

Emissions of Greenhouse Gases in the United States 2002

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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 eleventh 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.

Data for this report were obtained from the Energy Information Administration’s (EIA’s) July 2003 *Monthly Energy Review*. Additional detailed information on petroleum was obtained from unpublished material in support of EIA’s *Annual Energy Review 2002*. In keeping with current international practice, this year’s 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.

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Executive Summary

Overview

U.S. Anthropogenic Emissions of Greenhouse Gases, 1990-2002

| | Carbon Dioxide Equivalent |
|--|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 6,862.0 |
| Change Compared to 2001 (Million Metric Tons) | 33.2 |
| Change from 2001 (Percent) | 0.5% |
| Change Compared to 1990 (Million Metric Tons) | 706.2 |
| Change from 1990 (Percent) | 10.9% |
| Average Annual Increase, 1990-2002 (Percent) | 0.9% |

U.S. emissions of greenhouse gases in 2002 totaled 6,862.0 million metric tons carbon dioxide equivalent, 0.5 percent more than in 2001 (6,828.9 million metric tons carbon dioxide equivalent). Although emissions of carbon dioxide and emissions of hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride grew by 0.8 percent and 6.2 percent, respectively, those increases were moderated by reductions in methane (-2.7 percent) and nitrous oxide (-1.1 percent) emissions, resulting in a relatively low 0.5-percent growth in total greenhouse gas emissions. U.S. greenhouse gas emissions have averaged 0.9-percent annual growth since 1990. Even though the U.S. economy grew by 2.4 percent in 2002 (slightly less than its 2.9-percent growth trend for the 1990-2002 period), growth in total greenhouse gas emissions was

restrained somewhat due to a 1.1-percent reduction in output from the energy- and emissions-intensive manufacturing sector. Consequently, U.S. greenhouse gas intensity (greenhouse gas emissions per unit of real economic output) was 2.1 percent lower in 2002 than in 2001. From 1990 to 2002, U.S. greenhouse gas intensity has declined by 21.4 percent, or by an average of 2.0 percent per year.

U.S. greenhouse gas emissions in 2002 were 11.5 percent higher than 1990 emissions (6,155.8 million metric tons carbon dioxide equivalent). 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 (2.0 percent), or gross domestic product (2.9 percent). While the annual growth rate in carbon dioxide emissions since 1990 (1.2 percent) has closely tracked annual growth in population (1.2 percent) and energy consumption (1.2 percent), the average annual rate of growth in total greenhouse gas emissions has been lower (0.9 percent) because of reductions in methane and nitrous oxide emissions since 1990. Growth rates in electricity generation (2.0 percent) and gross domestic product (2.9 percent), meanwhile, have outstripped the growth in total greenhouse gas emissions because of the increased electrification of energy use and rapid growth in non-greenhouse-gas-intensive segments of the economy.

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 "radiative forcing." The GWP concept, developed by the Intergovernmental Panel on Climate Change (IPCC), provides a comparative measure of the

Table ES1. Summary of Estimated U.S. Emissions of Greenhouse Gases, 1990-2002
(Million Metric Tons of Gas)

| Gas | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|---|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Carbon Dioxide | 5,006.1 | 4,959.0 | 5,072.6 | 5,180.0 | 5,262.5 | 5,318.5 | 5,508.9 | 5,572.5 | 5,602.4 | 5,686.1 | 5,854.0 | 5,748.3 | 5,795.6 |
| Methane | 31.3 | 31.4 | 31.6 | 30.6 | 30.6 | 30.5 | 29.4 | 29.1 | 28.2 | 27.8 | 27.8 | 27.4 | 26.6 |
| Nitrous Oxide | 1.1 | 1.1 | 1.2 | 1.2 | 1.3 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 |
| HFCs, PFCs, and SF ₆ | M | M | M | M | M | M | M | M | M | M | M | M | M |

M = mixture of gases. 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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002).

Source: Estimates presented in this report.

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-2002
(Million Metric Tons Carbon Dioxide Equivalent)

| Gas | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|---|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Carbon Dioxide | 5,006 | 4,959 | 5,073 | 5,180 | 5,263 | 5,319 | 5,509 | 5,573 | 5,602 | 5,686 | 5,854 | 5,748 | 5,796 |
| Methane | 719 | 723 | 726 | 703 | 703 | 702 | 676 | 668 | 648 | 640 | 639 | 630 | 613 |
| Nitrous Oxide | 334 | 339 | 347 | 348 | 371 | 355 | 352 | 344 | 343 | 347 | 341 | 337 | 333 |
| HFCs, PFCs, and SF ₆ | 97 | 88 | 88 | 94 | 91 | 95 | 113 | 116 | 126 | 122 | 123 | 114 | 121 |
| Total | 6,156 | 6,109 | 6,233 | 6,324 | 6,428 | 6,470 | 6,650 | 6,701 | 6,720 | 6,795 | 6,957 | 6,829 | 6,862 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002).

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.

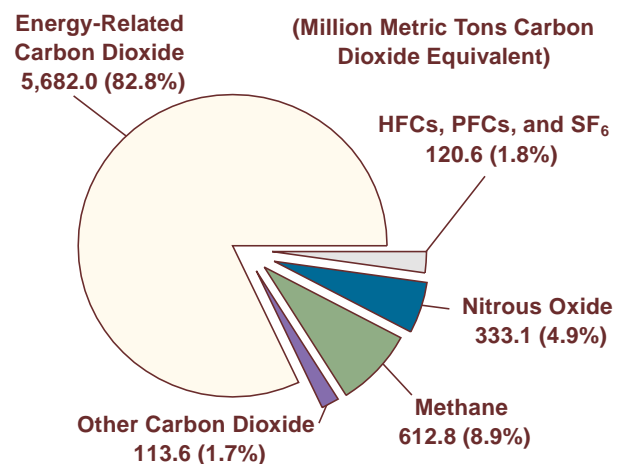
impacts of different greenhouse gases on global warming relative to the global warming potential of carbon dioxide.¹

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. For a discussion of GWPs and a comparison of U.S. carbon dioxide equivalent emissions calculated using the GWPs from the IPCC's Third and Second Assessment Reports see the box on page xiii. Generally, total U.S. carbon dioxide equivalent emissions are 0.6 percent higher when the GWPs from the Third Assessment Report are used.

During 2002, 82.8 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 2002 U.S. greenhouse gas emissions include carbon dioxide from non-combustion sources (1.7 percent of total U.S. greenhouse gas emissions), methane (8.9 percent), nitrous oxide (4.9 percent), and other gases (1.8 percent) (Figure ES1). Methane and nitrous oxide

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 2002



Source: Table ES2 and Table 4 in this report.

emissions are caused by the biological decomposition of various waste streams and fertilizer, fugitive emissions from chemical processes, fossil fuel production 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 (SF₆), used as an insulator in utility-scale electrical equipment.

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.

¹See "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).

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

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

Units for Measuring Greenhouse Gases

In this publication, EIA reports information in forms that are most likely to be familiar to users of the document. Therefore, energy and industrial data are reported in their native units. For example, oil production is reported in thousand barrels per day, and energy production and sales are reported in British thermal units (Btu). For readers familiar with metric units, Btu can be a relatively intuitive unit because an exajoule is only 5 to 6 percent larger in energy content than a quadrillion Btu.

Emissions data are reported in metric units. This report uses the familiar “million metric tons” common in European industry instead of “gigagram,” which is equal to 1,000 metric tons and is the term favored by the scientific community. Metric tons are also relatively intuitive for users of English units, because a metric ton is only about 10 percent heavier than an 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. It is important to note that, in previous issues of this report, greenhouse gas emissions were reported in carbon equivalents. This change is being made to be consistent with the current trend, both domestically and internationally, to report greenhouse gas emissions in carbon dioxide equivalents.

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 later in this chapter and delineated in Chapter 1, Table 3.

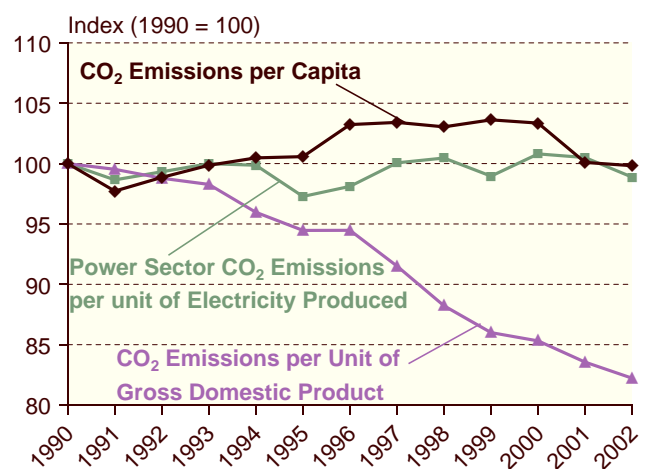
Carbon Dioxide

The preliminary estimate of U.S. carbon dioxide emissions from both energy consumption and industrial processes in 2002 is 5,795.6 million metric tons, which is 0.8 percent higher than in 2001 and accounts for 84.5 percent of total U.S. greenhouse gas emissions. U.S. carbon dioxide emissions have grown by an average of 1.2 percent annually since 1990. Although short-term changes in carbon dioxide emissions can result from temporary variations in weather, power generation fuel mixes, and the economy, in the longer term their growth is driven by population, income, and consumer choices of energy-using equipment, as well as the “carbon intensity” of energy use (carbon dioxide emissions per unit of energy consumed).

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 GDP have continued to fall relative to 1990; by 2002, this measure was 17.7 percent lower than in 1990. Carbon dioxide emissions per capita were 0.1 percent above the 1990 level in 2001 and 0.1 percent below the 1990 level in 2002. Population growth and other factors resulted in increased aggregate carbon dioxide emissions per year from 1990 through 2002 (a total increase of 15.8 percent). Carbon dioxide emissions per unit of net electricity generation in 2002 were 1.6 percent lower than in 2001.

Carbon dioxide emissions from the U.S. electric power sector (which includes utilities, independent power producers, and combined heat and power facilities whose primary business is the production and sale of electricity) in 2002 are estimated at 2,249.0 million metric tons, 1.0 percent higher than the 2001 level of 2,226.6 million metric tons. The 1-percent increase is less than the 2.7-percent increase in electricity generation during 2002

Figure ES2. Carbon Dioxide Emissions Intensity of U.S. Gross Domestic Product, Population, and Electricity Production, 1990-2002



Sources: Estimates presented in this report.

because of an increase in the average efficiency of natural-gas-fired power plants. Although total electricity generation from natural gas increased by 8.2 percent from 2001 to 2002, emissions from natural-gas-fired generators increased by only 3.4 percent, due to the improved efficiency of new natural-gas-fired combined-cycle generating units.

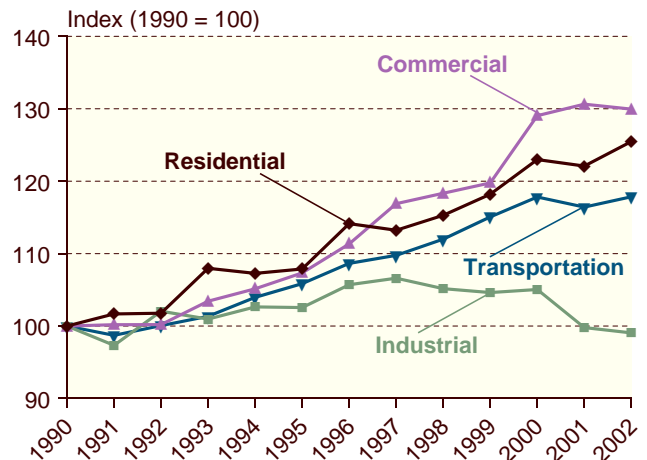
Figure ES3 illustrates trends in carbon dioxide emissions by energy consumption sector. In general, emissions have increased steadily at the sectoral level since 1990. Average annual growth rates in carbon dioxide emissions by sector during the 1990-2002 period were 2.2 percent for the commercial sector, 1.9 percent for the residential sector, and 1.4 percent for the transportation sector. Industrial sector carbon dioxide emissions, after peaking in 1997, have continued to fall and are now below 1990 levels.

In the residential sector, total carbon dioxide emissions were up by 2.8 percent, from 1,160.8 million metric tons in 2001 to 1,193.0 million metric tons in 2002. The increase is attributed mainly to a 1.2-percent rise in natural gas use due to colder winter weather that increased heating degree-days by 1.4 percent. Emissions attributable to purchased electricity also rose by 3.3 percent, which also contributed to the overall increase in residential carbon dioxide emissions. Since 1990, residential carbon dioxide emissions have grown by an average of 1.9 percent annually.

Carbon dioxide emissions in the commercial sector fell by 0.5 percent, from 1,018.3 million metric tons in 2001 to 1,012.9 million metric tons in 2002. Emissions attributable to purchased electricity decreased by 1.2 percent, from 791.1 million metric tons in 2001 to 781.8 million metric tons in 2002. Carbon dioxide emissions from the direct combustion of fossil fuels in the commercial sector, primarily natural gas, rose from 227.1 million metric tons in 2001 to 231.1 million metric tons in 2002, a 1.7-percent increase. Despite the slight decrease in 2002, commercial sector emissions of carbon dioxide have increased at an average annual rate of 2.2 percent since 1990.

Energy-related carbon dioxide emissions in the industrial sector in 2002 are estimated at 1,673.7 million metric tons, which is approximately equal to the level of emissions in 1990. After peaking in 1997, industrial emissions have generally fallen with the exception of a slight upturn in 2000. Historically, industrial energy consumption and carbon dioxide emissions have been more sensitive to economic growth than to the weather. The most recent decline, in 2002, is a case in point: industrial emissions fell by 0.7 percent in 2002, coinciding with a 1.1-percent decrease in manufacturing output.

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1990-2002



Note: Sectoral emissions include both direct emissions and emissions attributable to purchased electricity.
Sources: Estimates presented in this report.

Industrial energy consumption and emissions are concentrated in a few energy-intensive industries, and their performance is more closely correlated with carbon dioxide emissions than is the performance of the industrial sector as a whole. 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 2002 (see text box in Chapter 2, page 20). Declines in output relative to 2001 were seen in 2002 for the primary metals and pulp and paper industries (-3.0 percent and -2.3 percent, respectively), while increases in output were seen for the chemicals industry (3.9 percent) and stone, clay and glass products (1.0 percent). Smaller increases in output were seen for the other energy-intensive industries: food (0.5 percent) and petroleum refining (0.5 percent). By fuel type, industrial sector carbon dioxide emissions from purchased electricity rose by 0.9 percent, while emissions from natural gas and coal fell by 2.0 percent and 6.9 percent, respectively. Carbon dioxide emissions from petroleum use in the industrial sector increased by 0.7 percent in 2002.

Carbon dioxide emissions in the transportation sector, at 1,849.7 million metric tons, were 1.2 percent higher in 2002 than in 2001. Emissions of carbon dioxide from gasoline consumption (61.6 percent of transportation sector emissions) grew by 2.5 percent, while emissions from jet fuel use for air travel fell by 2.5 percent. Transportation sector carbon dioxide emissions have grown by an average of 1.4 percent annually since 1990.

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 (CO₂), 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 CO₂. 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, and because the IPCC is generally considered the authoritative source for GWPs, 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*

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 ₂ F ₆) | 9,200 | 11,900 |
| Sulfur Hexafluoride (SF ₆) | 23,900 | 22,200 |

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

U.S. Greenhouse Gas Emissions and Sinks: 1990-2002, scheduled for release in April 2004.

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 2002 is 0.6 percent higher when the revised GWPs are used. The estimates for earlier years generally follow the same pattern. 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 SF₆ are lower for some years and higher for others, depending on the relative shares of the three gases.

| Gas | Annual GWP-Weighted Emissions (Million Metric Tons Carbon Dioxide Equivalent) | | | | | | | | | | |
|---|--|------|--------------|--------------|-------------------|--------------|--------------|-------------------|--------------|--------------|-------------------|
| | IPCC GWP | | 1990 | | | 2001 | | | 2002 | | |
| | 1996 | 2001 | 1996 GWP | 2001 GWP | Percent Change | 1996 GWP | 2001 GWP | Percent Change | 1996 GWP | 2001 GWP | Percent Change |
| Carbon Dioxide | 1 | 1 | 5,006 | 5,006 | 0.0 | 5,748 | 5,748 | 0.0 | 5,796 | 5,796 | 0.0 |
| Methane | 21 | 23 | 657 | 719 | 9.5 | 575 | 630 | 10.0 | 560 | 613 | 9.5 |
| Nitrous Oxide | 310 | 296 | 350 | 334 | -4.5 | 353 | 337 | -5.0 | 349 | 333 | -4.5 |
| HFCs, PFCs, and SF ₆ | M | M | 101 | 97 | -4.1 | 110 | 114 | 3.1 | 117 | 121 | 3.4 |
| Total | — | — | 6,113 | 6,156 | 0.7 | 6,787 | 6,829 | 0.6 | 6,820 | 6,862 | 0.6 |

M = mixture of gases.

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

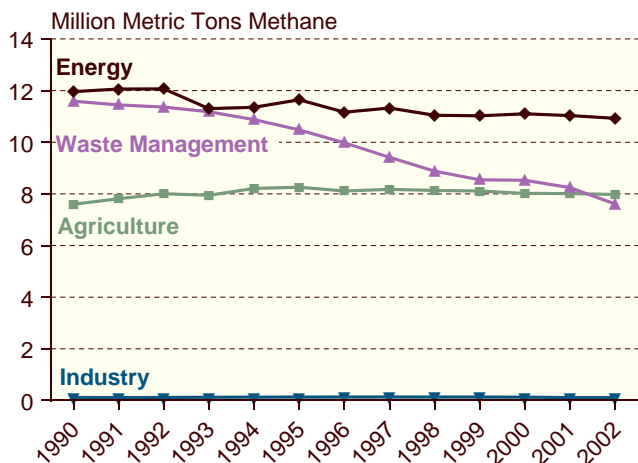
Methane

U.S. emissions of methane in 2002 were 2.7 percent lower than in 2001, at 26.6 million metric tons of methane or 612.8 million metric tons carbon dioxide equivalent (8.9 percent of total U.S. greenhouse gas emissions). Total U.S. methane emissions in 2001 were 27.4 million metric tons of methane or 630.2 million metric tons carbon dioxide equivalent (9.2 percent of total U.S. greenhouse gas emissions). The 2002 decline resulted primarily from decreases in methane emissions from landfills and, to a smaller extent, from reductions in methane emissions from coal mining.

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 41.1, 29.9, and 28.6 percent, respectively, of total 2002 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) declined from 11.0 million metric tons of methane in 2001 to 10.9 million metric tons of methane in 2002, representing a 0.7-percent reduction in emissions from energy sources. Methane emissions from energy sources have fallen by 8.5 percent since 1990. The drop in 2002 was the result of reductions in emissions associated with natural gas production, lower emissions from underground coal mines, a drop in residential wood combustion, and lower emissions from petroleum systems and the transportation sector.

Figure ES4. U.S. Emissions of Methane by Source, 1990-2002



Source: Estimates presented in this report.

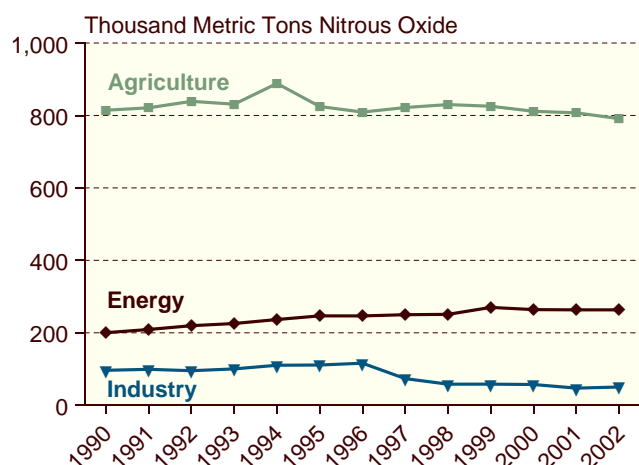
Methane emissions from agricultural sources (8.0 million metric tons) decreased by 0.5 percent in 2002. Agricultural methane emissions have several sources but are dominated by emissions from domestic livestock, including the animals themselves (enteric fermentation) and the anaerobic decomposition of their waste. Methane emissions from enteric fermentation in 2002 were slightly (0.03 percent) lower than in 2001, and methane emissions from animal waste were 0.9 percent lower. Agricultural emissions have increased by 5.0 percent since 1990.

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 decreased by 7.7 percent, from 8.2 million metric tons in 2001 to 7.6 million metric tons in 2002. Contributing to the decrease was an 8.5-percent decrease in emissions from landfills that resulted from a 0.6 million metric ton increase in methane recovery for energy use. Emissions of methane from waste management have declined by 34.3 percent since 1990 as a result of an increase in the amount of methane recovered from landfills (4.7 million metric tons more in 2002 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 volume 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 1.1 percent from 2001 to 2002, to 1.1 million metric tons of nitrous oxide or 333.1 million metric tons carbon dioxide equivalent (4.9 percent of total U.S. greenhouse gas emissions). The 2002 decline in nitrous oxide emissions resulted from decreases in emissions from agricultural sources. Since 1990, U.S. nitrous oxide emissions have fallen by 0.2 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

Figure ES5. U.S. Emissions of Nitrous Oxide by Source, 1990-2002

Source: Estimates presented in this chapter.

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 791 thousand metric tons of nitrous oxide or 234.2 million metric tons carbon dioxide equivalent, account for 70.3 percent of total U.S. nitrous oxide emissions. Emissions associated with nitrogen fertilization of soils, at 583 thousand metric tons or 172.5 million metric tons carbon dioxide equivalent, account for 73.7 percent of nitrous oxide emissions from agriculture. Emissions from the solid waste of animals, at 207 thousand metric tons or 61.2 million metric tons carbon dioxide equivalent, make up 26.1 percent of agricultural nitrous oxide emissions. Nitrous oxide emissions from agriculture have decreased by 2.8 percent since 1990.

U.S. nitrous oxide emissions associated with fossil fuel combustion in 2002 were 0.3 million metric tons of nitrous oxide, or 23.4 percent of total nitrous oxide emissions. Of these energy-related emissions, 81.4 percent comes from mobile sources, principally motor vehicles equipped with catalytic converters. The remainder comes from stationary source combustion of fossil fuels. Nitrous oxide emissions from energy sources have increased by 31.5 percent since 1990.

Industrial processes and wastewater treatment facilities are responsible for 6.2 percent of total nitrous oxide emissions. Industrial process emissions increased from 47 thousand metric tons (14.0 million metric tons carbon dioxide equivalent) in 2001 to 50 thousand metric tons (14.9 million metric tons carbon dioxide equivalent) in 2002. This represents the first increase in industrial nitrous oxide emissions since 1996. The increase can be

attributed to the leveling off of emissions reductions from adipic acid production, as well as a slight increase in emissions from nitric acid production. Emissions from wastewater treatment facilities were 20 thousand metric tons of nitrous oxide (6.0 million metric tons carbon dioxide equivalent), an increase of 0.3 thousand metric tons (0.1 million metric tons carbon dioxide equivalent) or 1.4 percent from 2001.

Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

HFCs, PFCs, and SF₆ are three classes of engineered gases that account for 1.8 percent of U.S. GWP-weighted emissions of greenhouse gases. At 120.6 million metric tons carbon dioxide equivalent in 2002, their emissions were 6.2 percent higher than in 2001. The increase in emissions of the engineered gases from 2001 to 2002 resulted largely from increases in HFC emissions (8.4 percent) that counteracted decreases in emissions of PFCs (-2.2 percent) and SF₆ (-4.7 percent).

At 83.1 million metric tons carbon dioxide equivalent, emissions of HFCs make up the majority of this category, followed by SF₆ at 16.7 million metric tons and PFCs at 7.6 million metric tons. 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 2002, their combined emissions totaled 13.2 million metric tons carbon dioxide equivalent. Emissions in this "other" group in 2002 were 13.5 percent higher than in 2001 and orders of magnitude higher than in 1990, when emissions were less than 180,000 metric tons carbon dioxide equivalent. Since 1990, HFC emissions from U.S. sources have increased by 126.0 percent, PFC emissions have decreased by 60.8 percent, and SF₆ emissions have decreased by 58.7 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 SF₆) 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 2001 at 838.1 million metric tons carbon dioxide equivalent. In 1990, land use change and forestry practices represented an offset of more than 17 percent of total U.S. anthropogenic carbon dioxide emissions. By 2001, the offset had declined to 12 percent.

1. U.S. Emissions of Greenhouse Gases in Perspective

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 tenth annual update, covering national emissions over the period 1990-2001, with preliminary estimates of emissions for 2002. 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 (see "What's New in This Report," page 4). 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.

Chapter 1 of this report briefly summarizes some background information about global climate change and the greenhouse effect and discusses important 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.

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 -19° Celsius, rather than the $+14^{\circ}$ Celsius actually observed.¹ 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 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.² Concentrations of other greenhouse gases, such as methane and nitrous oxide, are a fraction of that for carbon dioxide (Table 1).

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 chemicals also were rising. Because current concentrations of greenhouse gases

¹Intergovernmental 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.

²The United Nations Framework Convention on Climate Change, 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, which has not yet "entered into force," would require 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.

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 a global scale. 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, estimates that the global average surface temperature has increased by $0.6^{\circ} \pm 0.2^{\circ}\text{C}$ since the late 19th century.³ 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."⁴

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.⁵ 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:⁶

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.

While both the extent and consequences of human-induced global climate change remain uncertain, the threat of climate change has put in motion an array of efforts by the United States and other governments to

Table 1. Global Atmospheric Concentrations of Selected Greenhouse Gases

| Item | Carbon Dioxide | Methane | Nitrous Oxide | Sulfur Hexafluoride | Perfluoromethane |
|---|---------------------|--------------------|------------------|----------------------|------------------|
| | (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 |

^aThe rate has fluctuated between 0.9 and 2.8 parts per million per year for CO₂ and between 0 and 0.013 parts per million per year for methane over the 1990-1999 period.

^bNo single lifetime can be defined for CO₂ because uptake rates differ for different removal processes.

^cThis 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.

³Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 26.

⁴Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 10.

⁵National 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/>.

⁶National 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/>.

find some mechanism for limiting the risk of climate change and ameliorating possible consequences. To date, efforts have focused primarily on identifying levels and sources of emissions of greenhouse gases and on possible mechanisms for reducing emissions or increasing sequestration of greenhouse gases.

Global Sources of Greenhouse Gases

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 (human-made) 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 2 illustrates the relationship between anthropogenic (human-made) and natural emissions and absorption of the principal greenhouse gases.

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 through natural evaporation from oceans, lakes, and soils and is returned to Earth in the form of rain and

snow. As a natural emission generally beyond human control, water vapor has not been included in climate change options under the United Nations Framework Convention on Climate Change. The recent IPCC report, however, cites a possible positive feedback from increased water vapor formation due to increased warming caused by rising atmospheric CO₂ concentrations.⁷ 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 counter-vailing 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 under-saturated.

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

Table 2. Global Natural and Anthropogenic Sources and Absorption of Greenhouse Gases

| 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 |

^aCarbon 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.

^bMethane 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.

^cNitrous 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).

⁷Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 49.

What's New in This Report

This year, we have written expanded documentation that will be published in a separate volume. As a result, there are only three appendixes to this volume: Common Conversion Factors (Appendix A), Emissions of Energy-Related Carbon Dioxide in the United States, 1949-2002 (Appendix B), and Energy-Related Carbon Dioxide Emissions by State (Appendix C).

Chapter 2

- Beginning with this year's report, EIA is reporting carbon dioxide emissions at the full weight of the gas. For consistency, all other gases are reported in carbon dioxide equivalent units. The ratio of carbon dioxide to carbon alone is approximately 44/12.

Chapter 3

- The animal population data and methodologies used to estimate methane emissions from the solid waste of domesticated animals and those produced by cattle from enteric fermentation have been revised, affecting estimates of methane emissions for all years. The revised population estimates eliminate previous double counting of beef cattle in feedlots, reducing the estimates of emissions from enteric fermentation and solid waste from beef cattle for 1990 through 2002. The revised methodology for enteric fermentation in cattle changed the trend of emissions from this source. For both the old and new methods, enteric fermentation emissions peaked in 1995; however, the results of the new method show emissions decreasing since then. The changes to the model of emissions from solid waste from domesticated animals reduced the magnitude of emissions but produced similar emissions trends for each animal category since 1990.
- To estimate emissions produced by cattle from enteric fermentation, EIA applied adjusted methane emissions factors, which reflect the greater detail that the U.S. Environmental Protection Agency (EPA) incorporated into the Tier 2 methodology outlined in the IPCC's *Good Practice Guidance*.^a For other animal categories, EIA continued to apply the Tier 1 emission factors recommended in the *Revised 1996 IPCC Guidelines*.^b Emissions factors for sheep and goats have been revised, reducing the estimates of methane emissions from sheep and goats.

- To estimate methane associated with solid waste from domesticated animals, EIA revised the typical animal mass for all animal categories, including revising swine sizes to correspond more closely with the classifications used by the U.S. Department of Agriculture. In addition, EIA updated the volatile solids factors and altered the distribution of waste management systems to reflect the general shift to larger, more managed farms.

Chapter 4

- Estimates of nitrous oxide (N₂O) emissions from the application of sewage sludge have been included in EIA's calculation of N₂O emissions from agricultural sources. EIA's emissions estimate for sewage sludge was calculated by multiplying EPA estimates of annual sludge generation, annual percentage applied to land, and a figure for average nitrogen content.

Chapter 5

- The data presented in Chapter 5 for other gases (HFCs, PFCs, and SF₆) are provided by the EPA. Revisions in historical emissions estimates are explained below:
 - **Electricity Transmission and Distribution.** The primary change in the methodology for calculating emissions from electricity transmission and distribution was an increase in the assumed rate of emissions from equipment manufacturing. This revision resulted in an average annual increase in estimated SF₆ emissions of 3.7 percent for the period 1990 through 2000.
 - **Magnesium Production and Processing.** The emissions estimates for this report were revised to reflect new activity data for magnesium production and processing and a revised emissions factor for die-casting. The combination of these changes and the methodological revision described above resulted in an average annual decrease in estimated SF₆ emissions of about 1.9 percent for the period 1990 through 2000.
 - **Substitution of Ozone-Depleting Substances.** The EPA updated assumptions for its Vintaging Model in the fire-extinguishing sector. These changes resulted in an average annual decrease

(continued on page 5)

^aIPCC National Greenhouse Gas Inventories Programme, *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), Chapter 4, "Agriculture," web site www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm.

^bIntergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 4.10, web site www.ipcc.ch/pub/guide.htm.

What's New in This Report (Continued)

Chapter 5 (continued)

in estimated HFC and PFC emissions of 0.7 percent for the period 1994 through 2000.

- **Aluminum Production.** In cooperation with the EPA's Voluntary Aluminum Industrial Partnership program, participants provided additional smelter-specific information on aluminum production and the frequency and duration of anode effects. The new information resulted in a decrease in estimated PFC emissions of 0.3 percent for 2000.

Chapter 6

- The data for net carbon dioxide fluxes due to changes in carbon stocks in forests, urban trees, agricultural soil, and landfilled yard trimmings are provided by the U.S. Forest Service. This year, all values are presented in million metric tons carbon dioxide equivalent. 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.

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. 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 the past 420,000 years, and likely not during the past 20 million years.⁸

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.⁹ 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.¹⁰ 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.¹¹

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.¹² The main sources of absorption are thought to be tropospheric reactions with hydroxyl (OH) radicals that break down methane into CH_3 and water vapor (506 million metric tons), stratospheric reactions with hydroxyl radicals and chlorine (40 million metric tons), and decomposition by

⁸Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 185.

⁹Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 188, 191.

¹⁰Intergovernmental Panel on Climate Change, *Land Use, Land-Use Change, and Forestry. A Special Report to the IPCC* (Cambridge, UK: Cambridge University Press, 2000).

¹¹Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 208.

¹²Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 248.

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.¹³

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.¹⁴

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. A particular family of engineered gases is the halocarbons. A 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 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 a direct radiative forcing effect hundreds or thousands of times greater, gram-per-gram, than that of carbon dioxide.

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.¹⁵

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 2002.¹⁶ 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.

¹³Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.2, p. 250.

¹⁴Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.4, p. 252.

¹⁵Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Figures 4.6 and 4.7, p. 255.

¹⁶Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254; and estimates presented in this report.

Another new class of engineered halocarbons is the perfluorocarbons (PFCs), which include perfluoromethane (CF₄) and perfluoroethane (C₂F₆). 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 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.¹⁷ 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.¹⁸

Sulfur hexafluoride (SF₆) is used as an insulator in utility-scale electrical equipment and as a cover gas in magnesium smelting. It is not a halocarbon, but it is a powerful greenhouse gas. SF₆ has a 100-year GWP of 22,200 and a lifetime of 3,200 years. Like perfluoromethane, SF₆ 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 SF₆ are photolysis and ion reactions in the mesosphere.

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 (SF₅CF₃) as a new anthropogenic greenhouse gas in the atmosphere.¹⁹ It is believed that SF₅CF₃ is created by the breakdown of SF₆ in high-voltage equipment, which produces CF₃ that reacts with SF₅ 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, SF₅CF₃ has the largest radiative forcing on a per-molecule basis of any gas found in the atmosphere.²⁰ The United Nations Framework Convention on Climate Change 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 SF₆).

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 (O₃) 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

¹⁷Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

¹⁸Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

¹⁹W.T. Sturges et al., “A Potent Greenhouse Gas Identified in the Atmosphere: SF₅CF₃,” *Science*, Vol. 289 (July 28, 2000), pp. 611-613.

²⁰Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 254.

square meter.²¹ 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.²² 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, via 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.²³

Nitrogen oxides, including NO and NO₂, 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 also reduce atmospheric carbon dioxide concentrations by fertilizing the biosphere.²⁴

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).²⁵

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 (SO₂), 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.²⁶ Although the indirect climate effects of aerosols are uncertain, some preliminary evidence points to an indirect cooling effect due to cloud formation.²⁷

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. For example, among the "Kyoto gases," carbon dioxide is the most prominent in terms of emissions, atmospheric concentration, and radiative forcing, but it is among the least effective as a greenhouse gas. Other compounds, on a gram-per-gram basis, appear to have much greater effects.

²¹Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 43.

²²Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 43.

²³Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 44.

²⁴Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 44.

²⁵Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.7(a), p. 258.

²⁶Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 45.

²⁷Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Summary for Policymakers* (Cambridge, UK: Cambridge University Press, 2001), p. 45.

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 a given gas relative to carbon dioxide over a specific time horizon. Over the past decade, 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*,²⁸ and subsequently updated in *Climate Change 1995*²⁹ and *Climate Change 2001*.³⁰

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.³¹ The uncertainty takes several forms:

- The radiative efficiencies of greenhouse gases do not necessarily stay constant over time (as calculated in 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 3 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 "CO₂ 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 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.³²

²⁸Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

²⁹Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

³⁰Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

³¹Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 385-386.

³²Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 387-390.

Table 3. 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 ₂ F ₆) | 10,000 | 8,000 | 11,900 | 18,000 |
| Sulfur Hexafluoride (SF ₆) | 3,200 | 15,100 | 22,200 | 32,400 |

^aNo 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.

International Developments in Global Climate Change

Rising concentrations of carbon dioxide in the atmosphere were first detected in the early 1960s, and observations of atmospheric concentrations of methane, nitrous oxide, and other gases began in the late 1970s. Concern about the effects of rising atmospheric concentrations of greenhouse gases remained largely the province of atmospheric scientists and climatologists, however, until the mid-1980s, when a series of international scientific workshops and conferences began to move the topic onto the agenda of United Nations specialized agencies, particularly, the World Meteorological Organization (WMO).

The IPCC was established under the auspices of the United Nations Environment Program and the WMO in late 1988, to accumulate available scientific research on climate change and to provide scientific advice to policymakers. A series of international conferences provided impetus for an international treaty aimed at limiting the human impact on climate. In December 1990, the United Nations established the Intergovernmental

Negotiating Committee (INC) for a Framework Convention on Climate Change. Beginning in 1991, the INC hosted a series of negotiating sessions that culminated in the adoption, by more than 160 countries, including the United States, of the Framework Convention on Climate Change (FCCC), opened for signature at the “Earth Summit” in Rio de Janeiro, Brazil, on June 4, 1992.³³

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.*³⁴

The Framework Convention divided its signatories into two groups: the countries listed in Annex I, and all others (Annex II). 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

³³The 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.

³⁴The official text of the Framework Convention can be found at web site www.unfccc.de/index.html.

with economies in transition (Russia, Ukraine, and Eastern Europe).³⁵

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.

In April 1993, President Clinton committed to stabilizing U.S. emissions of greenhouse gases at the 1990 level by 2000, using an array of voluntary measures. In the following years, however, greenhouse gas emissions in the United States and many other Annex I countries continued to increase. The climate negotiators, continuing to meet as “the Conference of the Parties [to the Framework Convention]” (COP), took up the question of how to limit emissions in the post-2000 period, a topic on which the Framework Convention was silent. In 1995, COP-1, held in Berlin, Germany, agreed to begin negotiating a post-2000 regime. In 1996, COP-2, held in Geneva, Switzerland, agreed that the regime would encompass binding limitations on emissions for the parties, to be signed at COP-3, which was to be held in Kyoto, Japan, in December 1997.

The Kyoto Protocol

The most fundamental feature of the Kyoto Protocol to the Framework Convention, adopted on December 11, 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.³⁶ 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.³⁷ 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 (such as the EU) may band together to reallocate national targets within the group, so long as the collective target is met.
 - **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 when 55 countries and Annex I signatories with carbon dioxide emissions totaling 55 percent of total

³⁵The 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 if the Kyoto Protocol enters into force.

³⁶The text of the Kyoto Protocol can also be found at web site www.unfccc.de/index.html.

³⁷Several Eastern European states have been permitted to use emissions from the late 1980s, rather than 1990, as their baseline.

Annex I emissions “have deposited their instruments of ratification, acceptance, approval, or accession.” As of September 5, 2003, 117 countries have ratified or acceded to the Protocol. The Annex I nations that have ratified the Protocol represent 44.2 percent of total Annex I carbon dioxide emissions in 1990.³⁸

The U.S. Government formally signed the Kyoto Protocol on November 12, 1998. Under the U.S. Constitution, however, the Government may adhere to treaties only with the “advice and consent” of the Senate.³⁹ 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.”⁴⁰

U.S. Climate Change Initiatives

As an alternative to the Kyoto Protocol, President Bush committed the U.S. Government to pursue a broad range of strategies to address the issues of global climate change by launching three initiatives: the Climate Change Research Initiative to accelerate science-based climate change policy development; the National Climate Change Technology Initiative to advance energy and sequestration technology development; and increased international cooperation to engage and support other nations on climate change and clean technologies.⁴¹

Details of these initiatives were provided on February 14, 2002, when the President announced the Global Climate Change Initiative. This initiative calls on the United States to reduce its greenhouse gas intensity (total greenhouse gas emissions per unit of Gross Domestic Product) by 18 percent between 2002 and 2012 by voluntary measures. Under the Global Climate Change Initiative, the President directed the Secretary of Energy to propose improvements in the Department of Energy’s Voluntary Reporting of Greenhouse Gases Program. The improvements are to be designed to

enhance the measurement accuracy, reliability and verifiability of emissions reductions reported to the Program. Reforms to the Program are to ensure that businesses and individuals that register reductions will not be penalized under any future climate policy, and to give transferable credits to companies that can show real emissions reductions.^{42,43}

On February 12, 2003, the U.S. Department of Energy, on behalf of President Bush, launched the President’s “Climate VISION” (Voluntary Innovative Sector Initiatives: Opportunities Now). Climate VISION is a voluntary, public-private partnership to pursue cost-effective initiatives to reduce the projected growth in U.S. greenhouse gas emissions. Climate VISION, to be administered through the Department of Energy, is intended to help meet the President’s goal of reducing U.S. greenhouse gas intensity by 18 percent by 2012.

Climate VISION involves Federal agencies, including the Department of Energy, Environmental Protection Agency, Department of Agriculture, and Department of Transportation, working with industrial partners to voluntarily reduce greenhouse gas emissions over the next decade. Industry groups making commitments include the Alliance of Automobile Manufacturers, Aluminum Association, American Chemistry Council, American Forest and Paper Association, American Iron and Steel Institute, American Petroleum Institute, American Public Power Association, Association of American Railroads, Business Roundtable, Edison Electric Institute, Electric Power Supply Association, Magnesium Coalition and the International Magnesium Association, National Mining Association, National Rural Electric Cooperative Association, Nuclear Energy Institute, Portland Cement Association, and Semiconductor Industry Association.

In July 2003, the Bush Administration also announced the U.S. Climate Change Strategic Plan. The Plan, to be implemented by the U.S. Climate Change Science Program, will organize the Federal Government’s climate change science research system, fund global climate observation research, and address some of the most complex questions and problems dealing with

³⁸See web site www.unfccc.int/resource/kpthermo.html.

³⁹Article II, Section 2, of the Constitution reads, in part: “He [the President] shall have power, by and with the advice and consent of the Senate, to make treaties, provided two thirds of the Senators present concur”

⁴⁰Letter from President Bush To Senators Hagel, Helms, Craig, and Roberts, Office of the Press Secretary, The White House (March 13, 2001).

⁴¹Remarks by President Bush on Global Climate Change, Office of the Press Secretary, The White House (June 11, 2001).

⁴²“President Announces Clear Skies & Global Climate Change Initiatives” web site www.whitehouse.gov/news/releases/2002/02/20020214-5.html (February 14, 2002).

⁴³Letter to President Bush from Secretary of Energy Spencer Abraham and Secretary of Commerce Donald L. Evans, “Reporting on Progress with the Climate Change Science and Technology Program,” web site www.climate-science.gov/Library/climateletter.htm (September 9, 2002).

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

From 2001 to 2002, the greenhouse gas intensity of the U.S. economy fell from 747 to 731 metric tons per million 1996 dollars of GDP (2.1 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 3.1 percent in the 1960s to 23.1 percent in the 1980s. From 1990 to 2002, total U.S. greenhouse gas intensity fell by 21.4 percent, at an average rate of 2 percent per year.

Historical Growth Rates for U.S. Carbon Intensity

| Decade | Overall Change in Intensity (Percent) | | Average Annual Change in Intensity (Percent) | |
|----------------|---------------------------------------|-----------|--|-----------|
| | Carbon Dioxide | Total GHG | Carbon Dioxide | Total GHG |
| History | | | | |
| 1950-1960 | -12.9 | — | -1.4 | — |
| 1960-1970 | -3.1 | — | -0.3 | — |
| 1970-1980 | -18.1 | — | -2.0 | — |
| 1980-1990 | -23.1 | -18.3 | -2.6 | -2.0 |
| 1990-2000 | -15.2 | -17.9 | -1.6 | -2.0 |

Source: Energy Information Administration, *Annual Energy Review 2002*, DOE/EIA-0384(2002) (Washington, DC, October 2003), 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 82 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.

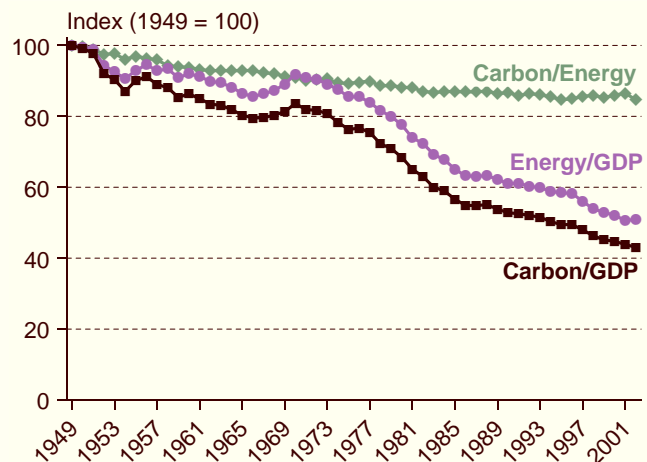
The carbon intensity of the economy can largely be decomposed into two basic elements: (1) energy intensity, defined as the amount of energy consumed per dollar of economic activity; and (2) carbon intensity of energy supply, defined as the amount of carbon emitted per unit of energy. As illustrated 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:

$$\text{Energy Intensity} \times \text{Carbon Intensity of Energy Supply} = \text{Carbon Intensity of the Economy}$$

or, algebraically,

$$\left(\frac{\text{Energy}}{\text{GDP}}\right) \times \left(\frac{\text{Carbon Emissions}}{\text{Energy}}\right) = \left(\frac{\text{Carbon Emissions}}{\text{GDP}}\right)$$

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 1949 until about the mid-1990s, after which it has remained relatively unchanged. The primary reason

(continued on page 14)

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; however, with nuclear generation projected to plateau between 2005 and 2015, this trend is expected to stabilize. 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.

long-term global climate variability and change. The Plan outlines the U.S. strategy for developing knowledge of variability and change in climate and related environmental and human systems.⁴⁴

Beyond the Kyoto Protocol

Since the signing of the Kyoto Protocol, the signatories have continued to shape the “work in progress.” At the fourth session of the Conference of the Parties (COP-4) in Buenos Aires, Argentina, in November 1998, a plan of action was adopted to finalize a number of the implementation issues of the Protocol. Negotiations at the fifth Conference of the Parties (COP-5) in Bonn, Germany, from October 25 through November 5, 1999, focused on developing rules and guidelines for emissions trading, joint implementation, and a Clean Development Mechanism (CDM), negotiating the definition and use of forestry activities and additional sinks, and understanding the basics of a compliance system, with an effort to complete this work at the sixth Conference of the Parties (COP-6) at The Hague, Netherlands, in November 2000.

