.usda.gov/oce/gcpo/

U.S. Department of Energy, Climate Vision Program.
www.climatevision.gov

U.S. Department of State, Climate Change Homepage.
www.state.gov/g/oes/climate/

U.S. Environmental Protection Agency,
Global Warming Homepage.
www.epa.gov/globalwarming/

U.S. Environmental Protection Agency,
Methane to Markets Partnership.
www.epa.gov/methanetomarkets/index.htm

U.S. Geological Survey, Global Change Research.
http://geochange.er.usgs.gov

Related Links

U.S. Global Change Research Office.
http://gcrio.gcrio.org

U.S. Global Change Research Program.
www.usgcrp.gov

U.S. Initiative on Joint Implementation.
www.gcrio.org/usiji/

U.S. National Aeronautics and Space Administration (NASA), Global Change Master Directory.
http://gcmd.gsfc.nasa.gov

U.S. National Oceanographic and Atmospheric Administration (NOAA), Office of Global Programs.
www.ogp.noaa.gov

U.S. White House, Global Climate Change Policy Book.
www.whitehouse.gov/news/releases/2002/02/climatechange.html

U.S. White House, Policies in Focus, Environment.
www.whitehouse.gov/infocus/environment/

World Bank Climate Change Web Site.
www.worldbank.org/climatechange

World Health Organization, Protection of the Human Environment.
www.who.int/phe/en/

World Meteorological Organization.
www.wmo.ch

World Resources Institute.
www.wri.org

Worldwatch Institute.
www.worldwatch.org

World Wildlife Fund, Climate Change Campaign.
www.panda.org/about_wwf/what_we_do/climate_change/index.cfm

Glossary

Acid stabilization: A circumstance where the pH of the waste mixture in an animal manure management system is maintained near 7.0, optimal conditions for methane production.

Aerobic bacteria: Microorganisms living, active, or occurring only in the presence of oxygen.

Aerobic decomposition: The breakdown of a molecule into simpler molecules or atoms by microorganisms under favorable conditions of oxygenation.

Aerosols: Airborne particles.

Afforestation: Planting of new forests on lands that have not been recently forested.

Agglomeration: The clustering of disparate elements.

Airshed: An area or region defined by settlement patterns or geology that results in discrete atmospheric conditions.

Albedo: The fraction of incident light or electromagnetic radiation that is reflected by a surface or body. See *Planetary albedo*.

Anaerobes: Organisms that live and are active only in the absence of oxygen.

Anaerobic bacteria: Microorganisms living, active, or occurring only in the absence of oxygen.

Anaerobic decomposition: The breakdown of molecules into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

Anaerobic lagoon: A liquid-based manure management system, characterized by waste residing in water to a depth of at least six feet for a period ranging between 30 and 200 days.

Anode: A positive electrode, as in a battery, radio tube, etc.

Anthracite: The highest rank of coal; used primarily for residential and commercial space heating. It is a hard, brittle, and black lustrous coal, often referred to as hard coal, containing a high percentage of fixed carbon and a low percentage of volatile matter. The moisture content of fresh-mined anthracite generally is less than 15 percent. The heat content of anthracite ranges from 22 to 28 million Btu per ton on a moist, mineral-matter-free basis. The heat content of anthracite coal consumed in the United States averages 25 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter). Note: Since the 1980's, anthracite refuse or mine waste has been used for steam electric power generation. This fuel typically has a heat content of 15 million Btu per ton or less.

Anthropogenic: Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation.

API Gravity: American Petroleum Institute measure of specific gravity of crude oil or condensate in degrees. An arbitrary scale expressing the gravity or density of liquid petroleum products. The measuring scale is calibrated in terms of degrees API; it is calculated as follows: Degrees API = (141.5/sp.gr.60 deg.F/60 deg.F) - 131.5.

Asphalt: A dark brown-to-black cement-like material obtained by petroleum processing and containing bitumens as the predominant component; used primarily for road construction. It includes crude asphalt as well as the following finished products: cements, fluxes, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cutback asphalts. Note: The conversion factor for asphalt is 5.5 barrels per short ton.

Associated natural gas: See *Associated-dissolved natural gas* and *Natural gas*.

Associated-dissolved natural gas: Natural gas that occurs in crude oil reservoirs either as free gas (associated) or as gas in solution with crude oil (dissolved gas). See *Natural gas*.

Aviation gasoline (finished): A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D 910 and Military Specification MIL-G-5572. Note: Data on blending components are not counted in data on finished aviation gasoline.

Balancing item: Represents differences between the sum of the components of natural gas supply and the sum of the components of natural gas disposition. These differences may be due to quantities lost or to the effects of data reporting problems. Reporting problems include differences due to the net result of conversions of flow data metered at varying temperature and pressure bases and converted to a standard temperature and pressure base; the effect of variations in company accounting and billing practices; differences between billing cycle and calendar period time frames; and imbalances resulting from the merger of data reporting systems that vary in scope, format, definitions, and type of respondents.

Biofuels: Liquid fuels and blending components produced from biomass (plant) feedstocks, used primarily for transportation.

Biogas: The gas produced from the anaerobic decomposition of organic material in a landfill.

Biogenic: Produced by the actions of living organisms.

Biomass: Organic nonfossil material of biological origin constituting a renewable energy source.

Biosphere: The portion of the Earth and its atmosphere that can support life. The part of the global carbon cycle that includes living organisms and biogenic organic matter.

Bituminous coal: A dense coal, usually black, sometimes dark brown, often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing and to make coke. Bituminous coal is the most abundant coal in active U.S. mining regions. Its moisture content usually is less than 20 percent. The heat content of bituminous coal ranges from 21 to 30 million Btu per ton on a moist, mineral-matter-free basis. The heat content of bituminous coal consumed in the United States averages 24 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

BOD_5: The biochemical oxygen demand of wastewater during decomposition occurring over a 5-day period. A measure of the organic content of wastewater.

Bromofluorocarbons (halons): Inert, nontoxic chemicals that have at least one bromine atom in their chemical makeup. They evaporate without leaving a residue and are used in fire extinguishing systems, especially for large computer installations.

Bunker fuel: Fuel supplied to ships and aircraft, both domestic and foreign, consisting primarily of residual and distillate fuel oil for ships and kerosene-based jet fuel for aircraft. The term "international bunker fuels" is used to denote the consumption of fuel for international transport activities. *Note*: For the purposes of greenhouse gas emissions inventories, data on emissions from combustion of international bunker fuels are subtracted from national emissions totals. Historically, bunker fuels have meant only ship fuel. See *Vessel bunkering*.

Calcination: A process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled.

Calcium sulfate: A white crystalline salt, insoluble in water. Used in Keene's cement, in pigments, as a paper filler, and as a drying agent.

Calcium sulfite: A white powder, soluble in dilute sulfuric acid. Used in the sulfite process for the manufacture of wood pulp.

Capital stock: Property, plant and equipment used in the production, processing and distribution of energy resources.

Carbon black: An amorphous form of carbon, produced commercially by thermal or oxidative decomposition of hydrocarbons and used principally in rubber goods, pigments, and printer's ink.

Carbon budget: Carbon budget: The balance of the exchanges (incomes and losses) of carbon between carbon sinks (e.g., atmosphere and biosphere) in the carbon cycle. See *Carbon cycle* and *Carbon sink*.

Carbon cycle: All carbon sinks and exchanges of carbon from one sink to another by various chemical, physical, geological, and biological processes. See *Carbon sink* and *Carbon budget*.

Carbon dioxide (CO_2): A colorless, odorless, nonpoisonous gas that is a normal part of Earth's atmosphere. Carbon dioxide is a product of fossil-fuel combustion as well as other processes. It is considered a greenhouse gas as it traps heat (infrared energy) radiated by the Earth into the atmosphere and thereby contributes to the potential for global warming. The global warming potential (GWP) of other greenhouse gases is measured in relation to that of carbon dioxide, which by international scientific convention is assigned a value of one (1). See *Global warming potential (GWP)* and *Greenhouse gases*.

Carbon dioxide equivalent: The amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas. Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured (for example, methane) by its estimated global warming potential (which is 21 for methane). "Carbon equivalent units" are defined as carbon dioxide equivalents multiplied by the carbon content of carbon dioxide (i.e., 12/44).

Carbon flux: See *Carbon budget*.

Carbon intensity: The amount of carbon by weight emitted per unit of energy consumed. A common measure of carbon intensity is weight of carbon per British thermal unit (Btu) of energy. When there is only one fossil fuel under consideration, the carbon intensity and the emissions coefficient are identical. When there are several fuels, carbon intensity is based on their combined emissions coefficients weighted by their energy consumption levels. See *Emissions coefficient* and *Carbon output rate*.

Carbon output rate: The amount of carbon by weight per kilowatthour of electricity produced.

Carbon sequestration: The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes.

Carbon sink: A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. The four sinks, which are regions of the Earth within which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels).

Catalytic converter: A device containing a catalyst for converting automobile exhaust into mostly harmless products.

Catalytic hydrocracking: A refining process that uses hydrogen and catalysts with relatively low temperatures and high pressures for converting middle boiling or residual material to high octane gasoline, reformer charge stock, jet fuel, and/or high grade fuel oil. The process uses one or more catalysts, depending on product output, and can handle high sulfur feedstocks without prior desulfurization.

Cesspool: An underground reservoir for liquid waste, typically household sewage.

Chlorofluorocarbon (CFC): Any of various compounds consisting of carbon, hydrogen, chlorine, and fluorine used as refrigerants. CFCs are now thought to be harmful to the earth's atmosphere.

Clean Development Mechanism (CDM): A Kyoto Protocol program that enables industrialized countries to finance emissions-avoiding projects in developing countries and receive credit for reductions achieved against their own emissions limitation targets. See *Kyoto Protocol*.

Climate: The average course or condition of the weather over a period of years as exhibited by temperature, humidity, wind velocity, and precipitation.

Climate change: A term used to refer to all forms of climatic inconsistency, but especially to significant change from one prevailing climatic condition to another. In some cases, "climate change" has been used synonymously with the term "global warming"; scientists, however, tend to use the term in a wider sense inclusive of natural changes in climate, including climatic cooling.

Clinker: Powdered cement, produced by heating a properly proportioned mixture of finely ground raw materials (calcium carbonate, silica, alumina, and iron oxide) in a kiln to a temperature of about 2,700ºF.

Cloud condensation nuclei: Aerosol particles that provide a platform for the condensation of water vapor, resulting in clouds with higher droplet concentrations and increased albedo.

Coal coke: See *Coke (coal)*.

Coalbed methane: Methane is generated during coal formation and is contained in the coal microstructure. Typical recovery entails pumping water out of the coal to allow the gas to escape. Methane is the principal component of natural gas. Coalbed methane can be added to natural gas pipelines without any special treatment.

Coke (coal): A solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal from which the volatile constituents are driven off by baking in an oven at temperatures as high as 2,000 degrees Fahrenheit so that the fixed carbon and residual ash are fused together. Coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. Coke from coal is grey, hard, and porous and has a heating value of 24.8 million Btu per ton.

Coke (petroleum): A residue high in carbon content and low in hydrogen that is the final product of thermal decomposition in the condensation process in cracking. This product is reported as marketable coke or catalyst coke. The conversion is 5 barrels (of 42 U.S. gallons each) per short ton. Coke from petroleum has a heating value of 6.024 million Btu per barrel.

Combustion: Chemical oxidation accompanied by the generation of light and heat.

Combustion chamber: An enclosed vessel in which chemical oxidation of fuel occurs.

Conference of the Parties (COP): The collection of nations that have ratified the Framework Convention on Climate Change (FCCC). The primary role of the COP is to keep implementation of the FCCC under review and make the decisions necessary for its effective implementation. See *Framework Convention on Climate Change (FCCC).*

Cracking: The refining process of breaking down the larger, heavier, and more complex hydrocarbon molecules into simpler and lighter molecules.

Criteria pollutant: A pollutant determined to be hazardous to human health and regulated under EPA's National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act require EPA to describe the health and welfare impacts of a pollutant as the "criteria" for inclusion in the regulatory regime.

Crop residue: Organic residue remaining after the harvesting and processing of a crop.

Cultivar: A horticulturally or agriculturally derived variety of a plant.

Deforestation: The net removal of trees from forested land.

Degasification system: The methods employed for removing methane from a coal seam that could not otherwise be removed by standard ventilation fans and thus would pose a substantial hazard to coal miners. These systems may be used prior to mining or during mining activities.

Degradable organic carbon: The portion of organic carbon present in such solid waste as paper, food waste, and yard waste that is susceptible to biochemical decomposition.

Desulfurization: The removal of sulfur, as from molten metals, petroleum oil, or flue gases.

Diffusive transport: The process by which particles of liquids or gases move from an area of higher concentration to an area of lower concentration.

Distillate fuel: A general classification for one of the petroleum fractions produced in conventional distillation operations. It includes diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. Products known as No. 1, No. 2, and No. 4 fuel oils are used primarily for space heating and electric power generation.

Efflux: An outward flow.

Electrical generating capacity: The full-load continuous power rating of electrical generating facilities, generators, prime movers, or other electric equipment (individually or collectively).

EMCON Methane Generation Model: A model for estimating the production of methane from municipal solid waste landfills.

Emissions: Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).

Emissions coefficient: A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., pounds of carbon dioxide emitted per Btu of fossil fuel consumed).

Enteric fermentation: A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

Eructation: An act or instance of belching.

ETBE (ethyl tertiary butyl ether): $(CH_3)_3COC_2H$: An oxygenate blend stock formed by the catalytic etherification of isobutylene with ethanol.

Ethylene: An olefinic hydrocarbon recovered from refinery processes or petrochemical processes. Ethylene is used as a petrochemical feedstock for numerous chemical applications and the production of consumer goods.

Ethylene dichloride: A colorless, oily liquid used as a solvent and fumigant for organic synthesis, and for ore flotation.

Facultative bacteria: Bacteria that grow equally well under aerobic and anaerobic conditions.

Flange: A rib or a rim for strength, for guiding, or for attachment to another object (e.g., on a pipe).

Flared: Gas disposed of by burning in flares usually at the production sites or at gas processing plants.

Flatus: Gas generated in the intestines or the stomach of an animal.

Flue gas desulfurization: Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Also referred to as scrubbers. Chemicals such as lime are used as scrubbing media.

Fluidized-bed combustion: A method of burning particulate fuel, such as coal, in which the amount of air required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of mineral ash in the proportions of 1 part fuel to 200 parts ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid.

Flux material: A substance used to promote fusion, e.g., of metals or minerals.

Fodder: Coarse food for domestic livestock.

Forestomach: See *Rumen*.

Fossil fuel: An energy source formed in the earths crust from decayed organic material. The common fossil fuels are petroleum, coal, and natural gas.

Framework Convention on Climate Change (FCCC): An agreement opened for signature at the "Earth Summit" in Rio de Janeiro, Brazil, on June 4, 1992, which has the goal of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent significant anthropogenically forced climate change. See *Climate change*.

Fuel cycle: The entire set of sequential processes or stages involved in the utilization of fuel, including extraction, transformation, transportation, and combustion. Emissions generally occur at each stage of the fuel cycle.

Fugitive emissions: Unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels.

Gasification: A method for converting coal, petroleum, biomass, wastes, or other carbon-containing materials into a gas that can be burned to generate power or processed into chemicals and fuels.

Gate station: Location where the pressure of natural gas being transferred from the transmission system to the distribution system is lowered for transport through small diameter, low pressure pipelines.

Geothermal: Pertaining to heat within the Earth.

Global climate change: See *Climate change*.

Global warming: An increase in the near surface temperature of the Earth. Global warming has occurred in the distant past as the result of natural influences, but the term is today most often used to refer to the warming that some scientists predict will occur as a result of increased anthropogenic emissions of greenhouse gases. See *Climate change*.

Global warming potential (GWP): An index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time, such as 100 years.

Greenhouse effect: The result of water vapor, carbon dioxide, and other atmospheric gases trapping radiant (infrared) energy, thereby keeping the earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap this radiation, which would otherwise escape into space, and subsequent re-radiation of some of this energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent. See *Greenhouse gases*.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving the Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

Gross gas withdrawal: The full-volume of compounds extracted at the wellhead, including nonhydrocarbon gases and natural gas plant liquids.

Gypsum: Calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), a sludge constituent from the conventional lime scrubber process, obtained as a byproduct of the dewatering operation and sold for commercial use.

Halogenated substances: A volatile compound containing halogens, such as chlorine, fluorine or bromine.

Halons: See *Bromofluorocarbons*.

Heating degree-days (HDD): A measure of how cold a location is over a period of time relative to a base temperature, most commonly specified as 65 degrees Fahrenheit. The measure is computed for each day by subtracting the average of the day's high and low temperatures from the base temperature (65 degrees), with negative values set equal to zero. Each day's heating degree-days are summed to create a heating degree-day measure for a specified reference period. Heating degree-days are used in energy analysis as an indicator of space heating energy requirements or use.

Herbivore: A plant-eating animal.

Hydrocarbon: An organic chemical compound of hydrogen and carbon in either gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simple (e.g., methane, a constituent of natural gas) to the very heavy and very complex.

Hydrochlorofluorocarbons (HCFCs): Chemicals composed of one or more carbon atoms and varying numbers of hydrogen, chlorine, and fluorine atoms.

Hydrofluorocarbons (HFCs): A group of man-made chemicals composed of one or two carbon atoms and varying numbers of hydrogen and fluorine atoms. Most HFCs have 100-year Global Warming Potentials in the thousands.

Hydroxyl radical (OH): An important chemical scavenger of many trace gases in the atmosphere that are greenhouse gases. Atmospheric concentrations of OH affect the atmospheric lifetimes of greenhouse gases, their abundance, and, ultimately, the effect they have on climate.

Intergovernmental Panel on Climate Change (IPCC): A panel established jointly in 1988 by the World Meteorological Organization and the United Nations Environment Program to assess the scientific information relating to climate change and to formulate realistic response strategies.

International bunker fuels: See *Bunker fuels*.

Jet fuel: A refined petroleum product used in jet aircraft engines. It includes kerosene-type jet fuel and naphtha-type jet fuel.

Joint Implementation (JI): Agreements made between two or more nations under the auspices of the Framework Convention on Climate Change (FCCC) whereby a developed country can receive “emissions reduction units” when it helps to finance projects that reduce net emissions in another developed country (including countries with economies in transition).

Kerosene: A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps. Kerosene has a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point, a final boiling point of 572 degrees Fahrenheit, and a minimum flash point of 100 degrees Fahrenheit. Included are No. 1-K and No. 2-K, the two grades recognized by ASTM Specification D 3699 as well as all other grades of kerosene called range or stove oil, which have properties similar to those of No. 1 fuel oil. See *Kerosene-type jet fuel*.

Kerosene-type jet fuel: A kerosene-based product having a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point and a final maximum boiling point of 572 degrees Fahrenheit and meeting ASTM Specification D 1655 and Military Specifications MIL-T-5624P and MIL-T-83133D (Grades JP-5 and JP-8). It is used for commercial and military turbojet and turboprop aircraft engines.