The major goals of the COP-6 negotiations were to develop the concepts in the Protocol in sufficient detail that the Protocol could be ratified by enough Annex I countries to be put into force, and to encourage significant action by the non-Annex I countries to meet the objectives of the Framework Convention.⁴⁵ The COP-6 negotiations focused on a range of technical issues, including emissions reporting and review, communications by non-Annex I countries, technology transfer, and assessments of capacity needs for developing countries and countries with economies in transition.

The COP-6 negotiations were suspended in November 2000 without agreement on a number of issues, including the appropriate amount of credit for carbon sinks, such as forests and farmlands, and the use of flexible mechanisms, such as international emissions trading

and the CDM, to reduce the cost of meeting the global emissions targets.⁴⁶

The COP-6 negotiations resumed in Bonn, Germany, on July 16, 2001 (COP-6 Part 2), again to focus on developing the concepts in the Protocol in sufficient detail that it could be ratified by enough Annex I countries to be put into force. On July 23, 2001, 178 members/nations of the United Nations Framework Convention on Climate Change reached an agreement (the “Bonn Agreement”) on the operational rulebook for the Kyoto Protocol.

The “Bonn Agreement” creates a Special Climate Change Fund and a Protocol Adaptation Fund to help developing countries adapt to climate change impacts, obtain clean technologies, and limit the growth in their emissions; allows developed nations to use carbon sinks to comply, in part, with their Kyoto Protocol emission reduction commitments; and establishes rules for the CDM, emissions trading, and Joint Implementation projects. The Bonn Agreement also emphasizes that domestic actions shall constitute a significant element of emission reduction efforts made by each Party and, also, establishes a Compliance Committee with a facilitative branch and an enforcement branch. In terms of compliance, for every ton of gas that a country emits over its target, it will be required to reduce an additional 1.3 tons during the Protocol’s second commitment period, which starts in 2013.

The Bonn Agreement was forwarded for official adoption at the Seventh Session of the Conference of the Parties (COP-7), which was held in Marrakech, Morocco, from October 29 to November 9, 2001. On November 9, 2001, 165 nations reached agreement on a number of implementation rules for the Bonn Agreement and the Kyoto Protocol. The agreement, referred to as the “Marrakech Accords,” covered a number of issues, including: (1) rules for international emissions trading; (2) a compliance regime to enforce emissions targets, with the issue of legally binding targets deferred to a future Conference; (3) fungible accounting rules that

⁴⁴The U.S. Climate Change Science Program, *Vision for the Program and Highlights of the Scientific Strategic Plan* (Washington, DC, July 2003), web site www.climatechange.gov/Library/stratplan2003/default.htm.

⁴⁵See U.N. Framework Convention on Climate Change, web site <http://cop6.unfccc.int/media/press.html>.

⁴⁶“U.N. Conference Fails to Reach Accord on Global Warming,” *New York Times* (November 26, 2000).

allow emissions trading among Annex I nations, as well as CDM and Joint Implementation mechanisms; and (4) a new emission unit for carbon sinks that cannot be banked for future commitment periods.⁴⁷

COP-8 met from October 23 to November 1, 2002, in New Delhi, India.⁴⁸ COP-8 focused on technical issues related to the development of rules for Clean Development Mechanisms, reporting guidelines, and compliance under the Kyoto Protocol. In addition, COP-8 adopted guidance for funds managed by the Global Environmental Facility to be used in assisting developing countries. COP-9 is scheduled for December 1-12, 2003, in Milan, Italy.

The Bush Administration has indicated that it has no objection to the participation of other countries in the Kyoto Protocol, even without U.S. participation. As mentioned above, the Administration has indicated that it intends to develop U.S. alternatives to the Kyoto Protocol, including the National Climate Change Technology Initiative, the Climate Change Research Initiative, and the Global Climate Change Initiative. As noted earlier, the Protocol can enter into force with ratification by at least 55 parties to the Protocol, accounting for 55 percent of total Annex I carbon dioxide emissions in 1990. Because the United States accounts for about 35 percent of 1990 Annex I carbon dioxide emissions, the Protocol can enter into force without U.S. ratification.

⁴⁷Pew Center on Global Climate Change, "Climate Talks in Marrakech—COP 7: Update, November 9, 2001—Final Analysis," web site www.pewclimate.org/cop7/update_110901.cfm.

⁴⁸United Nations Framework Convention on Climate Change, Press Release, "Governments Ready to Ratify Kyoto Protocol" (November 10, 2001), web site <http://unfccc.int/press/prel2001/pressrel101101.pdf>.

2. Carbon Dioxide Emissions

Overview

U.S. Anthropogenic Carbon Dioxide Emissions, 1990-2002

| | Carbon Dioxide | Carbon Equivalent |
|--|----------------|-------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 5,795.6 | 1,580.6 |
| Change Compared to 2001 (Million Metric Tons) | 47.2 | 12.9 |
| Change from 2001 (Percent) | 0.8% | 0.8% |
| Change Compared to 1990 (Million Metric Tons) | 789.5 | 215.3 |
| Change from 1990 (Percent) | 15.8% | 15.8% |
| Average Annual Increase, 1990-2002 (Percent) | 1.2% | 1.2% |

Total emissions of carbon dioxide in the United States and its territories were 5,795.6 million metric tons in 2002, 47.2 million metric tons (0.8 percent) more than the 2001 total (Tables 4 and 5). The increase in emissions from 2001 to 2002 can be attributed in large part to an increase in overall U.S. economic growth of 2.4 percent in 2002, colder winter weather that increased the demand for heating fuels, and an increase in electricity demand influenced by a hotter summer than the year before. The increase in emissions from 2001 to 2002 follows a decrease of 1.8 percent, or 105.7 million metric tons, from 2000 to 2001 (Figure 1). Since 1990, total U.S. carbon dioxide emissions have increased by an average of about 1.2 percent per year. As discussed below, factors such as a drop in carbon intensity in the electric power sector kept emissions growth in 2002 to less than the average annual growth rate since 1990.

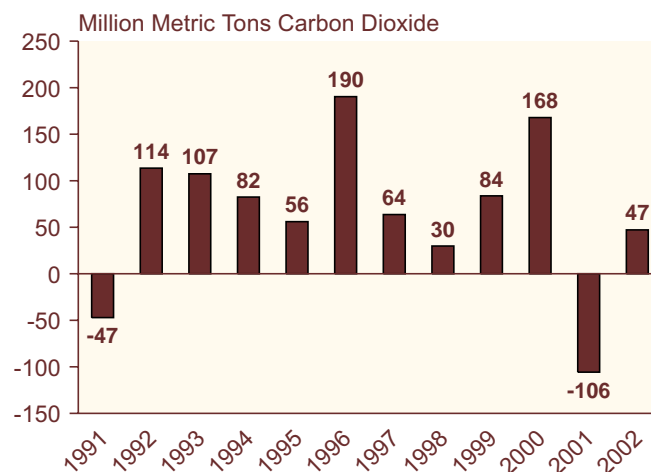
In the United States, most carbon dioxide (98 percent) is emitted as the result of the combustion of fossil fuels; consequently, carbon dioxide emissions and energy use are highly correlated. Historically, economic growth, the weather, the carbon and energy intensity of the economy, and movements in energy prices have caused year-to-year fluctuations in energy consumption and resulting carbon dioxide emissions. Annual economic growth in 2002 (2.4 percent) was considerably higher

than in 2001 (0.3 percent). In addition, there were both a colder winter and a hotter summer in 2002 than in 2001. The colder winter led to increased demand for heating fuels, such as natural gas and distillate fuel, and the hotter summer led to increased demand for electricity for air conditioning.

The increased demand for natural gas as a heating fuel can be seen in the residential and commercial sectors (Tables 6 and 7), 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 6), emissions of carbon dioxide increased by 2.8 percent, from 1,160.8 million metric tons of carbon dioxide in 2001 to 1,193.0 million metric tons in 2002. In the commercial sector (Table 7), carbon dioxide emissions decreased by 0.5 percent (from 1,018.3 million metric tons in 2001 to 1,012.9 million metric tons in 2002). Because commercial sector emissions are dominated by the sector's share of electricity generation, a decrease in the carbon intensity of electricity generation is the principal reason for the decrease in emissions.

Industrial production declined by 0.7 percent in 2002, following a 3.5-percent decline in 2001. Industrial emissions of carbon dioxide also fell by 0.7 percent, from 1,685.3 million metric tons in 2001 to 1,673.7 million metric tons in 2002 (Table 8). Of the six most energy-intensive manufacturing industries, two (primary metals and paper) had declines in output in 2002 compared with 2001 (3.0 percent and 2.3 percent, respectively).

Figure 1. Annual Change in U.S. Carbon Dioxide Emissions, 1990-2002



Source: Estimates presented in this chapter.

Output from the four other energy-intensive industries increased: chemicals by 3.9 percent, nonmetallic minerals by 1.0 percent, and food and petroleum refining both by 0.5 percent. Unlike 2001, when all of the decline in industrial output was attributable to the energy-intensive industries, 2002 saw a 1.5-percent decline in output from computer and electronic products—the first decline in 17 years. Estimates for 2002 indicate that carbon dioxide emissions in the transportation sector (Table 9) increased by 1.2 percent, from 1,827.3 million metric tons in 2001 to 1,849.7 million metric tons in 2002.

Net generation of electricity increased by 2.7 percent from 2001 to 2002, and total carbon dioxide emissions from the electric power sector increased by 1.0 percent, from 2,226.6 million metric tons in 2001 to 2,249.0 million metric tons in 2002 (Table 10). Accordingly, the overall carbon intensity of U.S. electricity production dropped by 1.6 percent. 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 299.3 million metric tons carbon dioxide equivalent in 2002, an increase of 6.5 million metric tons (2.2 percent) from 2001 (Table 11).⁴⁹ 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 19.8 million metric tons was emitted as carbon dioxide from the burning of the plastic components of municipal solid waste as well as other waste burning in 2001. The 2001 estimate of 19.8 million metric tons is used in this report as an estimate for 2002 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 0.7 percent, from 112.8 million metric tons in 2001 to 113.6 million metric tons in 2002 (Table 4).

⁴⁹Unlike 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.

Energy Consumption

Energy End-Use Sector Sources of U.S. Carbon Dioxide Emissions, 1990-2002

| Sector | Million Metric Tons Carbon Dioxide | | Percent Change | |
|----------------|------------------------------------|---------|----------------|-----------|
| | 1990 | 2002 | 1990-2002 | 2001-2002 |
| Residential | 950.8 | 1,193.0 | 25.5% | 2.8% |
| Commercial | 779.5 | 1,012.9 | 29.9% | -0.5% |
| Industrial | 1,688.8 | 1,673.7 | -0.9% | -0.7% |
| Transportation | 1,569.5 | 1,849.7 | 17.9% | 1.2% |

Note: Electric utility 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 2002 U.S. carbon dioxide emissions (adjusting for U.S. Territories and bunker fuels), 98.0 percent, or 5,682.0 million metric tons of carbon dioxide, resulted from the combustion of fossil fuels. This figure represents an increase of 0.8 percent from 2001 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 each sector (Table 5). Electricity-related emissions that are allocated across the end-use sectors include emissions from integrated electric utilities and emissions from nonutility power producers (including independent power producers and industrial CHP plants)

whose primary business is the production and sale of electricity.

Residential Sector

At 1,193.0 million metric tons, residential carbon dioxide emissions represented 20.8 percent of U.S. energy-related carbon dioxide emissions in 2002. The residential sector's pro-rated share of electric power sector emissions accounts for more than two-thirds of that amount (820.7 million metric tons).⁵⁰ Petroleum (mainly distillate fuel oil) accounted for 8.7 percent and natural gas 22.4 percent. Since 1990, residential electricity-related emissions have grown by 2.5 percent annually. In contrast, emissions from the direct combustion of fuels, primarily natural gas, in the residential sector have grown by 0.9 percent annually since 1990.

Total carbon dioxide emissions from the residential sector increased by 2.8 percent in 2002 (Table 6). 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 2002, relative to 2001, was a contributor to the 2002 increase in residential sector emissions.

Since 1990, the growth in carbon dioxide emissions attributable to the residential sector has averaged 1.9 percent per year. Residential sector emissions in 2002 were 242.2 million metric tons higher than in 1990, representing 32.7 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 the Sunbelt tends to increase summer air conditioning consumption and promote the use of electric heat pumps, which increases indirect emissions from electricity use (although the increase could be offset by a reduction in direct 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 1,012.9 million metric tons, account for about 17.7 percent of

total energy-related carbon dioxide emissions, of which 77.2 percent (781.8 million metric tons) is the sector's pro-rated share of electricity-related emissions. Petroleum contributes 5.2 percent and natural gas 16.7 percent of the sector's emissions. Commercial sector emissions largely have their origin in the space heating and cooling requirements of structures such as office buildings. Lighting is a more important component of commercial energy demand than it is in the residential sector. Thus, although commercial sector emissions are strongly affected by the weather, they are affected less 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 decreased by 1.2 percent in 2002, while emissions from the direct combustion of fuels (dominated by natural gas, as in the residential sector) increased by 1.7 percent. Overall, carbon dioxide emissions related to commercial sector activity decreased by 0.5 percent—from 1,018.3 to 1,012.9 million metric tons—between 2001 and 2002 (Table 7). 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 233.4 million metric tons since 1990, accounting for 31.5 percent of the total increase in U.S. energy-related carbon dioxide emissions.

Industrial Sector

Industrial sector emissions, at 1,673.7 million metric tons of carbon dioxide, accounted for 29.2 percent of total U.S. energy-related carbon dioxide emissions in 2002. In terms of fuel shares, electricity consumption was responsible for 38.4 percent of total industrial sector emissions (643.1 million metric tons), natural gas for 25.9 percent (432.7 million metric tons), petroleum for 24.7 percent (412.8 million metric tons), and coal for 10.7 percent (179.4 million metric tons).

Estimated 2002 energy-related carbon dioxide emissions in the industrial sector, at 1,673.7 million metric tons (Table 8), were 0.7 percent lower than the 2001 emissions level of 1,685.3 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

⁵⁰Sectoral (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.

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. This industrial subsector, which excludes agriculture, mining, and construction, accounts for 84 percent of both industrial energy-related carbon dioxide emissions and industrial energy consumption. The table below shows estimates of energy-related carbon dioxide emissions from the manufacturing subsector 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 21 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 1996 dollars). That ratio (C/Y) is calculated as the product of the subsector's *aggregate carbon dioxide emission coefficient*—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:

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

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 emission coefficient (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 carbon intensity of manufacturing (C/Y) is a combination of the energy intensity of manufacturing output and the carbon emission coefficient of the fuels consumed to meet manufacturing energy demand.^a

The overall carbon intensity of the manufacturing subsector (C/Y) fell by 12.9 percent from 1991 to 1998; however, the reduction was largely the result of a structural shift 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

(continued on page 21)

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 Dioxide Emission Coefficient (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 |

^aStandard Industrial Classification.

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

^aThe 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

| Fuel Type | SIC ^a Code | | | | | | Other Mfg. | Total |
|--|-----------------------|--------------|--------------|--------------|-------------|-------------|--------------|----------------|
| | 29 | 28 | 33 | 26 | 20 | 32 | | |
| 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 |

^aStandard Industrial Classification.

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 22)

Energy-Related Carbon Dioxide Emissions in Manufacturing (Continued)

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 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 dioxide emission coefficient (*C/E*). Overall, manufacturing industries had aggregate carbon dioxide coefficients of 50.92 and 49.42 million metric tons carbon dioxide equivalent per quadrillion Btu for 1991 and 1998, respectively; however, the carbon dioxide factors of the various industries differed markedly.

The petroleum and chemical industries both transform some energy fuel 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 coefficients 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 carbon dioxide emission coefficient, 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 emission coefficient: 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, 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,^b decomposition analysis suggests an *increase* in energy intensity across the manufacturing sector of 0.7 percent from 1991 to 1998.

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

| Industry Group | SIC ^a Code | 1991 | | | 1998 | | | Percent Change, 1991-1998 | | |
|---|-----------------------|------------|--------------|--------------|------------|--------------|--------------|---------------------------|-------------|--------------|
| | | <i>E/Y</i> | <i>C/E</i> | <i>C/Y</i> | <i>E/Y</i> | <i>C/E</i> | <i>C/Y</i> | <i>E/Y</i> | <i>C/E</i> | <i>C/Y</i> |
| 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 | — | — |

^aStandard Industrial Classification.

Notes: *E/Y* = energy consumed (thousand Btu) per constant 1996 dollar value of shipments. *C/E* = million metric tons CO₂ emitted per quadrillion Btu of energy consumed. *C/Y* = metric tons CO₂ 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).

^bThere 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.

emissions in 2002 were 0.9 percent (15.1 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 22.5 million short tons in 2002. Other industrial coal consumption declined from 76.3 million short tons in 1990 to 63.1 million short tons in 2002. 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 1,849.7 million metric tons, accounted for 32.3 percent of total U.S. energy-related carbon dioxide emissions in 2002. Almost all (97.9 percent) of transportation sector emissions result from the consumption of petroleum products: motor gasoline, at 61.6 percent of total transportation sector emissions; middle distillates (diesel fuel) at 20.5 percent; jet fuel at 12.7 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 1.2 percent in 2002, from 1,827.3 to 1,849.7 million metric tons of carbon dioxide (Table 9). 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 1,138.7 million metric tons of carbon dioxide, grew by 2.5 percent. 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 280.2 million metric tons, representing 37.8 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

The data in Table 10 represent estimates of carbon dioxide emissions for the electric power sector. These emissions when taken as a whole account for 39.3 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

Electric Power Sector Carbon Dioxide Emissions by Fuel Input, 1990-2002

| Fuel | Million Metric Tons Carbon Dioxide | | Percent Change | |
|-------------|--|---------|-------------------|---------------|
| | 1990 | 2002 | 1990- 2002 | 2001- 2002 |
| Petroleum | 99.2 | 72.2 | -27.3% | -27.5% |
| Natural Gas | 176.0 | 299.1 | 70.0% | 3.4% |
| Coal | 1,519.4 | 1,874.7 | 23.4% | 2.2% |
| Total | 1,795.5 | 2,249.0 | 25.3% | 1.0% |

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 (22.4 million metric tons), from 2,226.6 million metric tons in 2001 to 2,249.0 million metric tons in 2002 (Table 10). Emissions from natural-gas-fired generation increased by 3.4 percent, emissions from coal-fired generation increased by 2.2 percent, and emissions from petroleum-fired generation decreased by 27.5 percent. Carbon dioxide emissions from the electric power sector have grown by 25.3 percent since 1990, while total carbon dioxide emissions have grown by 14.8 percent.

Nonfuel Use of Energy Inputs

In 2002, carbon sequestration through nonfuel uses of fossil fuels totaled 299.3 million metric tons carbon dioxide equivalent (Table 11). The vast majority was sequestered in petroleum-based products (280.2 million metric tons carbon dioxide equivalent), with smaller amounts in natural-gas-based products (17.3 million metric tons) and coal-based products (1.8 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 2002 was 2.2 percent higher than in 2001, when 292.8 million metric tons carbon dioxide equivalent was sequestered. Since 1990, the annual sequestration of carbon in this manner has increased by 47.4 million metric tons or 18.8 percent. This translates to an average annual growth rate of 1.4 percent.

Carbon Dioxide Emissions and Economic Growth

Between 1990 and 2002, U.S. economic growth averaged 2.9 percent per year. Energy-related carbon dioxide emissions, however, grew by an average of 1.2 percent annually. As shown in Figure 2, U.S. energy intensity (energy consumed per dollar of GDP) fell by an average of 1.6 percent per year from 1990 to 2002. The carbon dioxide intensity of energy use (emissions per unit of energy consumed) has remained roughly at the 1990 level. Thus, it is the use of less energy per unit of economic output, not the use of low-carbon fuels, that has kept the growth rate of carbon dioxide emissions equal to about half the growth rate of GDP.

The decrease in the energy intensity of the U.S. economy has resulted, in part, from an increase in the non-energy-intensive sectors of the economy relative to the traditional energy-intensive manufacturing industries, as well as energy efficiency improvements. Economic growth does, however, have an indirect effect on emissions, in that consumers with more disposable income use more energy services (such as travel) and tend to live in larger houses. On the other hand, such income effects can be offset somewhat by more energy-efficient vehicles, building shells, appliances, and heating and cooling equipment. It is expected that the trend of increasing energy efficiency will continue in the future, further reducing the carbon intensity of the U.S. economy (carbon dioxide equivalent emissions of greenhouse gases per unit of GDP) at an average rate of 1.5 percent per year from 2001 through 2025.⁵¹

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."

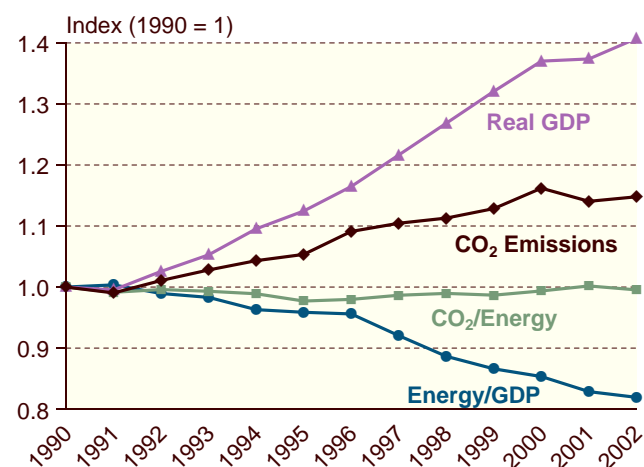
U.S. Territories

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 2002, total energy-related carbon dioxide emissions from the U.S. Territories are estimated at 42.9 million metric tons (Table 4).

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

Figure 2. Growth in U.S. Carbon Dioxide Emissions and GDP, Energy Intensity of GDP, and Carbon Dioxide Intensity of Energy Use, 1990-2002



Sources: Energy Information Administration, *Annual Energy Review 2001*, DOE/EIA-0384(2001) (Washington, DC, November 2002), Tables 1.1 and E1; and estimates presented in this chapter.

⁵¹Energy Information Administration, *Annual Energy Outlook 2003*, DOE/EIA-0383(2003) (Washington, DC, January 2003).

subtracted from the total, because they are also considered international bunker fuels under this definition.

For 2001, the carbon dioxide emissions estimate for military bunker fuels was 8.1 million metric tons.⁵² In 2002, approximately 90.2 million metric tons of carbon dioxide was emitted in total from international bunker fuels, including 82.1 million metric tons attributed to civilian consumption of bunker fuels. The total amount is subtracted from the U.S. total in Table 4. 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, 1990-2002

| | |
|--|-------|
| Estimated 2002 Emissions (Million Metric Tons Carbon Dioxide) | 113.6 |
| Change Compared to 2001 (Million Metric Tons Carbon Dioxide) | 0.7 |
| Change from 2001 (Percent) | 0.7% |
| Change Compared to 1990 (Million Metric Tons Carbon Dioxide) | 13.4 |
| Change from 1990 (Percent) | 13.3% |

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 2002, about 5.1 million metric tons of carbon dioxide was emitted in this way (Table 4).

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 18.1 million metric tons in 2002 (Table 4). Data on additional energy production sources that are excluded from this report are available in Energy Information Administration, *Documentation: Emissions of Greenhouse Gases in the United States 2002* (to be published).

Industrial Process Emissions

Industrial emissions of carbon dioxide not caused by the combustion of fossil fuels accounted for only 1.2 percent (70.6 million metric tons) of total U.S. carbon dioxide emissions in 2002 (Table 4). 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 2002 were 70.6 million metric tons (17.5 percent) higher than in 1990 and 1.4 million metric tons (2.1 percent) higher than in 2001 (Table 12). Sixty-one 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 2002, the United States manufactured an estimated 89.0 million metric tons of cement, resulting in the direct release of 43.3 million metric tons of carbon dioxide into the atmosphere. This calculation is independent of the carbon dioxide released by the production of energy consumed in making cement. The estimate for 2002 represents an increase in carbon dioxide emissions of 9.9 million metric tons (29.8 percent) compared with 1990 and an increase of about 1.8 million metric tons (4.4 percent) compared with 2001.

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

⁵²Data for 2002 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.

Carbon Dioxide Emissions

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 27.4 million metric tons of carbon dioxide was released in emissions from these other industrial process sources in 2002.

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 11. 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 19.8 million metric tons of carbon dioxide, as calculated by the U.S. EPA, with the most recent estimate being for 2001. The 2001 value has been used as an estimate for 2002.

Table 4. U.S. Carbon Dioxide Emissions from Energy and Industry, 1990-2002
(Million Metric Tons Carbon Dioxide)

| Fuel Type or Process | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|---|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Energy Consumption | | | | | | | | | | | | | |
| Petroleum | 2,177.7 | 2,123.4 | 2,173.9 | 2,168.1 | 2,211.5 | 2,193.8 | 2,277.6 | 2,295.4 | 2,347.2 | 2,415.1 | 2,439.4 | 2,457.8 | 2,452.7 |
| Coal | 1,783.9 | 1,768.1 | 1,781.2 | 1,847.3 | 1,858.4 | 1,876.5 | 1,958.8 | 2,002.5 | 2,016.0 | 2,019.3 | 2,112.0 | 2,041.9 | 2,070.1 |
| Natural Gas | 1,026.1 | 1,048.4 | 1,086.4 | 1,112.1 | 1,133.7 | 1,184.4 | 1,206.1 | 1,211.8 | 1,188.1 | 1,194.9 | 1,244.3 | 1,189.0 | 1,203.4 |
| Renewables ^a | 0.9 | 1.0 | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 2.9 | 3.0 | 3.0 |
| Energy Subtotal | 4,988.6 | 4,941.0 | 5,042.7 | 5,128.6 | 5,204.7 | 5,255.8 | 5,443.7 | 5,510.9 | 5,552.5 | 5,630.5 | 5,798.6 | 5,691.7 | 5,729.3 |
| Adjustments to Energy | | | | | | | | | | | | | |
| U.S. Territories (+) | 30.9 | 35.4 | 35.6 | 39.7 | 40.1 | 42.2 | 43.9 | 45.2 | 46.9 | 43.7 | 42.2 | 41.5 | 42.9 |
| Military Bunker Fuels (-) | 13.6 | 13.1 | 11.7 | 11.0 | 9.5 | 8.9 | 8.9 | 9.6 | 10.0 | 9.8 | 7.8 | 8.1 | 8.1 |
| International Bunker Fuels (-) | 100.1 | 106.7 | 98.1 | 88.6 | 88.4 | 91.9 | 93.3 | 100.1 | 104.9 | 97.4 | 93.5 | 89.6 | 82.1 |
| Total Energy Adjustments | -82.7 | -84.3 | -74.2 | -59.9 | -57.8 | -58.6 | -58.2 | -64.6 | -68.0 | -63.5 | -59.1 | -56.2 | -47.3 |
| Adjusted Energy Subtotal | 4,905.9 | 4,856.7 | 4,968.5 | 5,068.7 | 5,146.9 | 5,197.2 | 5,385.4 | 5,446.4 | 5,484.5 | 5,567.0 | 5,739.5 | 5,635.5 | 5,682.0 |
| Other Sources | | | | | | | | | | | | | |
| Gas Flaring | 9.1 | 10.3 | 10.2 | 13.7 | 13.8 | 17.2 | 16.5 | 15.5 | 6.2 | 6.7 | 5.5 | 5.2 | 5.1 |
| CO ₂ in Natural Gas | 14.0 | 14.5 | 15.4 | 16.3 | 17.0 | 16.7 | 17.8 | 18.0 | 18.0 | 17.8 | 18.2 | 18.6 | 18.1 |
| Cement Production | 33.3 | 32.5 | 32.8 | 34.7 | 36.8 | 36.9 | 37.2 | 38.4 | 39.3 | 40.1 | 41.3 | 41.4 | 43.3 |
| Other Industrial | 26.8 | 26.4 | 26.5 | 26.3 | 26.7 | 28.4 | 29.0 | 29.5 | 30.0 | 29.3 | 29.6 | 27.7 | 27.4 |
| Waste Combustion | 17.0 | 18.7 | 19.2 | 20.4 | 21.3 | 22.2 | 23.1 | 24.7 | 24.3 | 25.2 | 19.9 | 19.8 | 19.8 |
| Total Other Sources | 100.2 | 102.4 | 104.1 | 111.3 | 115.6 | 121.3 | 123.4 | 126.2 | 117.9 | 119.1 | 114.5 | 112.8 | 113.6 |
| Total | 5,006.1 | 4,959.0 | 5,072.6 | 5,180.0 | 5,262.5 | 5,318.5 | 5,508.9 | 5,572.5 | 5,602.4 | 5,686.1 | 5,854.0 | 5,748.3 | 5,795.6 |

P = preliminary data.

^aIncludes emissions from electricity generation using municipal solid waste and geothermal energy.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 5. U.S. Carbon Dioxide Emissions from Energy Consumption by End-Use Sector, 1990-2002
(Million Metric Tons Carbon Dioxide)

| End-Use Sector | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Residential | 950.8 | 966.7 | 967.7 | 1,026.7 | 1,020.0 | 1,025.7 | 1,085.3 | 1,076.6 | 1,096.2 | 1,123.9 | 1,169.4 | 1,160.8 | 1,193.0 |
| Commercial | 779.5 | 781.0 | 781.1 | 806.2 | 819.6 | 836.7 | 867.9 | 911.2 | 922.4 | 933.5 | 1,005.9 | 1,018.3 | 1,012.9 |
| Industrial | 1,688.8 | 1,643.9 | 1,723.5 | 1,705.1 | 1,733.5 | 1,732.0 | 1,785.2 | 1,800.4 | 1,776.0 | 1,767.0 | 1,774.1 | 1,685.3 | 1,673.7 |
| Transportation | 1,569.5 | 1,549.4 | 1,570.5 | 1,590.6 | 1,631.7 | 1,661.4 | 1,705.3 | 1,722.7 | 1,757.9 | 1,806.0 | 1,849.2 | 1,827.3 | 1,849.7 |
| Total | 4,988.6 | 4,941.0 | 5,042.7 | 5,128.6 | 5,204.7 | 5,255.8 | 5,443.7 | 5,510.9 | 5,552.5 | 5,630.5 | 5,798.6 | 5,691.7 | 5,729.3 |
| Electric Power | 1,795.5 | 1,792.2 | 1,803.7 | 1,883.6 | 1,908.9 | 1,922.9 | 1,994.0 | 2,061.7 | 2,149.6 | 2,161.9 | 2,269.2 | 2,226.6 | 2,249.0 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 4).

Sources: EIA estimates presented in this chapter.

Table 6. U.S. Carbon Dioxide Emissions from Residential Sector Energy Consumption, 1990-2002
(Million Metric Tons Carbon Dioxide)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|------------------------------------|--------------|--------------|--------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Petroleum | | | | | | | | | | | | | |
| Liquefied Petroleum Gas . . . | 22.5 | 24.0 | 23.6 | 24.6 | 24.4 | 24.9 | 29.2 | 28.4 | 26.7 | 32.9 | 34.8 | 33.0 | 34.9 |
| Distillate Fuel | 70.8 | 67.4 | 70.9 | 70.5 | 69.5 | 65.5 | 67.1 | 63.3 | 55.9 | 59.9 | 65.5 | 65.8 | 65.1 |
| Kerosene | 4.6 | 5.2 | 4.7 | 5.4 | 4.6 | 5.3 | 6.4 | 6.6 | 7.8 | 8.0 | 6.8 | 6.8 | 4.1 |
| Petroleum Subtotal | 97.9 | 96.6 | 99.2 | 100.5 | 98.6 | 95.8 | 102.6 | 98.4 | 90.4 | 100.8 | 107.1 | 105.6 | 104.0 |
| Coal | 2.4 | 2.2 | 2.3 | 2.3 | 2.0 | 1.6 | 1.6 | 1.5 | 1.2 | 1.3 | 1.1 | 1.1 | 1.1 |
| Natural Gas | 238.8 | 248.0 | 255.2 | 269.0 | 263.3 | 263.0 | 284.2 | 270.2 | 246.5 | 256.5 | 270.3 | 259.5 | 267.2 |
| Electricity ^a | 611.7 | 620.0 | 611.0 | 654.9 | 656.1 | 665.4 | 696.9 | 706.5 | 758.1 | 765.3 | 790.8 | 794.6 | 820.7 |
| Total | 950.8 | 966.7 | 967.7 | 1,026.7 | 1,020.0 | 1,025.7 | 1,085.3 | 1,076.6 | 1,096.2 | 1,123.9 | 1,169.4 | 1,160.8 | 1,193.0 |

^aShare 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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 7. U.S. Carbon Dioxide Emissions from Commercial Sector Energy Consumption, 1990-2002
(Million Metric Tons Carbon Dioxide)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|------------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|----------------|----------------|----------------|
| Petroleum | | | | | | | | | | | | | |
| Motor Gasoline | 7.8 | 6.0 | 5.6 | 2.1 | 1.8 | 1.3 | 1.9 | 3.0 | 2.7 | 2.0 | 3.1 | 2.6 | 2.7 |
| Liquefied Petroleum Gas. . . | 4.0 | 4.2 | 4.2 | 4.3 | 4.3 | 4.4 | 5.2 | 5.0 | 4.7 | 5.8 | 6.1 | 5.8 | 6.2 |
| Distillate Fuel. | 38.8 | 37.5 | 36.7 | 35.7 | 36.3 | 34.7 | 35.0 | 32.1 | 31.1 | 31.8 | 35.6 | 36.8 | 36.4 |
| Residual Fuel | 17.9 | 17.3 | 14.8 | 13.5 | 13.4 | 11.0 | 10.7 | 8.7 | 6.6 | 5.7 | 7.1 | 5.4 | 6.0 |
| Kerosene. | 0.8 | 0.9 | 0.8 | 1.0 | 1.4 | 1.6 | 1.5 | 1.8 | 2.2 | 1.9 | 2.1 | 2.2 | 1.3 |
| Petroleum Subtotal | 69.4 | 65.9 | 62.0 | 56.6 | 57.2 | 53.0 | 54.2 | 50.6 | 47.4 | 47.2 | 54.1 | 53.0 | 52.6 |
| Coal. | 12.1 | 11.1 | 11.2 | 11.2 | 11.1 | 11.0 | 11.5 | 12.2 | 8.7 | 9.7 | 8.6 | 9.2 | 9.2 |
| Natural Gas. | 142.6 | 148.5 | 152.6 | 155.3 | 157.3 | 164.3 | 171.3 | 174.3 | 163.5 | 165.2 | 174.3 | 165.0 | 169.4 |
| Electricity ^a | 555.4 | 555.5 | 555.3 | 583.1 | 594.0 | 608.3 | 630.9 | 674.1 | 702.8 | 711.4 | 768.9 | 791.1 | 781.8 |
| Total | 779.5 | 781.0 | 781.1 | 806.2 | 819.6 | 836.7 | 867.9 | 911.2 | 922.4 | 933.5 | 1,005.9 | 1,018.3 | 1,012.9 |

^aShare 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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 Industrial Sector Energy Consumption, 1990-2002
(Million Metric Tons Carbon Dioxide)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Petroleum | | | | | | | | | | | | | |
| Motor Gasoline | 13.0 | 13.6 | 13.7 | 12.7 | 13.6 | 14.1 | 14.0 | 14.9 | 14.0 | 10.6 | 10.5 | 20.7 | 21.3 |
| Liquefied Petroleum Gas . . | 39.8 | 39.8 | 46.0 | 43.9 | 46.9 | 46.2 | 47.3 | 49.2 | 40.2 | 49.2 | 53.4 | 46.7 | 50.4 |
| Distillate Fuel | 83.1 | 77.8 | 79.9 | 80.6 | 80.2 | 81.6 | 85.6 | 86.7 | 87.3 | 85.5 | 86.5 | 93.7 | 92.7 |
| Residual Fuel | 30.3 | 23.6 | 27.9 | 32.7 | 30.7 | 24.2 | 24.1 | 20.5 | 15.7 | 14.0 | 16.6 | 13.6 | 15.1 |
| Asphalt and Road Oil | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Lubricants | 6.8 | 6.1 | 6.2 | 6.4 | 6.6 | 6.5 | 6.3 | 6.7 | 7.0 | 7.1 | 7.0 | 6.4 | 6.3 |
| Kerosene | 0.9 | 0.8 | 0.7 | 0.9 | 1.2 | 1.1 | 1.3 | 1.3 | 1.6 | 0.9 | 1.1 | 1.7 | 1.0 |
| Petroleum Coke | 81.2 | 77.8 | 92.3 | 79.6 | 80.0 | 79.6 | 84.0 | 79.5 | 97.6 | 109.0 | 87.6 | 97.2 | 101.2 |
| Other Petroleum | 125.1 | 114.8 | 133.0 | 112.2 | 122.7 | 112.0 | 130.4 | 135.9 | 123.6 | 127.9 | 115.5 | 130.0 | 124.7 |
| Petroleum Subtotal | 380.3 | 354.3 | 399.8 | 368.9 | 381.9 | 365.5 | 393.0 | 394.7 | 387.0 | 404.3 | 378.2 | 410.0 | 412.8 |
| Coal | 249.5 | 234.8 | 225.7 | 224.8 | 226.1 | 224.3 | 219.0 | 215.3 | 201.2 | 196.6 | 199.5 | 192.7 | 179.4 |
| Coal Coke Net Imports | 0.5 | 0.9 | 3.2 | 2.5 | 5.4 | 5.7 | 3.2 | 5.3 | 7.4 | 6.5 | 7.1 | 4.0 | 5.8 |
| Natural Gas | 432.9 | 439.8 | 459.9 | 465.9 | 464.6 | 490.5 | 506.9 | 507.3 | 495.0 | 477.7 | 483.5 | 441.5 | 432.7 |
| Electricity^a | 625.7 | 614.1 | 634.8 | 643.0 | 655.5 | 646.0 | 663.0 | 677.9 | 685.4 | 682.0 | 705.8 | 637.2 | 643.1 |
| Total | 1,688.8 | 1,643.9 | 1,723.5 | 1,705.1 | 1,733.5 | 1,732.0 | 1,785.2 | 1,800.4 | 1,776.0 | 1,767.0 | 1,774.1 | 1,685.3 | 1,673.7 |

*Less than 50,000 metric tons carbon dioxide.

^aShare of total electric power sector carbon dioxide emissions weighted by sales to the industrial 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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 Transportation Sector Energy Consumption, 1990-2002
(Million Metric Tons Carbon Dioxide)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Petroleum | | | | | | | | | | | | | |
| Motor Gasoline | 955.2 | 950.4 | 964.5 | 986.1 | 997.8 | 1,015.5 | 1,034.0 | 1,042.5 | 1,072.9 | 1,099.9 | 1,105.9 | 1,111.2 | 1,138.7 |
| Liquefied Petroleum Gas . . | 1.3 | 1.2 | 1.1 | 1.2 | 2.0 | 1.0 | 0.9 | 0.8 | 1.0 | 0.8 | 0.7 | 0.8 | 0.8 |
| Jet Fuel | 220.4 | 213.0 | 211.2 | 213.0 | 221.6 | 219.9 | 229.8 | 232.1 | 235.6 | 242.9 | 251.2 | 240.4 | 234.4 |
| Distillate Fuel | 265.1 | 260.8 | 266.8 | 274.9 | 292.0 | 303.8 | 323.7 | 338.4 | 348.4 | 362.2 | 374.0 | 383.2 | 379.0 |
| Residual Fuel | 79.3 | 80.0 | 83.5 | 70.3 | 68.8 | 71.0 | 66.4 | 55.5 | 52.6 | 51.9 | 69.2 | 45.7 | 49.9 |
| Lubricants | 6.5 | 5.8 | 5.9 | 6.0 | 6.3 | 6.2 | 6.0 | 6.3 | 6.6 | 6.7 | 6.6 | 6.0 | 6.0 |
| Aviation Gasoline | 3.1 | 2.9 | 2.8 | 2.6 | 2.6 | 2.7 | 2.6 | 2.7 | 2.4 | 2.7 | 2.5 | 2.4 | 2.3 |
| Petroleum Subtotal | 1,530.9 | 1,514.0 | 1,535.8 | 1,554.1 | 1,591.0 | 1,620.1 | 1,663.3 | 1,678.4 | 1,719.5 | 1,767.1 | 1,810.2 | 1,789.7 | 1,811.2 |
| Coal | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Natural Gas | 35.9 | 32.7 | 32.1 | 34.0 | 37.4 | 38.2 | 38.9 | 41.1 | 35.1 | 35.6 | 35.5 | 33.9 | 35.2 |
| Electricity^a | 2.7 | 2.6 | 2.6 | 2.5 | 3.3 | 3.2 | 3.2 | 3.2 | 3.3 | 3.3 | 3.6 | 3.7 | 3.4 |
| Total | 1,569.5 | 1,549.4 | 1,570.5 | 1,590.6 | 1,631.7 | 1,661.4 | 1,705.3 | 1,722.7 | 1,757.9 | 1,806.0 | 1,849.2 | 1,827.3 | 1,849.7 |

*Less than 50,000 metric tons carbon dioxide.

^aShare 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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 Electric Power Sector Energy Consumption, 1990-2002
(Million Metric Tons Carbon Dioxide)

| Generator Type and Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Total Emissions from Fuel Use | | | | | | | | | | | | | |
| Petroleum | | | | | | | | | | | | | |
| Heavy Fuel Oil | 89.3 | 83.8 | 67.5 | 74.2 | 67.1 | 43.8 | 48.6 | 55.4 | 81.2 | 74.5 | 67.5 | 77.7 | 51.4 |
| Light Fuel Oil. | 7.0 | 6.1 | 5.3 | 6.3 | 8.7 | 7.8 | 7.9 | 8.0 | 9.8 | 10.1 | 12.6 | 11.8 | 7.8 |
| Petroleum Coke | 2.9 | 2.8 | 4.3 | 7.5 | 6.7 | 7.8 | 7.7 | 9.8 | 11.8 | 10.8 | 9.6 | 10.0 | 12.6 |
| Petroleum Subtotal. . . | 99.2 | 92.6 | 77.1 | 88.0 | 82.8 | 59.5 | 64.5 | 73.3 | 102.9 | 95.6 | 89.9 | 99.6 | 72.2 |
| Coal | 1,519.4 | 1,519.1 | 1,538.8 | 1,606.5 | 1,613.8 | 1,633.8 | 1,723.5 | 1,768.3 | 1,797.5 | 1,805.2 | 1,895.7 | 1,834.9 | 1,874.7 |
| Natural Gas | 176.0 | 179.4 | 186.6 | 187.9 | 211.1 | 228.4 | 204.9 | 218.9 | 248.0 | 259.9 | 280.7 | 289.1 | 299.1 |
| Municipal Solid Waste . . | 0.5 | 0.6 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 2.6 | 2.7 | 2.7 |
| Geothermal | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Total | 1,795.5 | 1,792.2 | 1,803.7 | 1,883.6 | 1,908.9 | 1,922.9 | 1,994.0 | 2,061.7 | 2,149.6 | 2,161.9 | 2,269.2 | 2,226.6 | 2,249.0 |
| Emissions from Fuel Use for Electricity Generation | | | | | | | | | | | | | |
| Petroleum | | | | | | | | | | | | | |
| Heavy Fuel Oil | 88.6 | 83.3 | 66.9 | 73.7 | 66.6 | 43.2 | 48.1 | 54.8 | 80.9 | 74.3 | 67.3 | 77.6 | 51.3 |
| Light Fuel Oil. | 6.9 | 6.0 | 5.3 | 6.1 | 8.5 | 7.6 | 7.8 | 7.9 | 9.8 | 10.1 | 12.5 | 11.5 | 7.6 |
| Petroleum Coke | 2.9 | 2.8 | 4.3 | 7.4 | 6.6 | 7.1 | 7.2 | 9.3 | 11.5 | 10.4 | 9.2 | 9.6 | 12.2 |
| Petroleum Subtotal. . . | 98.4 | 92.1 | 76.5 | 87.2 | 81.7 | 58.0 | 63.0 | 72.0 | 102.1 | 94.8 | 89.0 | 98.7 | 71.1 |
| Coal | 98.4 | 1,516.7 | 1,535.5 | 1,603.1 | 1,609.5 | 1,629.3 | 1,718.6 | 1,763.8 | 1,792.7 | 1,799.3 | 1,889.7 | 1,828.9 | 1,868.6 |
| Natural Gas | 170.8 | 174.0 | 179.9 | 180.9 | 203.4 | 220.7 | 197.0 | 210.2 | 238.7 | 250.4 | 270.4 | 276.9 | 286.5 |
| Geothermal | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Total | 1,786.8 | 1,783.0 | 1,792.1 | 1,871.3 | 1,894.7 | 1,908.1 | 1,978.8 | 2,046.0 | 2,133.6 | 2,144.6 | 2,249.2 | 2,204.6 | 2,226.2 |
| Emissions from Fuel Use for Thermal Energy Production | | | | | | | | | | | | | |
| Petroleum | | | | | | | | | | | | | |
| Heavy Fuel Oil | 0.7 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 | 0.3 | 0.3 | 0.2 | 0.1 | 0.1 |
| Light Fuel Oil. | 0.1 | * | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 | 0.2 |
| Petroleum Coke | * | * | * | 0.1 | 0.2 | 0.6 | 0.5 | 0.5 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 |
| Petroleum Subtotal. . . | 0.8 | 0.5 | 0.6 | 0.8 | 0.8 | 1.4 | 1.2 | 1.3 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Coal | 1.9 | 2.4 | 3.3 | 3.5 | 4.3 | 4.6 | 4.8 | 4.5 | 4.8 | 5.8 | 6.0 | 6.0 | 6.2 |
| Natural Gas | 5.2 | 5.4 | 6.7 | 7.0 | 7.8 | 7.7 | 7.9 | 8.7 | 9.3 | 9.5 | 10.4 | 12.2 | 12.6 |
| Total | 7.9 | 8.3 | 10.5 | 11.2 | 12.9 | 13.7 | 14.0 | 14.5 | 14.8 | 16.0 | 17.0 | 19.0 | 19.5 |

*Less than 50,000 metric tons carbon dioxide.