Kyoto Protocol: The result of negotiations at the third Conference of the Parties (COP-3) in Kyoto, Japan, in December of 1997. The Kyoto Protocol sets binding greenhouse gas emissions targets for countries that sign and ratify the agreement. The gases covered under the Protocol include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride.

Ketone-alcohol (cyclohexanol): An oily, colorless, hygroscopic liquid with a camphor-like odor. Used in soapmaking, dry cleaning, plasticizers, insecticides, and germicides.

Leachate: The liquid that has percolated through the soil or other medium.

Lignite: The lowest rank of coal, often referred to as brown coal, used almost exclusively as fuel for steam-electric power generation. It is brownish-black and has a high inherent moisture content, sometimes as high as 45 percent The heat content of lignite ranges from 9 to 17 million Btu per ton on a moist, mineral-matter-free basis. The heat content of lignite consumed in the United States averages 13 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

Liquefied petroleum gases: A group of hydrocarbon-based gases derived from crude oil refining or natural gas fractionation. They include ethane, ethylene, propane, propylene, normal butane, butylene, isobutane, and isobutylene. For convenience of transportation, these gases are liquefied through pressurization.

Lubricants: Substances used to reduce friction between bearing surfaces, or incorporated into other materials used as processing aids in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases.

Methane: A colorless, flammable, odorless hydrocarbon gas (CH4) which is the major component of natural gas. It is also an important source of hydrogen in various industrial processes. Methane is a greenhouse gas. See also *Greenhouse gases*.

Methanogens: Bacteria that synthesize methane, requiring completely anaerobic conditions for growth.

Methanol: A light alcohol that can be used for gasoline blending. See oxygenate.

Methanotrophs: Bacteria that use methane as food and oxidize it into carbon dioxide.

Methyl chloroform (trichloroethane): An industrial chemical (CH_3CCl_3) used as a solvent, aerosol propellant, and pesticide and for metal degreasing.

Methyl tertiary butyl ether (MTBE): A colorless, flammable, liquid oxygenated hydrocarbon containing 18.15 percent oxygen.

Methylene chloride: A colorless liquid, nonexplosive and practically nonflammable. Used as a refrigerant in centrifugal compressors, a solvent for organic materials, and a component in nonflammable paint removers.

Mole: The quantity of a compound or element that has a weight in grams numerically equal to its molecular weight. Also referred to as gram molecule or gram molecular weight.

Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer (1987). An international agreement, signed by most of the industrialized nations, to substantially reduce the use of chlorofluorocarbons (CFCs). Signed in January 1989, the original document called for a 50-percent reduction in CFC use by 1992 relative to 1986 levels. The subsequent London Agreement called for a complete elimination of CFC use by 2000. The Copenhagen Agreement, which called for a complete phaseout by January 1, 1996, was implemented by the U.S. Environmental Protection Agency.

Motor gasoline (finished): A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines. Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 to 158 degrees Fahrenheit at the 10 percent recovery point to 365 to 374 degrees Fahrenheit at the 90 percent recovery point. “Motor Gasoline” includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline, but excludes aviation gasoline. Note: Volumetric data on blending components, such as oxygenates, are not counted in data on finished motor gasoline until the blending components are blended into the gasoline.

Multiple cropping: A system of growing several crops on the same field in one year.

Municipal solid waste: Residential solid waste and some nonhazardous commercial, institutional, and industrial wastes.

Naphtha less than 401 degrees Fahrenheit: A naphtha with a boiling range of less than 401 degrees Fahrenheit that is intended for use as a petrochemical feedstock. Also see *Petrochemical feedstocks*.

Naphtha-type jet fuel: A fuel in the heavy naphtha boiling range having an average gravity of 52.8 degrees API, 20 to 90 percent distillation temperatures of 290 degrees to 470 degrees Fahrenheit, and meeting Military Specification MIL-T-5624L (Grade JP-4). It is used primarily for military turbojet and turboprop aircraft engines because it has a lower freeze point than other aviation fuels and meets engine requirements at high altitudes and speeds.

Natural gas: A mixture of hydrocarbons and small quantities of various nonhydrocarbons in the gaseous phase or in solution with crude oil in natural underground reservoirs.

Natural gas liquids (NGLs): Those hydrocarbons in natural gas that are separated as liquids from the gas. Includes natural gas plant liquids and lease condensate.

Natural gas, pipeline quality: A mixture of hydrocarbon compounds existing in the gaseous phase with sufficient energy content, generally above 900 Btu, and a small enough share of impurities for transport through commercial gas pipelines and sale to end-users.

Nitrogen oxides (NO_x): Compounds of nitrogen and oxygen produced by the burning of fossil fuels.

Nitrous oxide (N_2O): A colorless gas, naturally occurring in the atmosphere. Nitrous oxide has a 100-year Global Warming Potential of 310.

Nonmethane volatile organic compounds (NMVOCs): Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Octane: A flammable liquid hydrocarbon found in petroleum. Used as a standard to measure the antiknock properties of motor fuel.

Oil reservoir: An underground pool of liquid consisting of hydrocarbons, sulfur, oxygen, and nitrogen trapped within a geological formation and protected from evaporation by the overlying mineral strata.

Organic content: The share of a substance that is of animal or plant origin.

Organic waste: Waste material of animal or plant origin.

Oxidize: To chemically transform a substance by combining it with oxygen.

Oxygenates: Substances which, when added to gasoline, increase the amount of oxygen in that gasoline blend. Ethanol, Methyl Tertiary Butyl Ether (MTBE), Ethyl Tertiary Butyl Ether (ETBE), and methanol are common oxygenates.

Ozone: A molecule made up of three atoms of oxygen. Occurs naturally in the stratosphere and provides a protective layer shielding the Earth from harmful ultraviolet radiation. In the troposphere, it is a chemical oxidant, a greenhouse gas, and a major component of photochemical smog.

Ozone precursors: Chemical compounds, such as carbon monoxide, methane, nonmethane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone.

Paraffinic hydrocarbons: Straight-chain hydrocarbon compounds with the general formula C_nH_{2n+2}.

Perfluorocarbons (PFCs): A group of man-made chemicals composed of one or two carbon atoms and four to six fluorine atoms, containing no chlorine. PFCs have no commercial uses and are emitted as a byproduct of aluminum smelting and semiconductor manufacturing. PFCs have very high 100-year Global Warming Potentials and are very long-lived in the atmosphere.

Perfluoromethane: A compound (CF_4) emitted as a byproduct of aluminum smelting.

Petrochemical feedstocks: Chemical feedstocks derived from petroleum principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics.

Petroleum: A broadly defined class of liquid hydrocarbon mixtures. Included are crude oil, lease condensate, unfinished oils, refined products obtained from the processing of crude oil, and natural gas plant liquids. Note: Volumes of finished petroleum products include nonhydrocarbon compounds, such as additives and detergents, after they have been blended into the products.

Petroleum coke: See *Coke (petroleum)*.

Photosynthesis: The manufacture by plants of carbohydrates and oxygen from carbon dioxide and water in the presence of chlorophyll, with sunlight as the energy source. Carbon is sequestered and oxygen and water vapor are released in the process.

Pig iron: Crude, high-carbon iron produced by reduction of iron ore in a blast furnace.

Pipeline, distribution: A pipeline that conveys gas from a transmission pipeline to its ultimate consumer.

Pipeline, gathering: A pipeline that conveys gas from a production well/field to a gas processing plant or transmission pipeline for eventual delivery to end-use consumers.

Pipeline, transmission: A pipeline that conveys gas from a region where it is produced to a region where it is to be distributed.

Planetary albedo: The fraction of incident solar radiation that is reflected by the Earth-atmosphere system and returned to space, mostly by backscatter from clouds in the atmosphere.

Pneumatic device: A device moved or worked by air pressure.

Polystyrene: A polymer of styrene that is a rigid, transparent thermoplastic with good physical and electrical insulating properties, used in molded products, foams, and sheet materials.

Polyvinyl chloride (PVC): A polymer of vinyl chloride. Tasteless. odorless, insoluble in most organic solvents. A member of the family vinyl resin, used in soft flexible films for food packaging and in molded rigid products, such as pipes, fibers, upholstery, and bristles.

Post-mining emissions: Emissions of methane from coal occurring after the coal has been mined, during transport or pulverization.

Radiative forcing: A change in average net radiation at the top of the troposphere (known as the tropopause) because of a change in either incoming solar or exiting infrared radiation. A positive radiative forcing tends on average to warm the earth's surface; a negative radiative forcing on average tends to cool the earth's surface. Greenhouse gases, when emitted into the atmosphere, trap infrared energy radiated from the earth's surface and therefore tend to produce positive radiative forcing. See *Greenhouse gases*.

Radiatively active gases: Gases that absorb incoming solar radiation or outgoing infrared radiation, affecting the vertical temperature profile of the atmosphere. See *Radiative forcing*.

Ratoon crop: A crop cultivated from the shoots of a perennial plant.

Redox potential: A measurement of the state of oxidation of a system.

Reflectivity: The ratio of the energy carried by a wave after reflection from a surface to its energy before reflection.

Reforestation: Replanting of forests on lands that have recently been harvested or otherwise cleared of trees.

Reformulated gasoline: Finished motor gasoline formulated for use in motor vehicles, the composition and properties of which meet the requirements of the reformulated gasoline regulations promulgated by the U.S. Environmental Protection Agency under Section 211(k) of the Clean Air Act. Note: This category includes oxygenated fuels program reformulated gasoline (OPRG) but excludes reformulated gasoline blendstock for oxygenate blending (RBOB).

Renewable energy resources: Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

Residual fuel oil: A general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. It conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore powerplants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

Rumen: The large first compartment of the stomach of certain animals in which cellulose is broken down by the action of bacteria.

Sample: A set of measurements or outcomes selected from a given population.

Sequestration: See *Carbon sequestration*.

Septic tank: A tank in which the solid matter of continuously flowing sewage is disintegrated by bacteria.

Sinter: A chemical sedimentary rock deposited by precipitation from mineral waters, especially siliceous sinter and calcareous sinter.

Sodium silicate: A grey-white powder soluble in alkali and water, insoluble in alcohol and acid. Used to fireproof textiles, in petroleum refining and corrugated paperboard manufacture, and as an egg preservative. Also referred to as liquid gas, silicate of soda, sodium metasilicate, soluble glass, and water glass.

Sodium tripolyphosphate: A white powder used for water softening and as a food additive and texturizer.

Stabilization lagoon: A shallow artificial pond used for the treatment of wastewater. Treatment includes removal of solid material through sedimentation, the decomposition of organic material by bacteria, and the removal of nutrients by algae.

Still gas (refinery gas): Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. The principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Still gas is used as a refinery fuel and a petrochemical feedstock. The conversion factor is 6 million Btu per fuel oil equivalent barrel.

Stratosphere: The region of the upper atmosphere extending from the tropopause (8 to 15 kilometers altitude) to about 50 kilometers. Its thermal structure, which is determined by its radiation balance, is generally very stable with low humidity.

Stripper well: An oil or gas well that produces at relatively low rates. For oil, stripper production is usually defined as production rates of between 5 and 15 barrels of oil per day. Stripper gas production would generally be anything less than 60 thousand cubic feet per day.

Styrene: A colorless, toxic liquid with a strong aromatic aroma. Insoluble in water, soluble in alcohol and ether; polymerizes rapidly; can become explosive. Used to make polymers and copolymers, polystyrene plastics, and rubber.

Subbituminous coal: A coal whose properties range from those of lignite to those of bituminous coal and used primarily as fuel for steam-electric power generation. It may be dull, dark brown to black, soft and crumbly, at the lower end of the range, to bright, jet black, hard, and relatively strong, at the upper end. Subbituminous coal contains 20 to 30 percent inherent moisture by weight. The heat content of subbituminous coal ranges from 17 to 24 million Btu per ton on a moist, mineral-matter-free basis. The heat content of subbituminous coal consumed in the United States averages 17 to 18 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

Sulfur dioxide (SO_2): A toxic, irritating, colorless gas soluble in water, alcohol, and ether. Used as a chemical intermediate, in paper pulping and ore refining, and as a solvent.

Sulfur hexafluoride (SF_6): A colorless gas soluble in alcohol and ether, and slightly less soluble in water. It is used as a dielectric in electronics. It possesses the highest 100-year Global Warming Potential of any gas (23,900).

Sulfur oxides (SO_x): Compounds containing sulfur and oxygen, such as sulfur dioxide (SO_2) and sulfur trioxide (SO_3).

Tertiary amyl methyl ether ($(CH_3)_2(C_2H_5)COCH_3$): An oxygenate blend stock formed by the catalytic etherification of isoamylene with methanol.

Troposphere: The inner layer of the atmosphere below about 15 kilometers, within which there is normally a steady decrease of temperature with increasing altitude.

Nearly all clouds form and weather conditions manifest themselves within this region. Its thermal structure is caused primarily by the heating of the earth's surface by solar radiation, followed by heat transfer through turbulent mixing and convection.

Uncertainty: A measure used to quantify the plausible maximum and minimum values for emissions from any source, given the biases inherent in the methods used to calculate a point estimate and known sources of error.

Vapor displacement: The release of vapors that had previously occupied space above liquid fuels stored in tanks. These releases occur when tanks are emptied and filled.

Ventilation system: A method for reducing methane concentrations in coal mines to non-explosive levels by blowing air across the mine face and using large exhaust fans to remove methane while mining operations proceed.

Vessel bunkering: Includes sales for the fueling of commercial or private boats, such as pleasure craft, fishing boats, tugboats, and ocean-going vessels, including vessels operated by oil companies. Excluded are volumes sold to the U.S. Armed Forces.

Volatile organic compounds (VOCs): Organic compounds that participate in atmospheric photochemical reactions.

Volatile solids: A solid material that is readily decomposable at relatively low temperatures.

Waste flow: Quantity of a waste stream generated by an activity.

Wastewater: Water that has been used and contains dissolved or suspended waste materials.

Wastewater, domestic and commercial: Wastewater (sewage) produced by domestic and commercial establishments.

Wastewater, industrial: Wastewater produced by industrial processes.

Water vapor: Water in a vaporous form, especially when below boiling temperature and diffused (e.g., in the atmosphere).

Wax: A solid or semi-solid material derived from petroleum distillates or residues by such treatments as chilling, precipitating with a solvent, or de-oiling. It is a light-colored, more-or-less translucent crystalline mass, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Includes all marketable wax, whether crude scale or fully refined. The three grades included are microcrystalline, crystalline-fully refined, and crystalline-other. The conversion factor is 280 pounds per 42 U.S. gallons per barrel.

Weanling system: A cattle management system that places calves on feed starting at 165 days of age and continues until the animals have reached slaughter weight.

Wellhead: The point at which the crude (and/or natural gas) exits the ground. Following historical precedent, the volume and price for crude oil production are labeled as "wellhead," even though the cost and volume are now generally measured at the lease boundary. In the context of domestic crude price data, the term "wellhead" is the generic term used to reference the production site or lease property.

Wetlands: Areas regularly saturated by surface or groundwater and subsequently characterized by a prevalence of vegetation adapted for life in saturated-soil conditions.

Wood energy: Wood and wood products used as fuel, including roundwood (cordwood), limbwood, wood chips, bark, sawdust, forest residues, charcoal, pulp waste, and spent pulping liquor..

Yearling system: A cattle management system that includes a stocker period from 165 days of age to 425 days of age followed by a 140-day feedlot period.

Appendix A

Common Conversion Factors

Mass

1 kilogram = 10^3 grams = 2.20462 pounds
1 megagram (metric ton) = 10^6 grams = 2,204.62 pounds
1 gigagram = 10^9 = 1,000 metric tons
1 teragram = 10^{12} = 1 million metric tons
1 short ton = $.9072 * 10^6$ grams = 2,000 pounds

Energy

1 joule = .2388 calories = .0009478 Btu
1 terajoule = 10^{12} joules = $9.478 * 10^8$ Btu
1 exajoule = 10^{18} joules = $0.9478 * 10^{15}$ Btu
1 Mbtu = 1000 Btu = $1 * 10^3$ Btu
1 Mmbtu = 1 million Btu = $1 * 10^6$ Btu
1 Bbtu = 1 billion Btu = $1 * 10^9$ Btu
1 Tbtu = 1 trillion Btu = $1 * 10^{12}$ Btu
1 Qbtu = 1 quadrillion Btu = $1 * 10^{15}$ Btu

Area

1 acre = 0.4047 hectare (ha) = 4,407 m^2
1 hectare = 10,000m^2 = 2.47 acres

Volume

1 cubic centimeter = $3.5318 * 10^{-5}$ cubic feet
1 cubic foot = 0.02832 cubic meters
1 cubic meter = 35.3147 cubic feet
1 barrel = 42 gallons

Density

1 thousand cubic feet methane = 42.28 pounds methane
1 thousand cubic feet carbon dioxide = 115.97 pounds carbon dioxide

Table B1. Energy-Related Carbon Dioxide Emissions from the Residential and Commercial Sectors, by Fuel Type, 1949-2003

(Million Metric Tons of Carbon Dioxide)