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 11. U.S. Carbon Sequestered by Nonfuel Use of Energy Fuels, 1990-2002
(Million Metric Tons Carbon Dioxide Equivalent)

| End Use and Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|---------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Industrial | | | | | | | | | | | | | |
| Petroleum | | | | | | | | | | | | | |
| Liquefied Petroleum Gases . . . | 59.3 | 68.0 | 68.7 | 66.6 | 76.6 | 78.5 | 81.7 | 82.7 | 86.4 | 89.9 | 86.4 | 79.9 | 83.3 |
| Distillate Fuel | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Residual Fuel | 1.9 | 2.5 | 2.3 | 2.1 | 2.0 | 2.1 | 2.1 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |
| Asphalt and Road Oil | 88.5 | 81.4 | 83.3 | 86.9 | 88.7 | 89.1 | 88.9 | 92.5 | 95.5 | 100.1 | 96.4 | 95.0 | 93.7 |
| Lubricants | 6.9 | 6.2 | 6.3 | 6.4 | 6.7 | 6.6 | 6.4 | 6.8 | 7.1 | 7.2 | 7.0 | 6.5 | 6.4 |
| Other (Subtotal) | 72.1 | 70.2 | 74.3 | 80.8 | 83.2 | 83.1 | 85.2 | 90.7 | 92.7 | 94.9 | 88.7 | 83.9 | 88.1 |
| Pentanes Plus | 4.4 | 2.4 | 3.3 | 14.8 | 13.8 | 16.2 | 16.9 | 16.0 | 10.9 | 14.0 | 12.7 | 10.8 | 9.2 |
| Petrochemical Feed | 46.0 | 46.3 | 49.2 | 49.8 | 51.7 | 50.0 | 50.6 | 58.4 | 59.1 | 55.5 | 57.7 | 50.7 | 54.7 |
| Petroleum Coke | 9.1 | 7.8 | 11.8 | 6.3 | 7.0 | 6.8 | 7.6 | 6.0 | 10.9 | 14.5 | 7.2 | 10.6 | 12.0 |
| Waxes and Miscellaneous . . | 12.5 | 13.7 | 10.1 | 9.9 | 10.7 | 10.1 | 10.1 | 10.4 | 11.8 | 10.9 | 11.2 | 11.8 | 12.2 |
| Coal | 1.4 | 1.3 | 2.8 | 2.0 | 2.0 | 2.1 | 2.0 | 1.9 | 1.8 | 1.8 | 1.8 | 1.7 | 1.8 |
| Natural Gas | 15.0 | 14.3 | 12.7 | 14.2 | 18.3 | 17.4 | 17.3 | 18.6 | 21.9 | 18.5 | 18.8 | 17.1 | 17.3 |
| Transportation | | | | | | | | | | | | | |
| Lubricants | 6.5 | 5.8 | 6.0 | 6.1 | 6.3 | 6.2 | 6.0 | 6.4 | 6.7 | 6.8 | 6.7 | 6.1 | 6.0 |
| Total | 251.8 | 250.0 | 256.7 | 265.4 | 284.0 | 285.3 | 290.0 | 302.2 | 314.7 | 321.8 | 308.5 | 292.8 | 299.3 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 12. U.S. Carbon Dioxide Emissions from Industrial Processes, 1990-2002
(Million Metric Tons Carbon Dioxide)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Cement Manufacture | | | | | | | | | | | | | |
| Clinker Production | 32.6 | 31.8 | 32.1 | 33.9 | 36.0 | 36.1 | 36.3 | 37.6 | 38.4 | 39.2 | 40.4 | 40.5 | 42.3 |
| Masonry Cement | 0.1 | 0.1 | 0.1 | 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 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| Cement Subtotal | 33.3 | 32.5 | 32.8 | 34.7 | 36.8 | 36.9 | 37.2 | 38.4 | 39.3 | 40.1 | 41.3 | 41.4 | 43.3 |
| Other Industrial | | | | | | | | | | | | | |
| Limestone Consumption | | | | | | | | | | | | | |
| Lime Manufacture | 12.4 | 12.3 | 12.7 | 13.1 | 13.7 | 14.5 | 15.1 | 15.5 | 15.8 | 15.5 | 15.4 | 14.8 | 14.4 |
| Iron Smelting | 1.7 | 1.6 | 1.4 | 1.1 | 1.1 | 1.2 | 1.1 | 1.1 | 1.1 | 1.0 | 1.1 | 1.0 | 0.9 |
| Steelmaking | 0.3 | 0.3 | 0.3 | 0.5 | 0.5 | 0.5 | 0.4 | 0.3 | 0.4 | 0.3 | 0.5 | 0.6 | 0.6 |
| Copper Refining | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |
| Glass Manufacture | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 |
| Flue Gas Desulfurization | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 1.0 | 1.0 | 1.1 | 1.2 | 1.4 | 1.4 |
| Dolomite Manufacture | 0.5 | 0.4 | 0.3 | 0.3 | 0.3 | 0.2 | 0.3 | 0.3 | 0.3 | 0.1 | 0.3 | 0.3 | 0.3 |
| Limestone Subtotal | 15.9 | 15.5 | 15.7 | 16.0 | 16.7 | 17.8 | 18.3 | 18.5 | 18.9 | 18.3 | 18.7 | 18.4 | 17.9 |
| Soda Ash Manufacture | 3.4 | 3.4 | 3.4 | 3.3 | 3.4 | 3.8 | 3.8 | 3.9 | 3.8 | 3.7 | 3.6 | 3.6 | 3.5 |
| Soda Ash Consumption | | | | | | | | | | | | | |
| Glass Manufacture | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.3 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 |
| Flue Gas Desulfurization | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 |
| Sodium Silicate | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.3 | 0.3 |
| Sodium Tripolyphosphate | 0.1 | 0.1 | 0.1 | 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 | 0.5 | 0.5 | 0.6 | 0.7 | 0.8 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Carbon Dioxide Manufacture | 0.9 | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.2 | 1.2 | 1.3 | 1.3 | 1.4 |
| Aluminum Manufacture | 5.9 | 6.0 | 5.9 | 5.4 | 4.8 | 4.9 | 5.2 | 5.3 | 5.4 | 5.5 | 5.4 | 3.9 | 4.0 |
| Shale Oil Production | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Other Industrial Subtotal | 26.8 | 26.4 | 26.5 | 26.3 | 26.7 | 28.4 | 29.0 | 29.5 | 30.0 | 29.3 | 29.6 | 27.7 | 27.4 |
| Total | 60.1 | 58.8 | 59.3 | 61.0 | 63.5 | 65.3 | 66.1 | 67.9 | 69.3 | 69.4 | 70.9 | 69.2 | 70.6 |

*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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 26.6 | 612.8 |
| Change Compared to 2001 (Million Metric Tons) | -0.8 | -17.3 |
| Change from 2001 (Percent) | -2.7% | -2.7% |
| Change Compared to 1990 (Million Metric Tons) | -4.6 | -106.3 |
| Change from 1990 (Percent) | -14.8% | -14.8% |

U.S. anthropogenic methane emissions totaled 26.6 million metric tons of methane (612.8 million metric tons carbon dioxide equivalent)⁵³ in 2002, a decrease of 0.8 million metric tons of methane from 2001 levels (Table 13). The decline in total methane emissions was primarily the result of a 0.6 million metric ton decrease in methane emissions from landfills, as well as smaller decreases in emissions from coal mining and stationary combustion. The amount of methane generated from the decomposition of waste in landfills was nearly unchanged between 2001 and 2002, but a 0.6 million metric ton increase in methane recovered for energy reduced net emissions from this source substantially. In addition, U.S. coal production dropped by 3.0 percent.

Estimated U.S. emissions of methane in 2002 were 4.6 million metric tons below the 1990 level, a decrease equivalent to 106.3 million metric tons of carbon dioxide, or 1.5 percent of total U.S. anthropogenic

greenhouse gas emissions. In addition to a 4.1 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 14). The 32.8-percent decline in emissions from coal mining was the result of a 207.3 percent increase in methane recovery from coal mines and a shift in production away from gassy mines. Overall, methane emissions account for about 8.9 percent of total U.S. greenhouse gas emissions when weighted by methane's global warming potential factor.

As a result of revisions in estimation methods for emissions from enteric fermentation and the solid waste of domesticated animals, overall estimated levels of methane emissions in this report are lower than the estimates previously published by the Energy Information Administration (EIA). The downward revision amounts to approximately 0.7 million metric tons in 1990 and 1.2 million metric tons in 2001.

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.⁵⁴ Thus, methane emission estimates must often rely on proxy measurements.

Estimated U.S. anthropogenic methane emissions for 2002 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 three-fifths of all U.S. methane emissions. Thus, comparisons between 2001 and 2002 numbers are more likely to be valid in the context of directional change rather than magnitude of change. For example, because 2002 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.

⁵³Based on an estimated global warming potential factor of 23 for methane. For an expanded discussion of global warming potentials, see the Executive Summary, p. xiii.

⁵⁴Wherever 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: Emissions of Greenhouse Gases in the United States 2002* (to be published). The absence of measured emissions data for most sources of methane emissions and the reliance on emissions factors represent a source of uncertainty (further details are available in Energy Information Administration, *Documentation: Emissions of Greenhouse Gases in the United States 2002* (to be published)).

Principal Sources of U.S. Anthropogenic Methane Emissions, 1990-2002

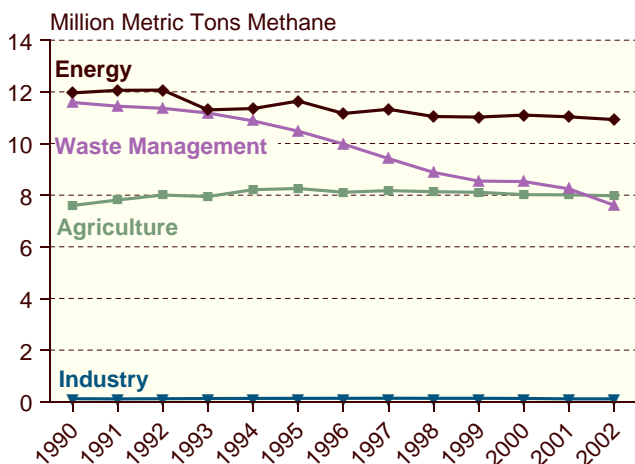
| Source | Million Metric Tons Methane | | Percent Change | |
|----------------------|-----------------------------|-------|----------------|-----------|
| | 1990 | 2002 | 1990-2002 | 2001-2002 |
| Energy | 11.96 | 10.95 | -8.5% | -0.7% |
| Waste Management | 11.59 | 7.61 | -34.3% | -7.7% |
| Agriculture | 7.60 | 7.98 | 5.0% | -0.5% |
| Industrial Processes | 0.12 | 0.11 | -4.4% | -0.4% |

Energy Sources

U.S. methane emissions from energy sources were estimated at 10.9 million metric tons in 2002 (251.8 million metric tons carbon dioxide equivalent), 0.1 million metric tons lower than 2001 levels and 1.0 million metric tons below 1990 levels (Figure 3). 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 32.8 percent (1.4 million metric tons) between 1990 and 2002. This decline resulted 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 gasiest underground mines in Central Appalachia.

Figure 3. U.S. Emissions of Methane by Source, 1990-2002



Source: Estimates presented in this chapter.

Between 1990 and 2002, the share of coal production represented by underground mines declined from 41.2 percent to 31.9 percent. Methane emissions from petroleum systems dropped from 1.3 million metric tons in 1990 to 1.0 million metric tons in 2002. 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 2002. Together, the declines in emissions from coal mining and stationary combustion more than compensated for the increase of 0.9 million metric tons in emissions from the natural gas system, attributed to increasing U.S. consumption of natural gas between 1990 and 2002.

Coal Mining

U.S. Methane Emissions from Coal Mining, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 2.9 | 65.7 |
| Change Compared to 2001 (Million Metric Tons) | -0.1 | -2.4 |
| Change from 2001 (Percent) | -3.6% | -3.6% |
| Change Compared to 1990 (Million Metric Tons) | -1.4 | -32.0 |
| Change from 1990 (Percent) | -32.8% | -32.8% |

The preliminary estimate of methane emissions from coal mines for 2002 is 2.9 million metric tons (Table 14), a decrease of 3.6 percent from the 2001 level.⁵⁵ This decrease can be traced to declines in coal production levels, which dropped by 3.0 percent in 2002 after rising by 5.0 percent in 2001.

U.S. coal production declined to 1.09 billion short tons in 2002, down from the record 2001 level of 1.13 billion short tons. The decline was primarily the result of a decrease in coal exports and high levels of coal stocks built up during 2001. Annual U.S. coal consumption was nearly constant between 2001 and 2002. Between 1990 and 2002, methane emissions from coal mines dropped by 32.8 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

⁵⁵Further details on emissions from abandoned coal mines are available in Energy Information Administration, *Documentation: Emissions of Greenhouse Gases in the United States 2002* (to be published).

tons in 1990 to about 0.8 million metric tons in 2002; (2) methane drainage from degasification in active mines decreased by more than 0.2 million metric tons between 1990 and 2002; and (3) methane emissions from ventilation systems at gassy mines dropped by about 0.6 million metric tons between 1990 and 2002 (Table 14).⁵⁶

Natural Gas Systems

U.S. Methane Emissions from Natural Gas Systems, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 6.5 | 148.9 |
| Change Compared to 2001 (Million Metric Tons) | 0.1 | 2.0 |
| Change from 2001 (Percent) | 1.4% | 1.4% |
| Change Compared to 1990 (Million Metric Tons) | 0.9 | 19.9 |
| Change from 1990 (Percent) | 15.5% | 15.5% |

At 6.5 million metric tons, 2002 estimated methane emissions from natural gas production, processing, and distribution were up from the revised estimate of 6.4 million metric tons for 2001 (Table 15). The 1.4-percent increase in emissions can be traced to an increase in gas withdrawals from storage in 2002; however, the 2002 estimate is preliminary, because pipeline data for 2002 had not been finalized as of the publication of this report. The estimated 2002 emissions level is 15.5 percent above the 1990 level, with about two-thirds of the increase attributable to increased mileage of distribution pipelines and one-third attributable to increases in gas withdrawals.⁵⁷

Petroleum Systems

Methane emissions from petroleum systems are estimated at 1.0 million metric tons in 2002, nearly unchanged from 2001 levels and down by 21.5 percent from 1.3 million metric tons in 1990. Domestic oil production in 2002 was 78.1 percent of the 1990 level, accounting for the decline in methane emissions from

U.S. Methane Emissions from Petroleum Systems, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 1.0 | 23.5 |
| Change Compared to 2001 (Million Metric Tons) | * | -0.2 |
| Change from 2001 (Percent) | -1.0% | -1.0% |
| Change Compared to 1990 (Million Metric Tons) | -0.3 | -6.4 |
| Change from 1990 (Percent) | -21.5% | -21.5% |

*Less than 0.05 million metric tons.

this source. Approximately 96.4 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, 90.3 percent was traced to venting, of which nearly half is attributable to venting from oil tanks (Table 16). A much smaller portion of methane emissions from petroleum systems can be traced to refineries and transportation of crude oil.

Stationary Combustion

U.S. methane emissions from stationary combustion in 2002 were 0.4 million metric tons, down by 12.3 percent from the 2001 level and 36.0 percent below 1990 levels (Table 17). 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 are, however, very uncertain (for further details, see Energy Information Administration, *Documentation: Emissions of Greenhouse Gases in the United States 2002* (to be published)). 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

⁵⁶The 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.

⁵⁷The EPA estimates that the companies participating in the Natural Gas STAR program together avoided emissions of 822,000 metric tons of methane in 2001 and 960,000 metric tons in 2002. 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).

U.S. Methane Emissions from Stationary Combustion, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 0.4 | 8.3 |
| Change Compared to 2001 (Million Metric Tons) | -0.1 | -1.2 |
| Change from 2001 (Percent) | -12.3% | -12.3% |
| Change Compared to 1990 (Million Metric Tons) | -0.2 | -4.7 |
| Change from 1990 (Percent) | -36.0% | -36.0% |

1997 RECS. Updated data on residential wood consumption for calendar year 2002 will be available from the 2003 RECS.

Mobile Combustion

U.S. Methane Emissions from Mobile Sources, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 0.2 | 5.5 |
| Change Compared to 2001 (Million Metric Tons) | * | -0.1 |
| Change from 2001 (Percent) | -1.0% | -1.0% |
| Change Compared to 1990 (Million Metric Tons) | * | -0.1 |
| Change from 1990 (Percent) | -2.3% | -2.3% |

*Less than 0.05 million metric tons.

Estimated U.S. methane emissions from mobile combustion in 2002 were 0.2 million metric tons, down by 1.0 percent from 2001 levels and 2.3 percent lower than the 1990 level (Table 18). Methane emissions from passenger cars have declined since 1990 as older cars with catalytic converters that are less efficient at destroying methane

have been taken off the road. However, from 1993 to 1999, rapid growth in the fleet of light-duty trucks and the related increase in methane emissions offset the declines from passenger cars. Since 1999, as growth in the fleet of light-duty trucks has moderated and the penetration of advanced catalytic converters has grown, emissions from both passenger cars and light-duty trucks have declined.

Waste Management

Methane emissions from waste management accounted for 28.6 percent of U.S. anthropogenic methane emissions in 2002 (Figure 3), down from 37.1 percent in 1990. Landfills represent 91.2 percent of the 7.6 million metric tons of methane emissions from waste management and remain the single largest source of U.S. anthropogenic methane emissions (Table 13). 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 landfills and industrial wastewater treatment. The U.S. Environmental Protection Agency (EPA) estimates some 1.7 million metric tons of methane emissions from these two sources during 2001 (1.0 million metric tons from industrial landfills and 0.7 million metric tons from wastewater treatment), or about 6.3 percent of total estimated U.S. methane emissions.⁵⁸

Landfills

Due to record levels of methane recovery for energy at U.S. landfills,⁵⁹ estimated methane emissions from landfills dropped to 6.9 million metric tons (159.7 million metric tons carbon dioxide equivalent) in 2002, 8.5 percent below the 2001 level of 7.6 million metric tons and 4.1 million metric tons (37.0 percent) below 1990 levels (Table 19). The dramatic decrease in methane emissions since 1990 is directly attributable to a 4.7 million metric ton increase in methane captured that otherwise would have been emitted to the atmosphere. Of the 5.9 million metric tons of methane believed to be captured from this source in 2002, 3.0 million metric tons was recovered for energy use, and 2.9 million metric tons was recovered and flared. In 2002, 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.⁶⁰

⁵⁸U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

⁵⁹U.S. Environmental Protection Agency, Landfill Methane Outreach Program, web site www.epa.gov/lmop.

⁶⁰Personal communication with Brian Gozzone, U.S. Environmental Protection Agency, Landfill Methane Outreach Program.

U.S. Methane Emissions from Landfills, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 6.9 | 159.7 |
| Change Compared to 2001 (Million Metric Tons) | -0.6 | -14.8 |
| Change from 2001 (Percent) | -8.5% | -8.5% |
| Change Compared to 1990 (Million Metric Tons) | -4.1 | -93.6 |
| Change from 1990 (Percent) | -37.0% | -37.0% |

While estimates of methane recovered and disposed of both by flaring and by recovery for energy are drawn from data collected by the EPA's Landfill Methane Outreach Program,⁶¹ there is less uncertainty in the estimate of methane recovered and used for energy. 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, and, absent a similar subsidy, the number of additional landfill gas-to-energy projects that are commercially viable may be limited.

H.R. 6, the comprehensive energy bill before the U.S. Senate in September 2003, contains new landfill gas-to-energy incentives under Section 45 of the Internal Revenue Code that would run through 2007. 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.

⁶¹U.S. Environmental Protection Agency, Landfill Methane Outreach Program, web site www.epa.gov/lmop.

⁶²For detailed discussion of the methods employed, see Energy Information Administration, *Documentation: Emissions of Greenhouse Gases in the United States 2002* (to be published).

Domestic and Commercial Wastewater Treatment**U.S. Methane Emissions from Domestic and Commercial Wastewater Treatment, 1990-2002**

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 0.7 | 15.3 |
| Change Compared to 2001 (Million Metric Tons) | * | 0.2 |
| Change from 2001 (Percent) | 1.3% | 1.3% |
| Change Compared to 1990 (Million Metric Tons) | 0.1 | 2.1 |
| Change from 1990 (Percent) | 15.6% | 15.6% |

*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 1.3 percent between 2001 and 2002 to 0.67 million metric tons. This is about 15.6 percent above the 1990 level of 0.58 million metric tons (Table 13). Methane emissions from industrial wastewater treatment are discussed in the box on page 38.

EIA has revised the estimates of methane emissions from domestic and commercial wastewater since publication of the previous edition of this inventory, *Emissions of Greenhouse Gases in the United States 2001*. Estimates of the fraction of organic content in wastewater and the portion of wastewater that decays anaerobically have been increased.⁶² The resulting estimates show annual emissions nearly four times as large as those previously published.

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 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

Methane Emissions from Industrial Wastewater Treatment

Industries generating high volumes of wastewater that includes large amounts of organic material are likely to generate methane emissions from the anaerobic decomposition of that organic material. Industries that fit this description include pulp and paper manufacturing, meat and poultry packing, and vegetable, fruit and juice processing. Determining total wastewater outflows, organic loadings, and the portion of anaerobic degradation of the loadings for each industry is difficult. Further, the emissions contribution of other industries is impossible to quantify at this time. Thus, EIA has chosen to exclude this emissions source from its estimates of overall methane emissions.

In its report, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, the U.S. Environmental Protection Agency (EPA), makes some assumptions about the level of anaerobic decomposition of organic wastes in wastewater for the three industries referenced above.^a For those three industries, the EPA estimates 900,000 metric tons of methane emissions in 2001, an amount equal to EIA's current estimate of methane emissions from wastewater treatment and equivalent to 2.5 percent of total estimated U.S. methane emissions.