	Residential					Commmercial				
Year	**Natural Gas**	**Petroleum**	**Coal**	**Electricity**	**Total**	**Natural Gas**	**Petroleum**	**Coal**	**Electricity**	**Total**
1949	55.2	85.1	110.9	69.5	320.6	18.2	48.3	154.6	54.9	276.0
1950	65.1	101.2	109.7	74.0	349.9	21.5	57.4	153.0	58.4	290.2
1951	79.8	110.3	96.8	82.6	369.5	26.3	62.6	135.0	65.2	289.1
1952	87.8	113.1	88.1	88.1	377.1	28.9	64.2	122.9	69.6	285.6
1953	90.9	114.9	75.6	96.2	377.7	30.0	65.2	105.5	75.9	276.6
1954	102.1	122.8	65.8	100.8	391.4	33.6	69.7	91.8	79.6	274.6
1955	113.2	132.0	65.4	110.0	420.5	37.3	74.9	91.2	86.8	290.2
1956	125.1	137.9	60.7	118.9	442.6	41.2	78.3	84.7	93.8	298.0
1957	134.6	133.8	46.6	127.4	442.4	44.4	75.9	65.0	100.6	285.9
1958	147.3	143.5	45.4	129.4	465.6	48.5	81.4	63.4	102.2	295.5
1959	159.6	146.2	38.8	143.3	487.9	52.6	83.0	54.1	113.1	302.8
1960	169.6	160.5	38.8	155.2	524.0	55.7	91.3	53.2	122.5	322.7
1961	177.5	165.2	35.3	162.7	540.7	58.8	92.7	48.5	126.9	326.9
1962	190.1	172.8	33.7	173.7	570.3	65.9	95.0	47.8	135.5	344.3
1963	195.1	173.9	29.4	190.2	588.6	68.7	93.6	40.8	152.7	355.8
1964	205.9	167.7	25.9	205.1	604.6	74.5	92.4	34.9	163.2	365.1
1965	212.2	175.2	24.1	220.9	632.4	78.3	103.1	33.1	175.5	390.1
1966	224.9	174.2	23.2	244.0	666.4	88.1	106.8	33.3	193.9	422.1
1967	234.4	180.3	20.0	256.1	690.7	106.4	110.4	28.5	204.4	449.6
1968	241.7	189.2	18.1	289.8	738.8	112.7	112.2	25.6	226.1	476.5
1969	256.8	192.4	16.8	319.3	785.3	122.3	112.7	24.1	243.3	502.5
1970	261.5	193.7	14.6	351.5	821.3	129.6	115.1	20.2	265.9	530.7
1971	268.8	195.3	13.7	369.7	847.5	135.6	111.9	18.9	279.9	546.3
1972	277.5	203.4	10.5	399.8	891.3	141.2	113.1	14.6	306.6	575.5
1973	264.0	198.7	10.0	430.9	903.6	140.4	115.9	13.8	331.1	601.2
1974	258.6	181.0	9.8	420.0	869.4	138.0	105.2	14.1	319.8	577.1
1975	265.2	175.5	8.0	414.8	863.6	134.9	96.5	11.4	330.3	573.2
1976	271.8	191.6	7.8	437.9	909.1	143.4	107.8	11.2	355.1	617.4
1977	259.4	189.9	7.9	473.0	930.3	134.5	111.6	11.3	376.9	634.2
1978	263.3	184.7	7.9	479.8	935.6	139.5	106.8	11.9	378.3	636.5
1979	266.7	149.6	6.9	491.8	915.0	149.6	98.6	10.6	391.3	650.1
1980	256.3	123.1	5.7	523.9	909.0	140.7	95.6	8.3	407.9	652.5
1981	245.6	108.5	6.7	517.0	877.8	136.1	80.5	9.2	426.5	652.2
1982	250.8	101.2	7.1	513.1	872.2	141.0	74.5	10.6	428.1	654.1
1983	238.3	94.9	7.1	526.0	866.4	132.2	82.5	11.0	434.8	660.5
1984	247.3	93.7	7.7	537.1	885.8	136.9	87.4	11.9	457.4	693.7
1985	241.0	103.9	6.5	548.2	899.7	132.2	75.7	10.1	476.2	694.0
1986	234.0	102.0	6.5	552.7	895.2	125.8	80.3	10.0	482.7	698.8
1987	234.2	105.5	6.2	576.1	921.9	131.9	78.7	9.4	504.6	724.6
1988	251.2	109.4	6.2	602.9	969.6	144.8	75.7	9.6	529.9	760.0
1989	260.2	108.8	2.6	623.2	994.8	147.9	70.9	11.1	558.6	788.5
1990	238.8	98.0	2.4	609.1	948.3	142.6	69.4	12.1	553.0	777.2
1991	248.0	96.7	2.2	620.8	967.6	148.5	65.9	11.1	556.1	781.7
1992	255.2	99.3	2.3	611.7	968.5	152.6	62.0	11.2	556.0	781.8
1993	269.0	100.6	2.3	655.8	1027.6	155.3	56.6	11.2	583.8	807.0
1994	263.3	98.7	2.0	656.9	1020.9	157.3	57.2	11.1	594.7	820.3
1995	263.0	95.9	1.6	666.0	1026.5	164.3	53.0	11.0	608.9	837.3
1996	284.2	102.7	1.6	697.6	1086.1	171.3	54.2	11.5	631.6	868.5
1997	270.2	98.5	1.5	707.3	1077.5	174.3	50.6	12.2	674.8	911.9
1998	246.5	90.5	1.2	745.1	1083.3	163.5	47.4	8.7	710.7	930.3
1999	256.5	101.0	1.3	748.3	1107.1	165.2	47.2	9.7	721.5	943.7
2000	270.3	107.2	1.1	791.7	1170.4	172.4	53.6	8.6	769.8	1004.3
2001	259.7	105.8	1.1	796.7	1163.3	164.5	54.0	9.2	793.3	1021.0
2002	265.9	101.4	1.0	825.6	1193.9	168.7	48.6	8.6	793.9	1019.8
2003 P	276.8	103.3	1.1	833.5	1214.8	170.5	49.6	8.9	796.7	1025.7

Notes: P = Preliminary.

Sources:		
	1990-2002	Estimates documented in this report .
	1960-1989	Calculated from energy data in the *State Energy Data Report* .
	1949-1959	Calculated from energy data in the *Annual Energy Review* .

Table B2. Energy-Related Carbon Dioxide Emissions from the Industrial and Transportation Sectors, by Fuel Type, 1949-2003

(Million Metric Tons of Carbon Dioxide)

	Industrial					Transportation				
Year	**Natural Gas**	**Petroleum**	**Coal**	**Electricity**	**Total/1**	**Natural Gas**	**Petroleum**	**Coal**	**Electricity**	**Total**
1949	168.4	211.7	482.4	121.5	984.0	7.1	436.8	157.5	1.9	603.3
1950	187.4	241.8	514.1	140.8	1084.2	10.4	475.5	142.5	2.1	630.5
1951	213.8	258.5	549.6	156.0	1177.9	11.5	523.1	125.6	2.2	662.3
1952	220.7	262.6	489.4	160.3	1133.0	12.6	546.8	89.7	2.1	651.2
1953	227.0	269.4	526.5	180.0	1203.0	12.6	572.3	66.9	2.3	654.0
1954	228.1	275.4	419.8	177.8	1101.1	13.7	578.6	42.0	2.3	636.6
1955	248.1	303.8	498.7	221.7	1272.3	16.4	623.0	38.5	2.4	680.2
1956	257.1	312.1	502.7	239.6	1311.5	16.4	646.9	31.0	2.5	696.8
1957	269.8	307.9	490.6	240.0	1308.2	16.9	659.4	22.1	2.5	700.9
1958	275.0	314.5	402.3	224.7	1216.5	19.1	672.1	10.5	2.5	704.2
1959	298.3	331.3	391.7	247.3	1268.5	19.1	698.7	8.1	2.8	728.7
1960	315.3	328.2	403.9	249.8	1297.3	19.0	716.8	6.9	2.4	745.0
1961	318.5	326.6	386.1	255.5	1286.7	20.6	730.8	1.7	2.6	755.7
1962	333.1	337.3	390.0	268.6	1328.9	20.9	762.4	1.6	2.5	787.3
1963	349.2	342.9	408.2	286.4	1386.7	23.1	790.1	1.5	2.4	817.1
1964	367.9	361.4	436.8	305.6	1471.7	23.8	813.5	1.6	2.2	841.0
1965	379.5	374.4	454.6	325.4	1533.9	27.3	839.3	1.5	2.1	870.2
1966	403.2	387.0	461.8	357.0	1609.0	29.2	884.0	1.4	2.2	916.7
1967	416.4	386.8	437.7	365.2	1606.0	31.3	928.1	1.0	2.0	962.4
1968	445.1	393.2	430.7	395.8	1664.8	32.1	1005.5	0.9	1.9	1040.4
1969	476.1	408.0	415.7	418.5	1718.2	34.2	1047.7	0.7	1.8	1084.4
1970	490.4	407.2	408.7	430.4	1736.7	39.1	1082.6	0.6	1.9	1124.2
1971	508.6	407.9	347.7	436.3	1700.5	40.2	1125.6	0.4	1.8	1168.0
1972	510.2	445.2	352.1	475.8	1783.2	41.5	1193.3	0.3	1.9	1237.0
1973	539.6	470.8	358.1	510.4	1879.0	39.3	1260.5	0.2	1.8	1301.9
1974	517.4	444.3	347.2	497.5	1806.6	36.1	1230.1	0.2	1.9	1268.3
1975	442.5	420.1	325.9	485.1	1673.5	31.4	1245.2	0.0	2.1	1278.8
1976	454.5	465.5	323.3	544.5	1787.9	29.5	1308.6	0.0	2.2	1340.4
1977	448.4	505.4	306.9	576.3	1837.0	28.7	1361.4	0.0	2.2	1392.4
1978	444.2	498.2	304.6	575.5	1822.6	28.6	1418.3	0.0	1.9	1448.7
1979	443.2	526.6	323.6	606.4	1899.8	32.3	1405.2	0.0	2.2	1439.8
1980	434.1	477.4	284.6	594.9	1787.7	34.3	1349.6	0.0	2.3	1386.2
1981	426.4	413.8	284.5	590.9	1714.2	34.8	1334.6	0.0	2.3	1371.7
1982	367.1	387.5	230.6	523.7	1506.9	32.4	1305.9	0.0	2.2	1340.5
1983	349.1	349.7	225.8	543.4	1466.7	26.7	1316.4	0.0	2.2	1345.3
1984	381.7	397.0	258.5	576.6	1612.6	28.8	1358.4	0.0	2.4	1389.6
1985	362.5	375.4	253.3	577.6	1567.6	27.5	1378.8	0.0	2.6	1408.9
1986	341.5	381.2	242.1	560.2	1523.4	26.5	1433.8	0.0	2.6	1462.9
1987	373.2	386.1	244.1	581.3	1585.6	28.4	1476.0	0.0	2.5	1506.9
1988	392.1	398.9	259.4	605.2	1659.3	33.4	1530.6	0.0	2.7	1566.8
1989	412.7	375.6	254.3	636.9	1682.3	34.3	1547.3	0.0	2.7	1584.3
1990	433.5	380.4	249.5	623.1	1686.9	35.9	1530.9	0.0	2.7	1569.5
1991	439.8	354.4	234.8	614.8	1644.8	32.7	1514.0	0.0	2.7	1549.4
1992	459.9	400.0	225.7	635.5	1724.4	32.1	1535.8	0.0	2.6	1570.5
1993	465.3	369.0	224.8	643.8	1705.5	34.0	1554.1	0.0	2.5	1590.6
1994	464.6	382.0	226.1	656.2	1734.4	37.4	1591.1	0.0	3.3	1631.7
1995	489.4	365.6	224.3	646.7	1731.6	38.2	1620.1	0.0	3.2	1661.4
1996	505.7	393.2	219.0	663.7	1784.8	38.9	1663.3	0.0	3.2	1705.3
1997	506.1	394.9	215.3	678.6	1800.1	41.1	1678.4	0.0	3.2	1722.7
1998	495.0	387.1	201.2	693.1	1783.8	35.1	1719.5	0.0	3.3	1757.9
1999	473.6	404.4	196.6	691.7	1772.9	35.6	1767.1	0.0	3.2	1806.0
2000	479.7	381.4	200.2	706.6	1775.0	35.5	1805.2	0.0	3.6	1844.2
2001	438.7	416.4	193.5	638.8	1691.4	33.9	1798.2	0.0	3.6	1835.8
2002	449.8	404.2	178.1	633.5	1671.5	37.1	1825.5	0.0	3.4	1866.0
2003 P	421.3	413.2	180.3	645.6	1666.2	35.4	1835.8	0.0	3.5	1874.7

Notes: P = Preliminary.

1/ Industrial total includes net coke imports.

Sources:		
	1990-2002	Estimates documented in this report .
	1960-1989	Calculated from energy data in the *State Energy Data Report* .
	1949-1959	Calculated from energy data in the *Annual Energy Review* .

Table B3. Total Energy-Related Carbon Dioxide Emissions by End-Use Sector, and the Electric Power Sector, by Fuel Type, 1949-2003

(Million Metric Tons of Carbon Dioxide)

	End-Use Sector					Electric Power Sector			
Year	**Residential**	**Commercial**	**Industrial**	**Transportation**	**Total**	**Natural Gas**	**Petroleum**	**Coal**	**Total/1**
1949	320.6	276.0	984.0	603.3	2183.9	30.1	31.9	185.8	247.8
1950	349.9	290.2	1084.2	630.5	2354.8	34.3	36.6	204.4	275.3
1951	369.5	289.1	1177.9	662.3	2498.8	41.7	31.1	233.2	306.0
1952	377.1	285.6	1133.0	651.2	2446.8	49.6	32.7	237.9	320.2
1953	377.7	276.6	1203.0	654.0	2511.2	56.5	39.7	258.3	354.5
1954	391.4	274.6	1101.1	636.6	2403.7	63.9	32.7	263.9	360.4
1955	420.5	290.2	1272.3	680.2	2663.3	62.8	36.6	321.5	420.9
1956	442.6	298.0	1311.5	696.8	2748.8	67.6	35.0	352.1	454.7
1957	442.4	285.9	1308.2	700.9	2737.4	72.9	38.9	358.6	470.4
1958	465.6	295.5	1216.5	704.2	2681.8	75.0	38.1	345.6	458.7
1959	487.9	302.8	1268.5	728.7	2787.9	89.2	42.8	374.4	506.4
1960	524.0	322.7	1297.3	745.0	2889.0	94.2	43.0	392.7	529.9
1961	540.7	326.9	1286.7	755.7	2910.1	99.7	43.4	404.6	547.7
1962	570.3	344.3	1328.9	787.3	3030.9	107.4	43.5	429.4	580.3
1963	588.6	355.8	1386.7	817.1	3148.2	117.2	45.5	469.1	631.7
1964	604.6	365.1	1471.7	841.0	3282.5	127.2	49.3	499.7	676.2
1965	632.4	390.1	1533.9	870.2	3426.6	127.1	56.2	540.7	724.0
1966	666.4	422.1	1609.0	916.7	3614.3	143.2	68.7	585.2	797.1
1967	690.7	449.6	1606.0	962.4	3708.8	150.6	78.6	598.5	827.7
1968	738.8	476.5	1664.8	1040.4	3920.5	172.3	91.8	649.5	913.6
1969	785.3	502.5	1718.2	1084.4	4090.4	190.5	122.1	670.4	983.0
1970	821.3	530.7	1736.7	1124.2	4212.9	213.7	164.8	671.2	1049.7
1971	847.5	546.3	1700.5	1168.0	4262.3	216.0	193.9	677.8	1087.7
1972	891.3	575.5	1783.2	1237.0	4487.0	215.6	240.2	728.2	1184.0
1973	903.6	601.2	1879.0	1301.9	4685.7	197.3	272.9	804.0	1274.3
1974	869.4	577.1	1806.6	1268.3	4521.3	185.4	261.1	792.8	1239.3
1975	863.6	573.2	1673.5	1278.8	4389.1	170.6	245.7	816.0	1232.3
1976	909.1	617.4	1787.9	1340.4	4654.8	166.5	269.9	903.4	1339.7
1977	930.3	634.2	1837.0	1392.4	4793.8	173.3	302.7	952.4	1428.4
1978	935.6	636.5	1822.6	1448.7	4843.5	173.9	309.7	951.9	1435.4
1979	915.0	650.1	1899.8	1439.8	4904.7	190.3	255.3	1046.3	1491.8
1980	909.0	652.5	1787.7	1386.2	4735.4	200.8	202.8	1125.3	1529.0
1981	877.8	652.2	1714.2	1371.7	4616.0	198.4	169.6	1168.5	1536.7
1982	872.2	654.1	1506.9	1340.5	4373.8	176.1	120.8	1170.1	1467.1
1983	866.4	660.5	1466.7	1345.3	4338.8	158.0	119.0	1229.4	1506.5
1984	885.8	693.7	1612.6	1389.6	4581.7	169.7	99.1	1304.4	1573.5
1985	899.7	694.0	1567.6	1408.9	4570.3	166.7	84.0	1353.7	1604.6
1986	895.2	698.8	1523.4	1462.9	4580.3	141.9	112.0	1343.9	1598.2
1987	921.9	724.6	1585.6	1506.9	4738.9	154.9	96.9	1412.4	1664.5
1988	969.6	760.0	1659.3	1566.8	4955.7	143.0	120.6	1476.9	1740.7
1989	994.8	788.5	1682.3	1584.3	5049.8	171.5	141.5	1505.5	1821.4
1990	948.3	777.2	1686.9	1569.5	4981.9	175.3	102.1	1507.1	1787.9
1991	967.6	781.7	1644.8	1549.4	4943.5	178.7	94.2	1519.1	1794.4
1992	968.5	781.8	1724.4	1570.5	5045.2	185.9	78.4	1538.9	1805.8
1993	1027.6	807.0	1705.5	1590.6	5130.7	187.2	89.4	1606.6	1885.9
1994	1020.9	820.3	1734.4	1631.7	5207.2	210.3	84.0	1613.8	1911.1
1995	1026.5	837.3	1731.6	1661.4	5256.8	227.5	60.3	1633.9	1924.8
1996	1086.1	868.5	1784.8	1705.3	5444.8	204.2	65.4	1723.5	1996.1
1997	1077.5	911.9	1800.1	1722.7	5512.2	218.1	74.3	1768.3	2063.9
1998	1083.3	930.3	1783.8	1757.9	5555.3	247.1	104.4	1797.6	2152.1
1999	1107.1	943.7	1772.9	1806.0	5629.6	259.1	96.8	1805.8	2164.7
2000	1170.4	1004.3	1775.0	1844.2	5793.9	279.9	91.0	1897.7	2271.6
2001	1163.3	1021.0	1691.4	1835.8	5711.4	289.4	100.7	1839.4	2232.5
2002	1193.9	1019.8	1671.5	1866.0	5751.2	306.2	76.7	1870.2	2256.4
2003 P	1214.8	1025.7	1666.2	1874.7	5781.4	275.3	96.5	1904.3	2279.3

Notes: Emissions from the electric power sector are apportioned to each end-use sector according to their share of electricty sales.

P = Preliminary.

1/Electric power sector total includes emissions from municipal solid waste and geothermal electricity generation.

Sources:

1990-2002	Estimates documented in this report
1960-1989	Calculated from energy data in the *State Energy Data Report.*
1949-1959	Calculated from energy data in the *Annual Energy Review*.

Appendix C – State Energy-related Carbon Dioxide Emissions Estimates

For the first time in this report, EIA is providing estimates of State energy-related carbon dioxide emissions. Although energy-related carbon dioxide emissions do not encompass a full greenhouse gas inventory, the State energy-related carbon dioxide emissions do give a good indicator of the relative importance of individual States to the national greenhouse gas inventory since energy-related carbon dioxide emissions represent 83 percent of total U.S. greenhouse gas emissions.

EIA emissions estimates at the State level for energy-related carbon dioxide emissions are based on data contained in the State Energy Data System (SEDS) for the years 1990 to 2001.[1] The State-level emissions estimates include energy consumption data for the following fuel categories: coal, natural gas, and ten petroleum products, including asphalt and road oil, aviation gasoline, distillate fuel (including some kerosene jet fuel), jet fuel, kerosene, LPG, lubricants, motor gasoline, residual fuel, and other petroleum products (including aviation gasoline blending components; crude oil [including lease condensate]; petroleum feedstocks - naphtha less than 401° F; petroleum feedstocks - other oils equal to or greater 401° F; petroleum feedstocks - still gas; motor gasoline blending components; miscellaneous petroleum products; natural gasoline [including isopentane]; petroleum coke; plant condensate; pentanes plus; still gas; special naphthas; unfinished oils; unfractionated stream; and waxes).

The data are presented in three tables:

Table 1. 2001 State Energy-related Carbon Dioxide Emissions by Fuel – The fuel-based estimates are developed from primary fuel inputs of coal, natural gas and petroleum for 2001. The Btu values for State-level energy consumption are multiplied by national-level carbon emission factors used in the national emissions inventory. No attempt is made to adjust national carbon emission factors by State.