^aU.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/ResourceCenterPublicationsGHG_EmissionsUSEmissionsInventory2003.html.

generated by wastewater are also sparse. EIA believes that emissions from this source are relatively small, representing 2.5 percent of all U.S. methane emissions in 2002. Thus, emissions are estimated using a default per-capita emissions factor and U.S. population data.

Agricultural Sources

Estimated agricultural methane emissions decreased by 0.5 percent between 2001 and 2002 due mainly to small decreases in emissions from animal waste and rice cultivation. At an estimated 8.0 million metric tons of methane (183.4 million metric tons carbon dioxide equivalent), methane emissions from agricultural activities in 2002 represent 29.9 percent of total U.S. anthropogenic methane emissions (Table 13). Ninety-four percent of methane emissions from agricultural activities result from livestock management. Sixty-seven 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.

Revisions to the estimation methods for enteric fermentation and the solid waste of domesticated livestock have lowered EIA's estimates of methane emissions from agriculture for 1990 by approximately 0.7 million metric tons and for 2001 by 1.2 million metric tons. Aside from the magnitude of the change, the most noticeable effect of the revised methods was to alter the trend line in emissions from enteric fermentation. Rather than increasing slowly between 1996 and 2000, emissions from this source are now estimated to have declined slightly during that period.

Enteric Fermentation in Domesticated Animals

U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 5.0 | 115.1 |
| Change Compared to 2001 (Million Metric Tons) | * | * |
| Change from 2001 (Percent) | * | * |
| Change Compared to 1990 (Million Metric Tons) | -0.2 | -4.9 |
| Change from 1990 (Percent) | -4.1% | -4.1% |

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

In 2002, estimated methane emissions from enteric fermentation in domesticated animals were unchanged from the 2001 level of 5.0 million metric tons (Table 20). Because cattle account for 95.1 percent of all emissions from enteric fermentation, trends in emissions correlate with trends in cattle populations. Between 2001 and 2002, cattle populations were nearly constant, with small declines in beef cattle populations offset by small increases in dairy cattle populations. Estimated methane emissions from enteric fermentation in 2002 are 4.1 percent below 1990 levels.

The animal population data and methodologies used to estimate methane emissions from enteric fermentation have been revised for the 2002 inventory, affecting the estimates for all years. The revised population estimates eliminate previous double counting of beef cattle in feedlots, in turn reducing emissions from enteric fermentation in beef cattle for 1990 through 2002. In addition, the adjusted methane emissions factors reflect greater detail that the EPA has incorporated into the Tier 2 methodology outlined in the “good practice guidance” of the Intergovernmental Panel on Climate Change.⁶³ Together, these changes alter the estimated trend in emissions from this source. Using both the old and new methods, estimated emissions from enteric fermentation peaked in 1995; however, previously published estimates showed emissions largely flat between 1996 and 2001, whereas the new methods show a decrease in emissions since 1996.

Solid Waste of Domesticated Animals

U.S. Methane Emissions from Solid Waste of Domesticated Animals, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|--|---------|---------------------------|
| Estimated 2002 Emissions (Million Metric Tons) | 2.5 | 56.8 |
| Change Compared to 2001 (Million Metric Tons) | * | -0.5 |
| Change from 2001 (Percent) | -0.9% | -0.9% |
| Change Compared to 1990 (Million Metric Tons) | 0.5 | 12.3 |
| Change from 1990 (Percent) | 27.6% | 27.6% |

*Less than 0.05 million metric tons.

Estimated methane emissions from the solid waste of domesticated animals decreased from 2.49 million metric tons in 2001 to 2.47 million metric tons in 2002 (Table 21). This small drop was the result of decreases in beef cattle and swine populations. The drop offset a larger trend over the past decade: in 2002, emissions from the solid waste of domesticated animals were 0.5 million metric tons above 1990 levels, an increase of 27.6 percent. Between 1990 and 2002 there was a shift of swine

populations to larger livestock operations, which are believed to be more likely to manage waste using liquid systems that tend to promote methane generation.⁶⁴ To capture this shift and other trends in the management of the solid waste of domesticated animals, EIA revised its estimation methods for this source. The typical animal mass was revised for all animal categories, including revisions to swine sizes to conform more closely with USDA classifications. In addition, EIA has updated volatile solids factors and altered the distribution of waste management systems to reflect the general shift to larger, more managed farms. Together, these changes lowered annual estimates of methane emissions from the solid waste of animals by about 0.6 million metric tons.

Rice Cultivation

Estimated methane emissions from U.S. rice cultivation declined to 0.46 million metric tons in 2002 from 0.47 million metric tons in 2001. The drop was the result of a 3.3-percent decrease in the number of acres harvested. Arkansas, Missouri, Louisiana, and Texas all saw decreases in acres harvested. Methane emissions from rice cultivation in 2002 were 13.4 percent higher than in 1990 (Table 13).

Burning of Crop Residues

Crop residue burning, the smallest contributor to agricultural greenhouse gas emissions, represents less than 0.2 percent of total U.S. methane emissions. Estimated 2002 methane emissions from the burning of crop residues were 0.05 million metric tons, down by 4.7 percent from 2001 levels but still 3.0 percent above 1990 levels (Table 13). The small decrease is attributable mainly to declines in corn, sorghum, barley, wheat, and soybean production.

Industrial Sources

Chemical Production

The preliminary estimate of methane emissions from U.S. chemical production in 2002 is 65.6 thousand metric tons, 2.1 percent more than in 2001. The increase is attributable to increased production of carbon black, ethylene, and styrene, more than offsetting a drop in methanol production. Methane emissions from chemical production in 2002 were 18.1 percent above their level in 1990 (Table 22).

⁶³IPCC National Greenhouse Gas Inventories Programme, *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), Chapter 4, “Agriculture,” web site www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm.

⁶⁴U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), p. 5-6, web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2001.html>.

U.S. Methane Emissions from Industrial Sources, 1990-2002

| | Methane | Carbon Dioxide Equivalent |
|---|----------------|--|
| Estimated 2002 Emissions (Million Metric Tons) | 0.1 | 2.6 |
| Change Compared to 2001 (Million Metric Tons) | * | * |
| Change from 2001 (Percent) | -0.4% | -0.4% |
| Change Compared to 1990 (Million Metric Tons) | * | -0.1 |
| Change from 1990 (Percent) | -4.4% | -4.4% |

*Less than 0.05 million metric tons.

Iron and Steel Production

With production of pig iron and sinter dropping, methane emissions from iron and steel production fell by 3.6 percent between 2001 and 2002, to the lowest levels in more than 20 years. Emissions in 2002, at 46.5 thousand metric tons, were 24.7 percent below the 1990 level of 61.7 thousand metric tons (Table 22).

Table 13. U.S. Methane Emissions from Anthropogenic Sources, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Million Metric Tons Methane | | | | | | | | | | | | | |
| Energy Sources | | | | | | | | | | | | | |
| Coal Mining | 4.25 | 4.10 | 4.05 | 3.44 | 3.51 | 3.66 | 3.19 | 3.50 | 3.28 | 3.12 | 2.98 | 2.96 | 2.86 |
| Natural Gas Systems | 5.60 | 5.83 | 5.89 | 5.88 | 5.89 | 5.98 | 6.00 | 6.01 | 6.02 | 6.19 | 6.41 | 6.38 | 6.47 |
| Petroleum Systems | 1.30 | 1.31 | 1.27 | 1.21 | 1.18 | 1.17 | 1.15 | 1.14 | 1.11 | 1.05 | 1.03 | 1.03 | 1.02 |
| Stationary Combustion | 0.56 | 0.59 | 0.62 | 0.54 | 0.53 | 0.58 | 0.58 | 0.44 | 0.39 | 0.42 | 0.44 | 0.41 | 0.36 |
| Mobile Sources | 0.25 | 0.24 | 0.24 | 0.24 | 0.24 | 0.25 | 0.24 | 0.24 | 0.24 | 0.26 | 0.25 | 0.24 | 0.24 |
| Total Energy Sources | 11.96 | 12.06 | 12.07 | 11.30 | 11.35 | 11.64 | 11.16 | 11.33 | 11.04 | 11.02 | 11.10 | 11.03 | 10.95 |
| Waste Management | | | | | | | | | | | | | |
| Landfills | 11.01 | 10.86 | 10.77 | 10.58 | 10.27 | 9.87 | 9.37 | 8.80 | 8.25 | 7.91 | 7.87 | 7.58 | 6.94 |
| Wastewater Treatment | 0.58 | 0.58 | 0.59 | 0.60 | 0.60 | 0.61 | 0.61 | 0.62 | 0.63 | 0.63 | 0.65 | 0.66 | 0.67 |
| Total Waste Management | 11.59 | 11.44 | 11.36 | 11.18 | 10.88 | 10.48 | 9.98 | 9.42 | 8.88 | 8.54 | 8.53 | 8.24 | 7.61 |
| Agricultural Sources | | | | | | | | | | | | | |
| Enteric Fermentation | 5.22 | 5.19 | 5.29 | 5.24 | 5.34 | 5.42 | 5.31 | 5.19 | 5.11 | 5.11 | 5.06 | 5.00 | 5.00 |
| Animal Waste | 1.93 | 2.19 | 2.21 | 2.26 | 2.34 | 2.35 | 2.34 | 2.48 | 2.51 | 2.46 | 2.46 | 2.49 | 2.47 |
| Rice Cultivation | 0.40 | 0.40 | 0.45 | 0.41 | 0.48 | 0.44 | 0.41 | 0.45 | 0.47 | 0.50 | 0.45 | 0.47 | 0.46 |
| Crop Residue Burning | 0.05 | 0.04 | 0.05 | 0.04 | 0.05 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Total Agricultural Sources | 7.60 | 7.81 | 8.01 | 7.95 | 8.21 | 8.26 | 8.11 | 8.18 | 8.13 | 8.11 | 8.02 | 8.01 | 7.98 |
| Industrial Processes | 0.12 | 0.11 | 0.12 | 0.12 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.11 | 0.11 |
| Total | 31.27 | 31.43 | 31.55 | 30.55 | 30.57 | 30.51 | 29.39 | 29.05 | 28.19 | 27.81 | 27.77 | 27.40 | 26.65 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Energy Sources | | | | | | | | | | | | | |
| Coal Mining | 97.68 | 94.24 | 93.24 | 79.03 | 80.83 | 84.18 | 73.46 | 80.39 | 75.55 | 71.67 | 68.44 | 68.11 | 65.67 |
| Natural Gas Systems | 128.91 | 134.00 | 135.51 | 135.21 | 135.48 | 137.61 | 138.04 | 138.24 | 138.39 | 142.29 | 147.36 | 146.85 | 148.85 |
| Petroleum Systems | 29.88 | 30.13 | 29.12 | 27.82 | 27.10 | 26.93 | 26.36 | 26.33 | 25.54 | 24.04 | 23.80 | 23.69 | 23.46 |
| Stationary Combustion | 12.97 | 13.60 | 14.28 | 12.34 | 12.12 | 13.33 | 13.35 | 10.06 | 9.07 | 9.63 | 10.05 | 9.47 | 8.30 |
| Mobile Sources | 5.65 | 5.41 | 5.43 | 5.56 | 5.61 | 5.78 | 5.58 | 5.49 | 5.48 | 5.93 | 5.66 | 5.58 | 5.53 |
| Total Energy Sources | 275.09 | 277.39 | 277.57 | 259.95 | 261.14 | 267.82 | 256.78 | 260.51 | 254.03 | 253.55 | 255.31 | 253.71 | 251.82 |
| Waste Management | | | | | | | | | | | | | |
| Landfills | 253.26 | 249.81 | 247.76 | 243.41 | 236.31 | 227.05 | 215.40 | 202.34 | 189.85 | 182.01 | 181.11 | 174.41 | 159.66 |
| Wastewater Treatment | 13.27 | 13.42 | 13.57 | 13.71 | 13.85 | 13.98 | 14.11 | 14.25 | 14.38 | 14.51 | 15.01 | 15.15 | 15.34 |
| Total Waste Management | 266.53 | 263.22 | 261.33 | 257.13 | 250.16 | 241.03 | 229.51 | 216.58 | 204.23 | 196.51 | 196.12 | 189.57 | 175.00 |
| Agricultural Sources | | | | | | | | | | | | | |
| Enteric Fermentation | 119.96 | 119.27 | 121.75 | 120.48 | 122.80 | 124.67 | 122.21 | 119.45 | 117.44 | 117.42 | 116.40 | 115.08 | 115.05 |
| Animal Waste | 44.49 | 50.38 | 50.93 | 51.95 | 53.92 | 54.07 | 53.83 | 57.15 | 57.78 | 56.56 | 56.67 | 57.32 | 56.78 |
| Rice Cultivation | 9.30 | 9.09 | 10.31 | 9.40 | 10.95 | 10.22 | 9.42 | 10.32 | 10.71 | 11.47 | 10.24 | 10.78 | 10.54 |
| Crop Residue Burning | 1.04 | 0.97 | 1.14 | 0.94 | 1.20 | 0.97 | 1.12 | 1.12 | 1.14 | 1.10 | 1.15 | 1.12 | 1.07 |
| Total Agricultural Sources | 174.79 | 179.71 | 184.13 | 182.76 | 188.87 | 189.93 | 186.58 | 188.05 | 187.08 | 186.55 | 184.45 | 184.30 | 183.44 |
| Industrial Processes | 2.70 | 2.55 | 2.69 | 2.85 | 2.97 | 3.04 | 3.08 | 3.09 | 3.05 | 3.07 | 2.93 | 2.59 | 2.58 |
| Total | 719.10 | 722.87 | 725.72 | 702.69 | 703.15 | 701.83 | 675.94 | 668.24 | 648.40 | 639.69 | 638.81 | 630.16 | 612.84 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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* (Washington, DC, various years), web site http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHG_Emissions.html.

Table 14. U.S. Methane Emissions from Coal Mining and Post-Mining Activities, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Million Metric Tons Methane | | | | | | | | | | | | | |
| Surface Mining | | | | | | | | | | | | | |
| Mining | 0.43 | 0.42 | 0.42 | 0.42 | 0.45 | 0.45 | 0.46 | 0.47 | 0.49 | 0.50 | 0.49 | 0.53 | 0.53 |
| Post-Mining | 0.68 | 0.65 | 0.65 | 0.56 | 0.64 | 0.64 | 0.66 | 0.67 | 0.67 | 0.63 | 0.61 | 0.62 | 0.57 |
| Underground Mining | | | | | | | | | | | | | |
| Ventilation (Gassy Mines) | 2.13 | 2.04 | 2.10 | 1.82 | 1.85 | 1.91 | 1.71 | 1.79 | 1.80 | 1.76 | 1.67 | 1.62 | 1.51 |
| Ventilation (Nongassy Mines) | 0.03 | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 |
| Degasification Systems | 1.26 | 1.23 | 1.17 | 1.05 | 1.06 | 1.21 | 1.02 | 1.06 | 0.95 | 0.79 | 0.87 | 0.93 | 1.03 |
| Post-Mining | 0.64 | 0.61 | 0.61 | 0.53 | 0.60 | 0.60 | 0.62 | 0.63 | 0.63 | 0.59 | 0.56 | 0.57 | 0.52 |
| Methane Recovery for Energy (-) | 0.26 | 0.27 | 0.31 | 0.44 | 0.51 | 0.57 | 0.69 | 0.54 | 0.67 | 0.61 | 0.70 | 0.76 | 0.81 |
| Net Emissions | 4.25 | 4.10 | 4.05 | 3.44 | 3.51 | 3.66 | 3.19 | 3.50 | 3.28 | 3.12 | 2.98 | 2.96 | 2.86 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Surface Mining | | | | | | | | | | | | | |
| Mining | 9.82 | 9.57 | 9.59 | 9.66 | 10.31 | 10.34 | 10.63 | 10.87 | 11.37 | 11.51 | 11.37 | 12.11 | 12.11 |
| Post-Mining | 0.85 | 0.83 | 0.83 | 0.84 | 0.90 | 0.90 | 0.92 | 0.95 | 0.99 | 1.00 | 0.99 | 1.05 | 1.05 |
| Underground Mining | | | | | | | | | | | | | |
| Ventilation (Gassy Mines) | 48.91 | 46.96 | 48.32 | 41.86 | 42.50 | 43.86 | 39.32 | 41.22 | 41.51 | 40.55 | 38.31 | 37.18 | 34.70 |
| Ventilation (Nongassy Mines) | 0.62 | 0.59 | 0.54 | 0.55 | 0.65 | 0.80 | 0.85 | 0.84 | 0.94 | 0.92 | 0.87 | 0.84 | 0.79 |
| Degasification Systems | 28.88 | 28.35 | 27.02 | 24.05 | 24.44 | 27.76 | 23.46 | 24.44 | 21.80 | 18.08 | 20.00 | 21.33 | 23.67 |
| Post-Mining | 14.69 | 14.09 | 14.09 | 12.15 | 13.81 | 13.71 | 14.19 | 14.56 | 14.46 | 13.56 | 12.93 | 13.17 | 12.06 |
| Methane Recovery for Energy (-) | 6.09 | 6.15 | 7.15 | 10.09 | 11.78 | 13.19 | 15.91 | 12.49 | 15.51 | 13.96 | 16.03 | 17.57 | 18.71 |
| Net Emissions | 97.68 | 94.24 | 93.24 | 79.03 | 80.83 | 84.18 | 73.46 | 80.39 | 75.55 | 71.67 | 68.44 | 68.11 | 65.67 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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-CO₂ 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-CO₂ Gases and Sequestration Branch, Coalbed Methane Outreach Program.

Table 15. U.S. Methane Emissions from Natural Gas Systems, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Million Metric Tons Methane | | | | | | | | | | | | | |
| Production | 1.47 | 1.49 | 1.49 | 1.51 | 1.55 | 1.57 | 1.58 | 1.65 | 1.67 | 1.62 | 1.73 | 1.82 | 1.80 |
| Gas Processing | 0.65 | 0.71 | 0.70 | 0.71 | 0.71 | 0.72 | 0.73 | 0.71 | 0.69 | 0.70 | 0.71 | 0.70 | 0.64 |
| Transmission and Storage | 2.10 | 2.21 | 2.23 | 2.15 | 2.11 | 2.14 | 2.11 | 2.05 | 2.00 | 2.06 | 2.15 | 2.00 | 2.16 |
| Distribution | 1.39 | 1.42 | 1.47 | 1.51 | 1.53 | 1.55 | 1.58 | 1.59 | 1.66 | 1.80 | 1.81 | 1.87 | 1.87 |
| Total | 5.60 | 5.83 | 5.89 | 5.88 | 5.89 | 5.98 | 6.00 | 6.01 | 6.02 | 6.19 | 6.41 | 6.38 | 6.47 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Production | 33.77 | 34.27 | 34.32 | 34.80 | 35.63 | 36.06 | 36.28 | 37.98 | 38.43 | 37.32 | 39.90 | 41.75 | 41.47 |
| Gas Processing | 14.85 | 16.23 | 16.06 | 16.36 | 16.25 | 16.50 | 16.90 | 16.39 | 15.97 | 16.13 | 16.43 | 16.01 | 14.73 |
| Transmission and Storage | 48.26 | 50.94 | 51.40 | 49.40 | 48.51 | 49.33 | 48.53 | 47.18 | 45.89 | 47.36 | 49.43 | 46.01 | 49.57 |
| Distribution | 32.03 | 32.56 | 33.73 | 34.65 | 35.08 | 35.73 | 36.32 | 36.68 | 38.10 | 41.49 | 41.60 | 43.08 | 43.08 |
| Total | 128.91 | 134.00 | 135.51 | 135.21 | 135.48 | 137.61 | 138.04 | 138.24 | 138.39 | 142.29 | 147.36 | 146.85 | 148.85 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). Totals may not equal sum of components due to independent rounding.

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(2003/07) (Washington, DC, July 2003); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Table 16. U.S. Methane Emissions from Petroleum Systems, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Million Metric Tons Methane | | | | | | | | | | | | | |
| Refineries | 0.02 | 0.02 | 0.02 | 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 | 1.27 | 1.23 | 1.17 | 1.14 | 1.13 | 1.11 | 1.11 | 1.07 | 1.01 | 1.00 | 0.99 | 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 | 0.01 | 0.01 | 0.01 |
| Total | 1.30 | 1.31 | 1.27 | 1.21 | 1.18 | 1.17 | 1.15 | 1.14 | 1.11 | 1.05 | 1.03 | 1.03 | 1.02 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Refineries | 0.57 | 0.56 | 0.55 | 0.57 | 0.58 | 0.58 | 0.59 | 0.61 | 0.62 | 0.62 | 0.64 | 0.62 | 0.62 |
| Exploration and Production | 29.01 | 29.28 | 28.29 | 26.97 | 26.26 | 26.08 | 25.50 | 25.45 | 24.66 | 23.17 | 22.93 | 22.85 | 22.62 |
| Crude Oil Transportation | 0.30 | 0.29 | 0.28 | 0.28 | 0.27 | 0.27 | 0.27 | 0.27 | 0.26 | 0.24 | 0.23 | 0.22 | 0.22 |
| Total | 29.88 | 30.13 | 29.12 | 27.82 | 27.10 | 26.93 | 26.36 | 26.33 | 25.54 | 24.04 | 23.80 | 23.69 | 23.46 |

*Less than 0.05 million metric tons of 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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). Totals may not equal sum of components due to independent rounding.

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 17. U.S. Methane Emissions from Stationary Combustion Sources, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Thousand Metric Tons Methane | | | | | | | | | | | | | |
| Residential | | | | | | | | | | | | | |
| Coal..... | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Fuel Oil ^a | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 5 |
| Natural Gas..... | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 5 | 5 | 5 |
| LPG..... | * | * | * | * | * | * | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Wood..... | 512 | 541 | 569 | 483 | 474 | 526 | 525 | 382 | 341 | 365 | 382 | 359 | 309 |
| Total..... | 522 | 550 | 579 | 493 | 484 | 535 | 535 | 392 | 350 | 374 | 392 | 369 | 319 |
| Commercial | | | | | | | | | | | | | |
| Coal..... | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Fuel Oil ^a | 1 | 1 | 1 | 1 | 1 | 1 | 1 | * | * | * | * | * | * |
| Natural Gas..... | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| LPG..... | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Wood..... | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Total..... | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 5 | 5 | 5 | 5 | 5 |
| Industrial | | | | | | | | | | | | | |
| Coal..... | 7 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 |
| Fuel Oil ^a | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Natural Gas..... | 11 | 12 | 12 | 12 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 11 |
| LPG..... | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Wood..... | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| Total..... | 25 | 25 | 26 | 26 | 27 | 27 | 28 | 28 | 26 | 26 | 26 | 25 | 24 |
| Electric Power | | | | | | | | | | | | | |
| Coal..... | 10 | 10 | 10 | 10 | 10 | 11 | 11 | 11 | 12 | 12 | 12 | 12 | 12 |
| Fuel Oil ^a | 1 | 1 | 1 | 1 | 1 | * | * | 1 | 1 | 1 | 1 | 1 | * |
| Natural Gas..... | * | * | * | * | * | * | * | * | * | * | 1 | 1 | 1 |
| Wood..... | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Total..... | 11 | 11 | 11 | 11 | 11 | 11 | 12 | 12 | 13 | 13 | 13 | 13 | 13 |
| Total All Fuels | | | | | | | | | | | | | |
| Coal..... | 18 | 17 | 17 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| Fuel Oil ^a | 8 | 7 | 7 | 8 | 7 | 7 | 7 | 6 | 6 | 6 | 7 | 6 | 6 |
| Natural Gas..... | 19 | 20 | 20 | 21 | 21 | 22 | 23 | 23 | 22 | 21 | 22 | 21 | 21 |
| LPG..... | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 3 | 4 | 4 | 4 | 4 |
| Wood..... | 516 | 544 | 573 | 487 | 478 | 530 | 529 | 387 | 346 | 370 | 386 | 363 | 313 |
| Total..... | 564 | 591 | 621 | 536 | 527 | 579 | 580 | 437 | 394 | 419 | 437 | 412 | 361 |

*Less than 500 metric tons of methane.

P = preliminary data.

^aFuel oil use in the residential sector consists of distillate fuel only. In the other sectors it includes both distillate and residual fuel oil.

See notes and sources at end of table.

Table 17. U.S. Methane Emissions from Stationary Combustion Sources, 1990-2002 (Continued)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|--------------|--------------|---------------|--------------|--------------|
| Thousand Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Residential | | | | | | | | | | | | | |
| Coal | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Fuel Oil ^a | 113 | 108 | 113 | 113 | 111 | 105 | 107 | 101 | 89 | 96 | 105 | 105 | 104 |
| Natural Gas | 100 | 104 | 107 | 112 | 110 | 110 | 119 | 113 | 103 | 107 | 113 | 109 | 112 |
| LPG | 10 | 10 | 10 | 11 | 11 | 11 | 13 | 12 | 12 | 14 | 15 | 14 | 15 |
| Wood | 11,783 | 12,432 | 13,081 | 11,114 | 10,891 | 12,087 | 12,067 | 8,782 | 7,849 | 8,396 | 8,782 | 8,254 | 7,098 |
| Total | 12,006 | 12,654 | 13,312 | 11,350 | 11,123 | 12,313 | 12,306 | 9,008 | 8,053 | 8,613 | 9,014 | 8,482 | 7,329 |
| Commercial | | | | | | | | | | | | | |
| Coal | 30 | 27 | 27 | 28 | 27 | 27 | 28 | 30 | 21 | 24 | 21 | 22 | 22 |
| Fuel Oil ^a | 16 | 15 | 14 | 13 | 13 | 12 | 12 | 10 | 9 | 9 | 10 | 10 | 10 |
| Natural Gas | 72 | 75 | 77 | 78 | 79 | 82 | 86 | 87 | 82 | 83 | 87 | 83 | 85 |
| LPG | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 |
| Wood | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 3 | 3 |
| Total | 122 | 122 | 123 | 124 | 124 | 126 | 132 | 133 | 118 | 122 | 125 | 120 | 123 |
| Industrial | | | | | | | | | | | | | |
| Coal | 151 | 142 | 137 | 136 | 137 | 136 | 133 | 130 | 122 | 119 | 121 | 124 | 116 |
| Fuel Oil ^a | 32 | 27 | 30 | 34 | 32 | 27 | 27 | 24 | 20 | 18 | 21 | 18 | 20 |
| Natural Gas | 263 | 266 | 277 | 282 | 283 | 298 | 307 | 308 | 303 | 291 | 295 | 269 | 264 |
| LPG | 51 | 55 | 59 | 57 | 63 | 64 | 66 | 68 | 65 | 71 | 72 | 65 | 69 |
| Wood | 89 | 87 | 90 | 91 | 97 | 102 | 104 | 107 | 99 | 100 | 101 | 89 | 93 |
| Total | 585 | 577 | 593 | 600 | 613 | 626 | 637 | 637 | 608 | 599 | 609 | 565 | 561 |
| Electric Power | | | | | | | | | | | | | |
| Coal | 225 | 226 | 229 | 239 | 240 | 242 | 256 | 262 | 267 | 268 | 281 | 273 | 277 |
| Fuel Oil ^a | 19 | 18 | 14 | 16 | 14 | 9 | 10 | 12 | 17 | 16 | 14 | 16 | * |
| Natural Gas | 7 | 8 | 8 | 8 | 9 | 10 | 9 | 9 | 10 | 11 | 12 | 12 | 13 |
| Wood | 1 | 1 | 1 | * | * | * | * | * | * | * | * | * | * |
| Total | 252 | 251 | 251 | 262 | 262 | 261 | 274 | 283 | 294 | 294 | 306 | 301 | 290 |
| Total All Fuels | | | | | | | | | | | | | |
| Coal | 406 | 395 | 393 | 403 | 404 | 405 | 417 | 423 | 410 | 410 | 422 | 419 | 416 |
| Fuel Oil ^a | 180 | 167 | 172 | 175 | 171 | 152 | 156 | 147 | 135 | 138 | 150 | 149 | 131 |
| Natural Gas | 442 | 452 | 468 | 480 | 481 | 500 | 521 | 518 | 499 | 492 | 507 | 472 | 473 |
| LPG | 62 | 68 | 71 | 69 | 76 | 77 | 81 | 82 | 78 | 88 | 90 | 82 | 87 |
| Wood | 11,875 | 12,522 | 13,175 | 11,208 | 10,991 | 12,192 | 12,174 | 8,891 | 7,951 | 8,499 | 8,886 | 8,346 | 7,194 |
| Total | 12,965 | 13,604 | 14,279 | 12,336 | 12,123 | 13,326 | 13,348 | 10,061 | 9,073 | 9,628 | 10,054 | 9,468 | 8,302 |

*Less than 500 metric tons carbon dioxide equivalent.

P = preliminary data.

^aFuel oil use in the residential sector consists of distillate fuel only. In the other sectors it includes both distillate and residual fuel oil.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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(2003/07) (Washington, DC, July 2003), and *Annual Energy Review*, DOE/EIA-0384(2001) (Washington, DC, various years).

Table 18. U.S. Methane Emissions from Mobile Sources, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|---|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Thousand Metric Tons Methane | | | | | | | | | | | | | |
| Motor Vehicles | | | | | | | | | | | | | |
| Passenger Cars | 142 | 132 | 131 | 126 | 117 | 109 | 107 | 105 | 105 | 106 | 100 | 99 | 99 |
| Buses | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Motorcycles..... | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Light-Duty Trucks | 64 | 64 | 64 | 75 | 86 | 100 | 93 | 92 | 92 | 108 | 101 | 101 | 100 |
| Other Trucks..... | 12 | 12 | 12 | 13 | 14 | 14 | 15 | 15 | 16 | 17 | 17 | 17 | 16 |
| Total | 223 | 212 | 212 | 220 | 222 | 229 | 220 | 217 | 218 | 236 | 223 | 222 | 221 |
| Other Transport..... | 23 | 23 | 24 | 22 | 22 | 23 | 23 | 21 | 21 | 21 | 23 | 21 | 20 |
| Total Transport | 246 | 235 | 236 | 242 | 244 | 251 | 242 | 239 | 238 | 258 | 246 | 243 | 240 |
| Thousand Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Motor Vehicles | | | | | | | | | | | | | |
| Passenger Cars | 3,265 | 3,035 | 3,019 | 2,901 | 2,701 | 2,515 | 2,467 | 2,406 | 2,404 | 2,427 | 2,310 | 2,288 | 2,272 |
| Buses | 21 | 21 | 21 | 23 | 24 | 24 | 24 | 25 | 26 | 28 | 28 | 26 | 29 |
| Motorcycles..... | 92 | 88 | 92 | 95 | 99 | 94 | 96 | 97 | 99 | 101 | 101 | 92 | 98 |
| Light-Duty Trucks | 1,474 | 1,463 | 1,464 | 1,735 | 1,967 | 2,292 | 2,133 | 2,111 | 2,113 | 2,495 | 2,317 | 2,319 | 2,310 |
| Other Trucks..... | 277 | 279 | 283 | 296 | 315 | 330 | 339 | 354 | 363 | 381 | 380 | 384 | 363 |
| Total | 5,129 | 4,887 | 4,879 | 5,049 | 5,105 | 5,256 | 5,058 | 4,993 | 5,005 | 5,432 | 5,137 | 5,110 | 5,072 |
| Other Transport..... | 525 | 526 | 548 | 507 | 502 | 521 | 518 | 494 | 473 | 494 | 519 | 474 | 454 |
| Total Transport | 5,654 | 5,412 | 5,427 | 5,556 | 5,607 | 5,777 | 5,576 | 5,488 | 5,478 | 5,926 | 5,655 | 5,584 | 5,527 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002).

Sources: Calculations based on vehicle miles traveled from U.S. Department of Transportation, *Federal Highway Statistics*, various years, Table VM-1. Vehicle 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. 1.65-1.75, web site www.ipcc.ch/pub/guide.htm. Distribution of passenger car and light duty truck fleet model years for 1983, 1985, 1988, 1991, 1994, and 1997 according to data in the Energy Information Administration's "Residential Transportation Energy Consumption Surveys" for those years. Distribution for passenger cars and light-duty trucks in other years computed by interpolation. Distribution of bus and other truck fleet according to model year computed assuming 10-percent attrition per annum of pre-1983 fleet for each year after 1984. Fuel consumption for other transport from Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, various years), and *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Table 19. U.S. Methane Emissions from Landfills, 1990-2002

| Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Million Metric Tons Methane | | | | | | | | | | | | | |
| Gross Emissions from Landfills | 12.20 | 12.32 | 12.44 | 12.50 | 12.56 | 12.61 | 12.61 | 12.59 | 12.57 | 12.58 | 12.72 | 12.85 | 12.81 |
| Methane Recovered for Energy (-) | 0.73 | 0.77 | 0.83 | 0.89 | 1.03 | 1.06 | 1.22 | 1.45 | 1.75 | 2.00 | 2.19 | 2.40 | 3.00 |
| Methane Assumed Flared (-) | 0.46 | 0.69 | 0.84 | 1.02 | 1.26 | 1.67 | 2.02 | 2.34 | 2.57 | 2.66 | 2.66 | 2.87 | 2.87 |
| Net Emissions | 11.01 | 10.86 | 10.77 | 10.58 | 10.27 | 9.87 | 9.37 | 8.80 | 8.25 | 7.91 | 7.87 | 7.58 | 6.94 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Gross Emissions from Landfills | 280.64 | 283.41 | 286.14 | 287.49 | 288.86 | 289.92 | 290.06 | 289.51 | 289.21 | 289.26 | 292.62 | 295.46 | 294.67 |
| Methane Recovered for Energy (-) | 16.84 | 17.76 | 19.00 | 20.52 | 23.64 | 24.47 | 28.06 | 33.40 | 40.30 | 46.05 | 50.30 | 55.11 | 69.07 |
| Methane Assumed Flared (-) | 10.53 | 15.80 | 19.34 | 23.53 | 28.87 | 38.36 | 46.55 | 53.77 | 59.06 | 61.20 | 61.20 | 65.94 | 65.94 |
| Net Emissions | 253.26 | 249.81 | 247.76 | 243.41 | 236.31 | 227.05 | 215.40 | 202.34 | 189.85 | 182.01 | 181.11 | 174.41 | 159.66 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002).

Sources: Municipal solid waste landfilled from "Nationwide Survey: The State of Garbage in America," *Biocycle* (various years) for years before 2001. Waste generation and waste landfilled for 2001 and 2002 estimated on the basis of annual economic growth. Emissions calculations based on S.A. Thorne 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 Environmental Change* (December 1992), pp. 311-328. Methane recovered and flared from U.S. Environmental Protection Agency, Office of Air and Radiation, Non-CO2 Gases and Sequestration Branch, Landfill Methane Outreach Program, web site www.epa.gov/lmop/.

Table 20. U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-2002

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Million Metric Tons Methane | | | | | | | | | | | | | |
| Cattle | 4.94 | 4.91 | 5.02 | 4.97 | 5.07 | 5.16 | 5.06 | 4.94 | 4.85 | 4.86 | 4.82 | 4.76 | 4.76 |
| Sheep | 0.08 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.08 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |
| Pigs | 0.09 | 0.09 | 0.09 | 0.08 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 |
| Goats | 0.01 | 0.01 | 0.01 | 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 | 0.09 | 0.09 | 0.09 | 0.09 | 0.10 | 0.10 |
| Total | 5.22 | 5.19 | 5.29 | 5.24 | 5.34 | 5.42 | 5.31 | 5.19 | 5.11 | 5.11 | 5.06 | 5.00 | 5.00 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Cattle | 113.68 | 112.90 | 115.41 | 114.25 | 116.59 | 118.67 | 116.37 | 113.54 | 111.53 | 111.75 | 110.75 | 109.38 | 109.43 |
| Sheep | 1.88 | 1.99 | 2.01 | 2.00 | 2.06 | 2.01 | 1.94 | 2.11 | 2.15 | 2.05 | 2.04 | 2.06 | 2.05 |
| Pigs | 2.09 | 2.06 | 1.99 | 1.88 | 1.81 | 1.65 | 1.56 | 1.48 | 1.44 | 1.33 | 1.29 | 1.28 | 1.23 |
| Goats | 0.22 | 0.21 | 0.23 | 0.23 | 0.23 | 0.21 | 0.22 | 0.19 | 0.16 | 0.16 | 0.15 | 0.16 | 0.14 |
| Horses | 2.10 | 2.11 | 2.12 | 2.12 | 2.12 | 2.12 | 2.13 | 2.14 | 2.17 | 2.14 | 2.17 | 2.19 | 2.19 |
| Total | 119.96 | 119.27 | 121.75 | 120.48 | 122.80 | 124.67 | 122.21 | 119.45 | 117.44 | 117.42 | 116.40 | 115.08 | 115.05 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.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 21. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1990-2002

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|---|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Thousand Metric Tons Methane | | | | | | | | | | | | | |
| Cattle | | | | | | | | | | | | | |
| Beef Cattle..... | 176 | 194 | 198 | 202 | 207 | 210 | 209 | 204 | 200 | 198 | 195 | 194 | 194 |
| Dairy Cattle..... | 553 | 556 | 559 | 594 | 631 | 662 | 695 | 732 | 738 | 743 | 758 | 772 | 766 |
| Swine | | | | | | | | | | | | | |
| Market Swine..... | 879 | 1,089 | 1,103 | 1,097 | 1,139 | 1,111 | 1,070 | 1,171 | 1,199 | 1,147 | 1,142 | 1,157 | 1,143 |
| Breeding Swine..... | 152 | 176 | 173 | 174 | 170 | 165 | 160 | 169 | 163 | 152 | 153 | 151 | 146 |
| Poultry | | | | | | | | | | | | | |
| Layers..... | 72 | 73 | 75 | 76 | 78 | 79 | 80 | 81 | 83 | 86 | 88 | 89 | 90 |
| Broilers..... | 69 | 73 | 76 | 85 | 90 | 94 | 96 | 99 | 100 | 103 | 98 | 99 | 101 |
| Other Animals | | | | | | | | | | | | | |
| Sheep..... | 5 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Goats..... | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Horses..... | 27 | 27 | 27 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 29 | 27 | 27 |
| Total..... | 1,934 | 2,191 | 2,214 | 2,259 | 2,344 | 2,351 | 2,340 | 2,485 | 2,512 | 2,459 | 2,464 | 2,492 | 2,469 |
| Thousand Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Cattle | | | | | | | | | | | | | |
| Beef Cattle..... | 4,040 | 4,458 | 4,552 | 4,636 | 4,760 | 4,838 | 4,814 | 4,682 | 4,592 | 4,547 | 4,496 | 4,470 | 4,454 |
| Dairy Cattle..... | 12,717 | 12,790 | 12,849 | 13,665 | 14,502 | 15,236 | 15,992 | 16,829 | 16,970 | 17,092 | 17,430 | 17,746 | 17,614 |
| Swine | | | | | | | | | | | | | |
| Market Swine..... | 20,217 | 25,045 | 25,379 | 25,220 | 26,196 | 25,547 | 24,610 | 26,922 | 27,579 | 26,380 | 26,261 | 26,621 | 26,292 |
| Breeding Swine..... | 3,502 | 4,045 | 3,978 | 4,010 | 3,916 | 3,788 | 3,681 | 3,893 | 3,739 | 3,488 | 3,508 | 3,474 | 3,364 |
| Poultry | | | | | | | | | | | | | |
| Layers..... | 1,663 | 1,682 | 1,726 | 1,755 | 1,794 | 1,814 | 1,838 | 1,871 | 1,913 | 1,979 | 2,016 | 2,052 | 2,076 |
| Broilers..... | 1,590 | 1,671 | 1,749 | 1,966 | 2,059 | 2,158 | 2,199 | 2,266 | 2,298 | 2,372 | 2,255 | 2,284 | 2,313 |
| Other Animals | | | | | | | | | | | | | |
| Sheep..... | 115 | 44 | 42 | 40 | 39 | 35 | 33 | 31 | 31 | 28 | 28 | 27 | 26 |
| Goats..... | 20 | 21 | 21 | 20 | 19 | 18 | 17 | 17 | 16 | 15 | 14 | 13 | 13 |
| Horses..... | 625 | 628 | 631 | 633 | 636 | 638 | 641 | 643 | 646 | 654 | 657 | 628 | 630 |
| Total..... | 44,491 | 50,383 | 50,927 | 51,946 | 53,920 | 54,073 | 53,826 | 57,154 | 57,783 | 56,556 | 56,665 | 57,316 | 56,782 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), Table M-2, web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.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 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), 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 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), Table M-4.

Table 22. U.S. Methane Emissions from Industrial Processes, 1990-2002
(Thousand Metric Tons Methane)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|---|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Thousand Metric Tons Methane | | | | | | | | | | | | | |
| Chemical Production | | | | | | | | | | | | | |
| Ethylene | 17 | 18 | 19 | 19 | 20 | 21 | 22 | 23 | 23 | 25 | 23 | 20 | 21 |
| Ethylene Dichloride | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 |
| Styrene | 15 | 15 | 16 | 18 | 20 | 21 | 22 | 21 | 21 | 22 | 20 | 16 | 18 |
| Methanol | 8 | 8 | 7 | 10 | 10 | 10 | 11 | 12 | 11 | 11 | 9 | 9 | 6 |
| Carbon Black | 14 | 13 | 15 | 16 | 16 | 17 | 17 | 17 | 18 | 18 | 17 | 16 | 17 |
| Total | 56 | 57 | 60 | 66 | 70 | 72 | 75 | 77 | 77 | 80 | 72 | 64 | 66 |
| Iron and Steel Production | | | | | | | | | | | | | |
| Coke ^a | 11 | 9 | 9 | 9 | 8 | 9 | 8 | 7 | 7 | 6 | 7 | 6 | 6 |
| Sinter | 6 | 5 | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 6 | 5 | 5 | 5 |
| Pig Iron | 45 | 40 | 43 | 43 | 44 | 46 | 44 | 45 | 43 | 42 | 43 | 38 | 36 |
| Total | 62 | 54 | 57 | 58 | 59 | 61 | 59 | 58 | 56 | 54 | 55 | 48 | 46 |
| Total Industrial Processes | 117 | 111 | 117 | 124 | 129 | 132 | 134 | 134 | 133 | 133 | 127 | 112 | 112 |
| Thousand Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Chemical Production | | | | | | | | | | | | | |
| Ethylene | 380 | 417 | 427 | 430 | 465 | 488 | 511 | 531 | 540 | 578 | 521 | 470 | 493 |
| Ethylene Dichloride | 58 | 57 | 63 | 75 | 78 | 72 | 79 | 84 | 82 | 91 | 82 | 78 | 78 |
| Styrene | 335 | 339 | 376 | 420 | 470 | 475 | 496 | 476 | 477 | 499 | 452 | 357 | 415 |
| Methanol | 174 | 182 | 169 | 220 | 226 | 225 | 245 | 267 | 262 | 254 | 218 | 211 | 137 |
| Carbon Black | 331 | 310 | 345 | 367 | 378 | 386 | 395 | 402 | 407 | 415 | 384 | 363 | 386 |
| Total | 1,277 | 1,304 | 1,380 | 1,512 | 1,616 | 1,646 | 1,726 | 1,760 | 1,767 | 1,837 | 1,658 | 1,479 | 1,509 |
| Iron and Steel Production | | | | | | | | | | | | | |
| Coke ^a | 251 | 206 | 202 | 199 | 191 | 201 | 193 | 172 | 163 | 148 | 155 | 130 | 132 |
| Sinter | 141 | 122 | 132 | 143 | 140 | 144 | 136 | 132 | 125 | 127 | 124 | 106 | 104 |
| Pig Iron | 1,028 | 913 | 981 | 997 | 1,022 | 1,053 | 1,023 | 1,027 | 998 | 958 | 991 | 872 | 833 |
| Total | 1,420 | 1,241 | 1,314 | 1,339 | 1,353 | 1,399 | 1,352 | 1,330 | 1,286 | 1,233 | 1,271 | 1,108 | 1,068 |
| Total Industrial Processes | 2,697 | 2,545 | 2,694 | 2,851 | 2,969 | 3,044 | 3,078 | 3,090 | 3,053 | 3,070 | 2,928 | 2,587 | 2,577 |

^aBased 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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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, 1990-2002

| | Nitrous Oxide | Carbon Dioxide Equivalent |
|---|---------------|---------------------------|
| Estimated 2002 Emissions (Thousand Metric Tons) | 1,125.2 | 333,056 |
| Change Compared to 2001 (Thousand Metric Tons) | -13 | -3,721 |
| Change from 2001 (Percent) | -1.1% | -1.1% |
| Change Compared to 1990 (Thousand Metric Tons) | -2.6 | -777 |
| Change from 1990 (Percent) | -0.2% | -0.2% |

Estimated U.S. anthropogenic nitrous oxide emissions totaled 1,125 thousand metric tons in 2002, 1.1 percent less than in 2001 and 0.2 percent below 1990 levels (Table 23). Almost all of the decrease from 2001 can be attributed to nitrogen fertilization of agricultural soils. Emissions from this source decreased by 16 thousand metric tons of nitrous oxide compared with 2001 levels. Emissions of nitrous oxide from industrial sources in 2002 increased by 3 thousand metric tons from their 2001 level.

The decrease in emissions of nitrous oxide from 1990 can be attributed to emissions from nitrogen fertilization of agricultural soils and industrial sources (adipic acid and nitric acid production), which fell by a combined 67 thousand metric tons between 1990 and 2002, more than offsetting the increase of 59 thousand metric tons in emissions from mobile combustion sources since 1990.