Table 2. 2001 State Energy-related Carbon Dioxide Emissions by Energy Sectors– Emissions from primary fuel inputs are estimated by end-use sector, as well as the electric power sector for 2001. At the national level, electric power sector emissions are shared out to the end-use sectors via the amount of electricity sales.[2] At the State-level, electric power sector emissions are not shared out to the other sectors but are represented independently. This avoids complicated trans-boundary issues between States that are not encountered when doing a national emission estimate. In other words, regardless of where the electricity is consumed, the emissions from the primary energy consumed to generate the electricity are attributed to the State in which the generation occurred. For some States slight discrepancies exist between the fuel and sector estimates (0.1 percent). When this occurs, the differences are shared out to the sectors so that the sector tables agree with the fuel tables.

---

[1] See EIA website http://www.eia.doe.gov/emeu/states/_use_multistate.html.

[2] The electric power sector consists of NAICS-22 generators whose primary business is to produce electricity. Emissions from generators in the industrial and commercial sectors whose primary business is other than the generation of electricity remain in those sectors.

Table 3. Summary of State Energy-related Carbon Dioxide Emissions, 1990 - 2001 – A time series presents emissions estimates by State for 1990 to 2001. This table utilizes the fuel-based estimates to produce State totals.

Carbon Sequestered by Nonfuel Uses of Energy – All three tables net out carbon, and hence carbon dioxide emissions, that is sequestered due to the fact that a small portion of energy consumption is not combusted because it is used for nonfuel purposes. At the national level, carbon sequestered in nonfuel products is subtracted through a relatively complex process from total national-level emissions. Because of State-level data constraints, a more simplified process is used to allocate the national-level nonfuel sequestration values to the individual States. Three separate methods are used, depending on the nonfuel source.

1. For petroleum products, such as asphalt and road oil and lubricants, where all uses are nonfuel and the sequestration rates are straightforward, the amount of nonfuel sequestered was directly calculated based on State-level activity data and the related national-level carbon coefficients for the particular product.
2. For liquefied petroleum gases (LPG), industry data were used to apportion the total national-level nonfuel sequestration amounts for LPGs to the individual States.[3]
3. For petroleum products other than the above (petroleum coke, residual fuel, and distillate fuel), natural gas, and coal, value added at the NAICS 3251 Basic Chemicals level was used to apportion the total national-level nonfuel sequestration to the individual States.[4]

Municipal Solid Waste and Geothermal Power Generation - A line item for Municipal Solid Waste (MSW) and geothermal power generation is not apportioned to any State because it is not part of the SEDS database. This value fluctuates between 2.4 to 3.5 million metric tons during the 1990 to 2001 time frame. As such, this source ranges from 0.05 to 0.07 percent of total U.S. greenhouse gas emissions.

Balancing Item - The balancing item accounts for minor differences between the national-level inventory and state-level emissions calculations totals. Some of the difference is caused by adjustments that were made at the national level, but were more difficult to make at the state level. The balancing item is not attributed to any State. This source ranges from -12.9 million metric tons to 19.9 million metric tons. In percentage terms, the balancing item ranges form -0.3 to 0.37 percent of total U.S. greenhouse gas emissions.

---

[3] American Petroleum Institute, *2001 Sales of Natural Gas Liquids and Liquefied Refinery Gases*. November 2002. Data were aggregated and averaged in order to avoid disclosure of proprietary material.

[4] U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau, Annual survey of Manufactures, Geographic Area Statistics: 2000, Issued September 2002, http://www.census.gov/prod/2002pubs/m00as-3.pdf

Table C1. State Energy-related Carbon Dioxide Emissions by Fuel, 2001 (million metric tons carbon dioxide)

State Code	Coal	Petroleum	Natural Gas	Total
AK	1.5	19.9	21.8	**43.2**
AL	79.6	32.8	17.3	**129.6**
AR	25.8	25.6	12.0	**63.4**
AZ	40.0	35.8	12.9	**88.7**
CA	6.3	244.5	132.3	**383.1**
CO	37.7	30.7	20.3	**88.8**
CT	3.8	31.0	7.8	**42.6**
DC	0.1	2.4	1.6	**4.1**
DE	3.6	10.1	2.7	**16.4**
FL	68.4	140.4	29.9	**238.8**
GA	72.7	68.9	18.8	**160.5**
HI	1.7	17.4	0.2	**19.2**
IA	41.9	25.6	11.9	**79.4**
ID	1.0	10.1	4.3	**15.5**
IL	93.5	83.0	50.5	**227.1**
IN	147.5	55.9	26.9	**230.2**
KS	33.4	24.2	14.3	**71.9**
KY	95.2	45.9	11.0	**152.2**
LA	22.4	75.8	67.2	**165.3**
MA	10.3	53.7	19.2	**83.1**
MD	29.9	37.6	9.9	**77.4**
ME	0.7	16.6	5.3	**22.7**
MI	75.0	69.0	48.7	**192.7**
MN	33.3	44.4	18.2	**95.9**
MO	67.5	47.3	15.1	**129.9**
MS	18.7	32.6	17.7	**69.0**
MT	17.4	11.6	3.5	**32.4**
NC	71.3	63.1	11.0	**145.4**
ND	39.5	9.0	3.3	**51.8**
NE	21.4	14.9	6.5	**42.9**
NH	3.8	12.6	1.3	**17.7**
NJ	10.5	80.3	30.1	**120.9**
NM	28.0	17.3	13.8	**59.2**
NV	17.8	17.3	9.6	**44.6**
NY	29.6	118.7	63.2	**211.5**
OH	126.5	82.7	43.2	**252.3**
OK	35.5	39.6	29.0	**104.0**
OR	4.1	25.1	12.4	**41.6**
PA	129.8	97.3	34.8	**261.9**
RI	0.0	7.0	5.2	**12.2**
SC	39.0	29.4	7.1	**75.5**
SD	4.2	7.4	2.0	**13.5**
TN	64.7	43.6	13.1	**121.4**
TX	140.2	289.3	226.6	**656.1**
UT	36.7	17.8	8.9	**63.4**
VA	45.4	61.8	12.8	**119.9**
VT	0.0	6.1	0.4	**6.5**
WA	9.4	57.9	16.9	**84.2**
WI	46.6	44.0	19.1	**109.7**
WV	82.2	12.7	7.5	**102.3**
WY	47.1	10.7	5.5	**63.3**
State Total	**2,062.2**	**2,458.2**	**1,184.7**	**5,705.1**
MSW and Geothermal				**3.1**
Balancing Item				**3.2**
National Total				**5,711.4**

Notes: Most of the MSW and Geothermal emissions consist of Municipal Solid Waste (MSW) -- geothermal carbon dioxide emissions are 0.3 to 0.4 million metric tons per year. The balancing item accounts for other differences between the national-level inventory and state-level emissions calculations totals. Some of the difference is caused by adjustments that were made at the national level, but were more difficult to make at the state level.

Table C2. State Energy-related Carbon Dioxide Emissions by Energy Sectors, 2001
(million metric tons carbon dioxide)

State Code	Commercial	Electric Power	Residential	Industrial	Transportation	Total
AK	2.4	3.3	1.8	21.3	14.4	**43.2**
AL	2.0	73.8	3.6	19.0	31.2	**129.6**
AR	2.1	26.9	2.6	12.2	19.5	**63.4**
AZ	2.0	45.9	2.2	5.4	33.2	**88.7**
CA	14.7	55.8	28.7	73.5	210.4	**383.1**
CO	4.4	41.4	7.2	8.7	27.1	**88.8**
CT	4.2	9.6	8.3	3.8	16.7	**42.6**
DC	1.4	0.2	0.8	0.1	1.7	**4.1**
DE	0.6	5.2	1.2	4.7	4.7	**16.4**
FL	4.5	116.6	1.8	17.1	98.7	**238.8**
GA	3.7	70.1	7.4	18.8	60.5	**160.5**
HI	0.2	7.9	0.1	1.6	9.4	**19.2**
IA	3.6	36.1	4.8	16.0	18.9	**79.4**
ID	1.0	0.6	1.5	4.0	8.5	**15.5**
IL	11.7	85.7	24.1	39.8	65.7	**227.1**
IN	5.7	115.3	9.3	57.4	42.6	**230.2**
KS	2.5	34.9	4.2	13.2	17.3	**71.9**
KY	3.0	89.4	3.9	24.4	31.5	**152.2**
LA	2.1	37.6	3.2	69.2	53.3	**165.3**
MA	5.6	22.1	15.8	8.4	31.3	**83.1**
MD	4.7	30.3	6.8	7.1	28.4	**77.4**
ME	1.4	5.7	3.9	4.1	7.6	**22.7**
MI	10.8	72.8	23.0	29.8	56.2	**192.7**
MN	5.8	31.8	8.8	14.2	35.2	**95.9**
MO	5.0	67.1	8.5	10.0	39.3	**129.9**
MS	1.5	30.6	2.4	10.4	24.1	**69.0**
MT	0.9	17.5	1.4	5.1	7.6	**32.4**
NC	4.2	68.0	6.9	17.5	48.8	**145.4**
ND	0.9	30.6	1.3	13.1	6.0	**51.8**
NE	1.8	20.7	2.9	6.2	11.4	**42.9**
NH	1.3	4.2	2.8	2.1	7.2	**17.7**
NJ	9.7	18.7	16.1	14.0	62.4	**120.9**
NM	1.6	30.4	2.7	9.1	15.5	**59.2**
NV	1.4	24.2	2.0	2.5	14.5	**44.6**
NY	30.5	55.6	38.0	21.2	66.3	**211.5**
OH	11.1	118.2	19.3	35.0	68.8	**252.3**
OK	2.7	43.7	4.1	21.0	32.6	**104.0**
OR	2.1	8.6	2.7	6.6	21.5	**41.6**
PA	12.5	108.6	24.3	47.0	69.5	**261.9**
RI	1.2	3.2	2.6	0.6	4.6	**12.2**
SC	1.6	34.9	2.2	9.8	27.0	**75.5**
SD	0.7	3.9	1.1	2.1	5.8	**13.5**
TN	3.8	56.3	4.5	16.0	40.8	**121.4**
TX	11.8	217.4	14.1	224.2	188.6	**656.1**
UT	2.2	32.9	3.3	10.1	14.9	**63.4**
VA	5.2	42.5	7.5	16.5	48.2	**119.9**
VT	0.7	0.0	1.6	0.5	3.7	**6.5**
WA	3.8	14.0	6.0	18.0	42.4	**84.2**
WI	5.5	43.8	9.6	21.1	29.7	**109.7**
WV	1.9	74.8	2.5	10.8	12.4	**102.3**
WY	1.0	44.0	0.8	9.9	7.6	**63.3**
State Total	**226.8**	**2,233.4**	**366.3**	**1,033.9**	**1,844.7**	**5,705.1**
MSW and Geothermal						**3.1**
Balancing Item						**3.2**
National Total						**5711.4**

Notes: Most of the MSW and Geothermal emissions consist of Municipal Solid Waste (MSW) -- geothermal carbon dioxide emissions are 0.3 to 0.4 million metric tons per year. The balancing item accounts for other differences between the national-level inventory and state-level emissions calculations totals. Some of the difference is caused by adjustments that were made at the national level, but were more difficult to make at the state level.

Table C3. Summary of State Energy-related Carbon Dioxide Emissions, 1990-2001
(Million Metric Tons Carbon Dioxide)

State Code	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
AK	34.4	35.1	36.5	36.4	36.2	40.8	41.8	41.8	42.9	43.4	38.6	43.2
AL	107.6	111.5	118.2	122.9	120.8	128.3	133.0	129.7	128.8	131.0	138.0	129.6
AR	49.9	48.8	50.3	49.6	53.4	56.7	61.0	60.2	61.5	63.6	64.3	63.4
AZ	62.3	63.1	65.9	68.4	71.2	66.2	68.6	71.7	76.5	80.3	86.4	88.7
CA	362.5	349.4	353.5	343.6	360.5	349.3	347.5	349.9	359.6	363.4	378.8	383.1
CO	65.6	66.8	67.8	71.8	72.2	72.3	75.4	75.5	77.8	79.6	85.0	88.8
CT	40.7	39.9	40.3	38.4	37.7	36.9	40.6	43.7	41.3	42.6	43.9	42.6
DC	4.4	4.4	4.3	4.5	4.5	4.4	4.4	4.3	4.3	4.1	4.3	4.1
DE	17.6	17.9	17.5	19.2	18.5	17.5	18.2	16.9	16.3	16.5	16.9	16.4
FL	187.3	188.1	190.4	194.2	201.7	206.6	214.5	219.4	231.9	231.3	240.5	238.8
GA	138.0	131.2	130.9	140.7	143.5	151.6	155.1	156.2	157.2	159.6	168.6	160.5
HI	21.7	19.7	20.7	19.0	20.4	20.3	19.3	18.7	18.8	18.5	18.8	19.2
IA	62.7	64.5	63.2	67.7	68.8	72.2	74.4	73.9	77.7	78.9	80.5	79.4
ID	11.3	12.0	11.3	12.4	12.5	13.3	13.9	13.7	14.0	14.8	15.5	15.5
IL	193.9	195.2	191.4	208.4	208.7	212.1	222.6	226.4	216.6	226.7	235.2	227.1
IN	205.1	202.4	199.6	204.5	204.1	209.3	214.2	218.3	219.5	226.0	240.5	230.2
KS	69.3	67.8	65.6	70.9	71.2	68.5	74.6	71.7	70.6	74.3	76.4	71.9
KY	117.1	120.5	124.2	134.9	132.9	138.0	142.5	147.3	145.1	149.6	151.0	152.2
LA	178.8	173.3	179.2	181.0	185.8	186.3	178.4	181.2	167.6	167.7	190.0	165.3
MA	83.5	82.1	84.0	81.4	81.6	78.8	80.4	86.7	84.7	82.2	83.4	83.1
MD	69.6	68.6	66.6	69.0	70.1	69.5	71.6	71.8	74.8	77.4	77.3	77.4
ME	18.9	18.5	19.3	18.9	20.3	18.9	19.7	20.0	19.7	20.7	22.6	22.7
MI	181.1	180.7	179.7	180.4	188.5	190.9	196.7	194.4	193.3	201.3	197.4	192.7
MN	78.4	78.8	80.3	85.4	87.2	90.0	94.3	92.2	92.4	93.3	98.8	95.9
MO	103.9	102.4	102.1	100.6	108.1	115.1	120.9	124.4	129.0	129.7	125.3	129.9
MS	47.9	47.8	47.9	50.2	49.8	51.1	54.0	54.7	55.6	60.6	60.3	69.0
MT	27.5	28.6	29.9	27.9	30.6	30.0	27.3	29.2	31.2	31.8	31.1	32.4
NC	110.2	110.0	120.2	126.0	121.5	127.5	141.6	144.3	143.7	142.2	150.7	145.4
ND	44.2	45.2	46.9	47.3	47.7	47.6	48.4	47.1	48.2	49.3	50.9	51.8
NE	32.9	33.7	32.6	35.9	35.9	38.4	39.4	40.8	42.8	41.6	41.6	42.9
NH	14.6	14.2	14.3	14.9	15.0	15.0	16.1	17.4	17.4	17.6	18.3	17.7
NJ	114.6	114.8	121.7	118.3	128.0	127.2	123.1	125.0	120.2	124.0	124.0	120.9
NM	53.1	49.0	51.5	52.4	52.3	50.9	53.2	56.7	56.2	57.1	59.1	59.2
NV	30.4	32.2	33.2	33.8	36.0	35.2	37.7	37.7	40.4	41.1	45.3	44.6
NY	207.7	199.9	198.9	194.2	192.4	197.7	204.8	209.7	208.5	210.6	216.8	211.5
OH	244.2	242.4	247.3	252.6	249.1	250.9	263.0	258.7	257.8	256.9	264.9	252.3
OK	88.0	89.4	92.3	95.7	94.1	94.9	97.6	99.1	97.5	97.0	100.4	104.0
OR	30.6	34.4	35.5	35.8	37.2	34.5	36.6	36.1	41.8	43.1	41.6	41.6
PA	262.5	255.2	263.6	268.2	265.7	268.3	273.1	274.8	263.5	262.0	276.2	261.9
RI	8.8	10.7	13.0	10.8	12.8	12.0	13.5	13.5	13.8	13.2	11.7	12.2
SC	59.0	60.8	60.0	64.4	64.5	63.4	65.6	67.7	70.7	73.8	77.7	75.5
SD	11.8	11.5	11.6	12.4	13.0	12.8	12.7	13.2	12.8	13.4	14.2	13.5
TN	103.2	98.8	104.4	115.0	109.7	116.1	114.6	117.6	116.5	117.2	123.4	121.4
TX	552.6	547.3	553.4	566.2	565.7	568.7	619.5	640.3	645.6	629.2	657.5	656.1
UT	53.9	52.8	54.4	56.3	57.4	57.7	58.5	60.6	63.0	61.9	65.0	63.4
VA	94.2	95.8	97.1	101.6	100.6	102.6	107.6	109.8	111.6	113.6	123.0	119.9
VT	5.4	5.6	6.1	6.1	6.0	5.9	6.2	6.4	6.2	6.4	6.7	6.5
WA	70.0	71.2	79.3	75.2	79.9	77.5	79.8	78.1	81.9	83.1	82.8	84.2
WI	85.1	87.6	86.7	90.3	93.5	96.4	104.4	107.4	105.0	109.3	111.8	109.7
WV	106.7	96.9	98.9	100.0	107.5	105.7	104.3	107.7	111.4	112.1	112.2	102.3
WY	56.5	54.7	60.4	57.7	59.9	57.7	59.1	58.5	63.3	61.8	63.0	63.3
State Total	**4,980.8**	**4,932.9**	**5,023.9**	**5,133.2**	**5,206.3**	**5,259.3**	**5,445.3**	**5,522.1**	**5,548.4**	**5,606.6**	**5,808.1**	**5,705.1**
MSW and Geothermal	**3.5**	**2.4**	**2.7**	**2.7**	**2.9**	**3.0**	**3.0**	**3.1**	**3.1**	**3.1**	**3.0**	**3.1**
Balancing Item	**-2.4**	**8.2**	**18.6**	**-5.2**	**-2.0**	**-5.5**	**-3.5**	**-12.9**	**3.9**	**19.9**	**-17.1**	**3.2**
National Total	**4,981.9**	**4,943.5**	**5,045.2**	**5,130.7**	**5,207.2**	**5,256.8**	**5,444.8**	**5,512.2**	**5,555.3**	**5,629.6**	**5,793.9**	**5,711.4**

Notes: Most of the MSW and Geothermal emissions consist of Municipal Solid Waste (MSW) -- geothermal carbon dioxide emissions are 0.3 to 0.4 million metric tons per year. The balancing item accounts for other differences between the national-level inventory and state-level emissions calculations totals. Some of the difference is caused by adjustments that were made at the national level, but were more difficult to make at the state level.