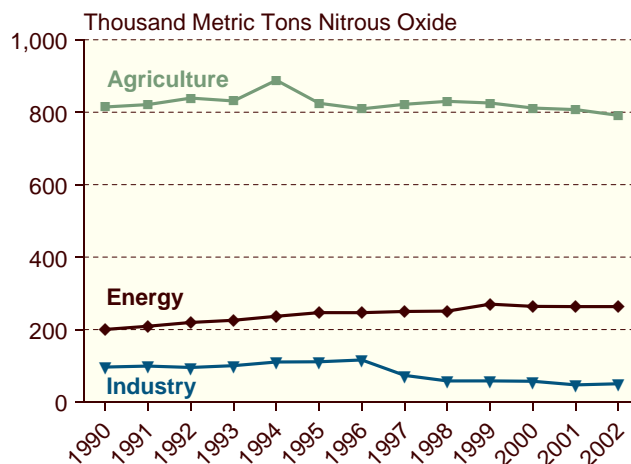
Weighted by global warming potential, total nitrous oxide emissions in 2002 were equivalent to 333.1 million metric tons carbon dioxide, or 4.9 percent of total U.S. greenhouse gas emissions. In 2001, total nitrous oxide emissions were equivalent to 336.8 million metric tons of carbon dioxide, or 4.9 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 70.3 percent of the total. Nitrogen fertilization of agricultural soils represents 73.7 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 791 thousand metric tons (or 234.2 million metric tons carbon dioxide equivalent) in 2002, 2.0 percent below 2001 levels and 2.8 percent below 1990 levels (Figure 4).

There are large uncertainties connected with the emissions consequences of adding nitrogen to agricultural soils. Models used for estimation are based on limited sources of experimental data.⁶⁵ The uncertainty increases when moving from emissions associated with animal manure to soil mineralization and atmospheric deposition, where both estimating emissions and partitioning emissions between anthropogenic and biogenic sources become increasingly difficult.

The second-largest source of anthropogenic nitrous oxide emissions is energy consumption, which includes mobile source combustion from passenger cars, buses,

Figure 4. U.S. Emissions of Nitrous Oxide by Source, 1990-2002



Source: Estimates presented in this chapter.

⁶⁵Intergovernmental 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.

Principal Sources of U.S. Anthropogenic Nitrous Oxide Emissions, 1990-2002

| Source | Thousand Metric Tons Nitrous Oxide | | Percent Change | |
|-------------|------------------------------------|------|----------------|-----------|
| | 1990 | 2002 | 1990-2002 | 2001-2002 |
| Energy | 200 | 263 | 31.5% | * |
| Agriculture | 814 | 791 | -2.8% | -2.0% |
| Industrial | 96 | 50 | -47.8% | 6.5% |

*Less than 0.05 percent.

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 263 thousand metric tons of nitrous oxide or 78.0 million metric tons carbon dioxide equivalent in 2002 (23.4 percent of total U.S. nitrous oxide emissions), only slightly (less than 0.05 percent) lower than in 2001 but 31.5 percent higher than in 1990. Industrial production of adipic and nitric acid, which releases nitrous oxide as a byproduct, accounted for emissions of 50 thousand metric tons of nitrous oxide or 14.9 million metric tons carbon dioxide equivalent in 2002 (4.5 percent of total U.S. nitrous oxide emissions), a 6.5-percent increase from 2001 levels and a 47.8-percent decrease from 1990 levels. The increase in emissions from this source in 2002 is a result of increased production of both adipic acid and nitric acid by 86 and 336 thousand metric tons, respectively, compared with compared with 2001 (10.3 and 4.7 percent, respectively). The large decline in emissions of nitrous oxide from adipic acid production since 1990 is a result of the implementation 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, 1990-2002

| | |
|--|-------|
| Estimated 2002 Emissions (Thousand Metric Tons Nitrous Oxide) | 263 |
| Change Compared to 2001 (Thousand Metric Tons Nitrous Oxide) | * |
| Change from 2001 (Percent) | ** |
| Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide) | 63 |
| Change from 1990 (Percent) | 31.5% |

*Less than 0.5 thousand metric tons.

**Less than 0.05 percent.

The energy use category includes nitrous oxide emissions from both mobile and stationary sources as byproducts of fuel combustion. Estimated 2002 energy-related emissions were 263 thousand metric tons, or 23.4 percent of total U.S. anthropogenic nitrous oxide emissions (Table 23). Emissions from energy use are dominated by mobile combustion (81.4 percent of nitrous oxide emissions from energy use in 2002).

Mobile Combustion

Nitrous oxide emissions from mobile source combustion in 2002 were 214 thousand metric tons or 63.5 million metric tons carbon dioxide equivalent, a decrease of 0.2 thousand metric tons nitrous oxide or 0.1 million metric tons carbon dioxide equivalent (0.1 percent) from 2001 levels (Table 24). 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 are the source of 94.3 percent of nitrous oxide emissions from mobile combustion (Table 24).

Nitrous oxide emissions from motor vehicles are caused primarily by the conversion of nitrogen oxides (NO_x) into nitrous oxide (N₂O) 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 1995 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 1995 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 2002, estimated nitrous oxide emissions from stationary combustion sources were 49 thousand metric tons or

14.5 million metric tons carbon dioxide equivalent, 0.3 percent higher than in 2001 and 9.8 percent higher than in 1990 (Table 25). The emissions increase from this source between 1990 and 2002 can be attributed principally to coal-fired electricity generation, which grew in response to the growing demand for electricity and lower costs and improved availability at coal-fired power plants. Coal-fired combustion systems produced 63.6 percent of the 2002 emissions of nitrous oxide from stationary combustion. During combustion, nitrous oxide is produced as a result of chemical interactions between nitrogen oxides (mostly NO₂) 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, 1990-2002

| | |
|--|-------|
| Estimated 2002 Emissions (Thousand Metric Tons Nitrous Oxide) | 791 |
| Change Compared to 2001 (Thousand Metric Tons Nitrous Oxide) | -16 |
| Change from 2001 (Percent) | -2.0% |
| Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide) | -23 |
| Change from 1990 (Percent) | -2.8% |

Nitrous oxide emissions from agricultural activities fell by 2.8 percent between 1990 and 2002. Agricultural activities were responsible for 70.3 percent of U.S. nitrous oxide emissions in 2002, roughly the same percentage that agricultural practices contribute to nitrous oxide emissions globally.⁶⁶ Nitrogen fertilization of agricultural soils accounted for 73.7 percent of U.S. agricultural emissions of nitrous oxide (Table 23). 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 2002.

Nitrogen Fertilization of Agricultural Soils

EIA estimates that a total of 583 thousand metric tons of nitrous oxide (or 172.5 million metric tons carbon dioxide equivalent) was released into the atmosphere as a result of direct and indirect emissions associated with fertilization practices in 2002 (Table 26). Estimated emissions decreased by 2.5 percent compared with 2001 levels and were 3.4 percent lower than in 1990. Nitrous oxide emissions from the application of nitrogen-based fertilizers and biological fixation in crops accounted for 57.3 percent of total nitrous oxide emissions from this source during 2002.

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.⁶⁷ 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. Adding excess nitrogen to the soil also enriches ground and surface waters, such as rivers and streams, which generate indirect emissions of nitrous oxide. Additional indirect emissions occur from "atmospheric deposition," in which soils emit other nitrogen compounds that react to form nitrous oxide in the atmosphere.

Crop Residue Burning

In 2002, 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 0.5 thousand metric tons nitrous oxide (4.8 percent) from 2001 levels (Table 23). 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).

Solid Waste of Domesticated Animals

Estimated 2002 nitrous oxide emissions from animal waste management were 207 thousand metric tons (or 61.2 million metric tons carbon dioxide equivalent), down by 0.5 percent from 2001 levels and 1.3 percent lower than 1990 levels (Table 27), making animal waste the second-largest U.S. agricultural source of nitrous oxide emissions, after nitrogen fertilization of soils.

⁶⁶A.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.

⁶⁷A.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).

Nitrous oxide emissions from animal waste are dominated by emissions from cattle waste, which account for 92.6 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 nearly to 1991 levels.

Waste Management

U.S. Nitrous Oxide Emissions from Waste Management, 1990-2002

| | |
|--|-------|
| Estimated 2002 Emissions (Thousand Metric Tons Nitrous Oxide) | 20 |
| Change Compared to 2001 (Thousand Metric Tons Nitrous Oxide) | * |
| Change from 2001 (Percent) | 1.4% |
| Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide) | 4 |
| Change from 1990 (Percent) | 22.1% |

*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 2002, 1.8 percent of all U.S. anthropogenic nitrous oxide emissions (Table 23). During 2002, emissions from human sewage in wastewater were responsible for 95.7 percent of the estimated emissions from this source, and the remainder

was associated with waste combustion. Estimated emissions from waste management increased by 1.4 percent between 2001 and 2002 and by 22.1 percent between 1990 and 2002. 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.

Waste Combustion

In 2002, estimated nitrous oxide emissions from waste combustion were 1 thousand metric tons, down 5.6 percent from 2001 levels and 3.6 percent above 1990 levels. Data on the amount of waste generated in the United States in 2002 were not available in time for this report; therefore, EIA scaled the 2002 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 2001 to 2002, and the total volume of waste generated is estimated to have increased by 9.0 percent. The total volume of waste generated in the United States increased by 58.2 percent between 1990 and 2002; however, the share of waste burned in 2002 was just 7.5 percent, compared with 11.5 percent in 1990.⁶⁸

Human Sewage in Wastewater

In 2002, nitrous oxide emissions from wastewater were 19 thousand metric tons (or 5.7 million metric tons carbon dioxide equivalent), a 1.3-percent increase from 2001 levels and a 23.7-percent increase from the 1990 level (Table 23). Estimates of nitrous oxide emissions from human waste are scaled to population size and per capita protein intake. U.S. population has grown by 13.7 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 6.5 percent above 1990 levels. Data on protein intake are taken from the United Nations Food and Agriculture Organization (FAO).⁶⁹

Nitrous oxide is emitted from wastewater that contains nitrogen-based organic materials, such as those found in human or animal waste. Two natural processes—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),⁷⁰ and nitrogen concentration.

⁶⁸"Nationwide Survey: The State of Garbage in America 1999," *Biocycle* (April 2000). Waste streams were estimated for 2002 by scaling to economic growth, and the share of waste combusted was held constant at the 2001 level.

⁶⁹Food and Agriculture Organization of the United Nations, statistical databases, web site <http://apps.fao.org>.

⁷⁰Biochemical oxygen demand is a measure of the organic content within the wastewater that is subject to decomposition.

Industrial Sources

U.S. Nitrous Oxide Emissions from Industrial Sources, 1990-2002

| | |
|--|--------|
| Estimated 2002 Emissions (Thousand Metric Tons Nitrous Oxide) | 50 |
| Change Compared to 2001 (Thousand Metric Tons Nitrous Oxide) | 3 |
| Change from 2001 (Percent) | 6.5% |
| Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide) | -46 |
| Change from 1990 (Percent) | -47.8% |

Emissions of nitrous oxide from industrial sources were 50 thousand metric tons (or 14.9 million metric tons carbon dioxide equivalent) in 2002, an increase of 3 thousand metric tons or 0.9 million metric tons carbon dioxide equivalent (6.5 percent) from 2001 and a decrease of 46 thousand metric tons or 13.7 million metric tons carbon dioxide equivalent (47.8 percent) since 1990. Nitrous oxide is emitted as a byproduct of certain chemical production processes. Table 28 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 rose from 12 thousand metric tons of nitrous oxide (or 3.5 million metric tons carbon dioxide equivalent) in 2001 to 13 thousand metric tons (or 3.9 million metric tons carbon dioxide equivalent) in 2002—an increase of 10.3 percent. As discussed below, emissions from this source have been in the range of 12 to 14 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.⁷¹ 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 28).

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.⁷² 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.⁷³ Estimated emissions of nitrous oxide from uncontrolled adipic acid production decreased from 22 thousand metric tons in 1997 to 8 thousand metric tons in 2002, and 2002 emissions of nitrous oxide from controlled plants remained relatively 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 6.8 million metric tons of nitric acid manufactured in 2002 resulted in estimated emissions of 37 thousand metric tons of nitrous oxide, equivalent to 11.0 million metric tons of carbon dioxide (Table 28). This estimate was 5.2 percent higher than 2001 levels and 6.1 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 an uncertainty of plus or minus 75 percent in the emissions estimate.⁷⁴ Nitric acid, a primary ingredient in fertilizers, usually is manufactured by oxidizing ammonia (NH₃) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation.

⁷¹M.H. Thiemens and W.C. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 1991).

⁷²Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

⁷³R.A. Reimer, R.A. Parrett, and C.S. Slaten, "Abatement of N₂O Emissions Produced in Adipic Acid," in *Proceedings of the Fifth International Workshop on Nitrous Oxide Emissions* (Tsukuba, Japan, July 1992).

⁷⁴Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris France, 1997), p 2.18, web site www.ipcc.ch/pub/guide.htm.

Table 23. Estimated U.S. Emissions of Nitrous Oxide, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Thousand Metric Tons Nitrous Oxide | | | | | | | | | | | | | |
| Energy | | | | | | | | | | | | | |
| Mobile Combustion | 156 | 165 | 175 | 180 | 190 | 200 | 198 | 201 | 203 | 221 | 214 | 215 | 214 |
| Stationary Combustion. | 45 | 44 | 45 | 46 | 46 | 47 | 49 | 49 | 48 | 49 | 50 | 49 | 49 |
| Total | 200 | 209 | 220 | 226 | 237 | 247 | 247 | 250 | 251 | 270 | 264 | 263 | 263 |
| Agriculture | | | | | | | | | | | | | |
| Nitrogen Fertilization of Soils | 604 | 609 | 624 | 613 | 667 | 601 | 587 | 604 | 616 | 613 | 601 | 598 | 583 |
| Crop Residue Burning | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Solid Waste of Domesticated Animals . . | 209 | 211 | 214 | 216 | 220 | 222 | 220 | 216 | 213 | 211 | 209 | 208 | 207 |
| Total | 814 | 821 | 839 | 831 | 888 | 825 | 809 | 822 | 830 | 826 | 812 | 807 | 791 |
| Waste Management | | | | | | | | | | | | | |
| Waste Combustion. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Human Sewage in Wastewater | 16 | 16 | 16 | 16 | 17 | 17 | 17 | 17 | 18 | 18 | 19 | 19 | 19 |
| Total | 17 | 17 | 17 | 17 | 18 | 18 | 18 | 18 | 18 | 19 | 20 | 20 | 20 |
| Industrial Processes | 96 | 99 | 95 | 100 | 110 | 111 | 116 | 74 | 58 | 58 | 57 | 47 | 50 |
| Total | 1,128 | 1,146 | 1,171 | 1,174 | 1,253 | 1,200 | 1,190 | 1,164 | 1,158 | 1,173 | 1,153 | 1,138 | 1,125 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Energy | | | | | | | | | | | | | |
| Mobile Combustion | 46.1 | 48.9 | 51.7 | 53.3 | 56.3 | 59.2 | 58.6 | 59.5 | 60.0 | 65.5 | 63.2 | 63.5 | 63.5 |
| Stationary Combustion. | 13.2 | 13.1 | 13.3 | 13.5 | 13.7 | 13.8 | 14.4 | 14.5 | 14.3 | 14.5 | 14.9 | 14.4 | 14.5 |
| Total | 59.3 | 61.9 | 65.0 | 66.8 | 70.1 | 73.0 | 73.0 | 74.0 | 74.3 | 80.0 | 78.2 | 78.0 | 78.0 |
| Agriculture | | | | | | | | | | | | | |
| Nitrogen Fertilization of Soils | 178.6 | 180.1 | 184.6 | 181.6 | 197.4 | 178.0 | 173.9 | 178.9 | 182.2 | 181.4 | 177.7 | 176.9 | 172.5 |
| Crop Residue Burning | 0.5 | 0.5 | 0.5 | 0.4 | 0.6 | 0.5 | 0.5 | 0.5 | 0.6 | 0.5 | 0.6 | 0.6 | 0.5 |
| Solid Waste of Domesticated Animals . . | 62.0 | 62.5 | 63.2 | 64.0 | 65.0 | 65.7 | 65.2 | 63.9 | 62.9 | 62.4 | 61.9 | 61.5 | 61.2 |
| Total | 241.1 | 243.1 | 248.3 | 246.0 | 263.0 | 244.1 | 239.6 | 243.3 | 245.7 | 244.4 | 240.2 | 238.9 | 234.2 |
| Waste Management | | | | | | | | | | | | | |
| Waste Combustion. | 0.3 | 0.2 | 0.3 | 0.2 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 |
| Human Sewage in Wastewater | 4.6 | 4.8 | 4.8 | 4.9 | 5.0 | 5.0 | 5.1 | 5.1 | 5.2 | 5.4 | 5.6 | 5.6 | 5.7 |
| Total | 4.9 | 5.0 | 5.1 | 5.1 | 5.3 | 5.3 | 5.4 | 5.4 | 5.4 | 5.7 | 5.9 | 5.9 | 6.0 |
| Industrial Processes | 28.6 | 29.4 | 28.2 | 29.7 | 32.7 | 32.9 | 34.3 | 21.8 | 17.2 | 17.2 | 17.0 | 14.0 | 14.9 |
| Total | 333.8 | 339.3 | 346.7 | 347.6 | 371.0 | 355.3 | 352.3 | 344.4 | 342.6 | 347.2 | 341.2 | 336.8 | 333.1 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

Table 24. U.S. Nitrous Oxide Emissions from Mobile Combustion, 1990-2002

| Item | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Thousand Metric Tons Nitrous Oxide | | | | | | | | | | | | | |
| Motor Vehicles | | | | | | | | | | | | | |
| Passenger Cars | 99 | 107 | 115 | 112 | 111 | 108 | 109 | 109 | 110 | 112 | 108 | 107 | 106 |
| Buses | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Motorcycles..... | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Light-Duty Trucks | 38 | 40 | 41 | 50 | 60 | 72 | 69 | 71 | 72 | 88 | 84 | 87 | 88 |
| Other Trucks..... | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 8 | 8 | 8 | 8 | 8 | 8 |
| Total | 144 | 153 | 162 | 168 | 178 | 188 | 185 | 189 | 190 | 209 | 200 | 202 | 203 |
| Other Mobile Sources..... | 12 | 12 | 12 | 12 | 12 | 12 | 13 | 12 | 12 | 13 | 13 | 12 | 12 |
| Total | 156 | 165 | 175 | 180 | 190 | 200 | 198 | 201 | 203 | 221 | 214 | 215 | 214 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Motor Vehicles | | | | | | | | | | | | | |
| Passenger Cars | 29 | 32 | 34 | 33 | 33 | 32 | 32 | 32 | 32 | 33 | 32 | 32 | 31 |
| Buses | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles..... | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Light-Duty Trucks | 11 | 12 | 12 | 15 | 18 | 21 | 20 | 21 | 21 | 26 | 25 | 26 | 26 |
| Other Trucks..... | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Total | 42 | 45 | 48 | 50 | 53 | 56 | 55 | 56 | 56 | 62 | 59 | 60 | 60 |
| Other Mobile Sources..... | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 |
| Total | 46 | 49 | 52 | 53 | 56 | 59 | 59 | 59 | 60 | 65 | 63 | 64 | 63 |

*Less than 500 metric tons of nitrous oxide.

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 25. U.S. Nitrous Oxide Emissions from Stationary Combustion, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Thousand Metric Tons Nitrous Oxide | | | | | | | | | | | | | |
| Residential | | | | | | | | | | | | | |
| Coal | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Fuel Oil ^a | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Natural Gas | * | * | * | * | * | * | 1 | * | * | * | * | * | * |
| Wood | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| Total | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| Commercial | | | | | | | | | | | | | |
| Coal | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Fuel Oil ^a | 1 | 1 | 1 | * | * | * | * | * | * | * | * | * | * |
| Natural Gas | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Wood | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Total | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Industrial | | | | | | | | | | | | | |
| Coal | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Fuel Oil ^a | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 5 | 6 | 6 | 6 | 6 |
| Natural Gas | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Wood | 6 | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 6 | 6 | 6 | 6 | 6 |
| Total | 10 | 9 | 10 | 9 | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 10 | 9 |
| Electric Power | | | | | | | | | | | | | |
| Coal | 23 | 23 | 23 | 24 | 24 | 25 | 26 | 27 | 27 | 27 | 28 | 28 | 28 |
| Fuel Oil ^a | 1 | 1 | 1 | 1 | 1 | * | * | 1 | 1 | 1 | 1 | 1 | 1 |
| Natural Gas | * | * | * | * | * | * | * | * | * | * | 1 | 1 | 1 |
| Wood | 1 | * | 1 | 1 | 1 | * | 1 | 1 | 1 | 1 | 1 | * | 1 |
| Total | 24 | 24 | 25 | 26 | 26 | 26 | 27 | 28 | 29 | 29 | 30 | 30 | 30 |
| Fuel Totals | | | | | | | | | | | | | |
| Coal | 27 | 27 | 27 | 28 | 28 | 28 | 30 | 30 | 30 | 30 | 32 | 31 | 31 |
| Fuel Oil^a | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 8 | 8 | 8 | 8 |
| Natural Gas | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Wood | 9 | 9 | 9 | 9 | 9 | 10 | 10 | 9 | 9 | 9 | 9 | 8 | 8 |
| Total | 45 | 44 | 45 | 46 | 46 | 47 | 49 | 49 | 48 | 49 | 50 | 49 | 49 |

See notes and sources at end of table.

Table 25. U.S. Nitrous Oxide Emissions from Stationary Combustion, 1990-2002 (Continued)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Thousand Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Residential | | | | | | | | | | | | | |
| Coal | 11 | 10 | 10 | 10 | 9 | 7 | 7 | 7 | 5 | 6 | 5 | 5 | 5 |
| Fuel Oil ^a | 251 | 249 | 255 | 259 | 254 | 247 | 266 | 255 | 235 | 263 | 279 | 275 | 272 |
| Natural Gas | 129 | 133 | 137 | 145 | 142 | 142 | 153 | 145 | 133 | 138 | 146 | 140 | 144 |
| Wood | 677 | 714 | 751 | 638 | 626 | 694 | 693 | 504 | 451 | 482 | 504 | 474 | 408 |
| Total | 1,067 | 1,106 | 1,154 | 1,052 | 1,030 | 1,090 | 1,119 | 912 | 824 | 889 | 934 | 894 | 828 |
| Commercial | | | | | | | | | | | | | |
| Coal | 54 | 49 | 49 | 50 | 49 | 49 | 51 | 54 | 38 | 43 | 38 | 40 | 40 |
| Fuel Oil ^a | 170 | 162 | 153 | 139 | 141 | 131 | 134 | 126 | 118 | 118 | 135 | 132 | 132 |
| Natural Gas | 77 | 80 | 82 | 84 | 85 | 88 | 92 | 94 | 88 | 89 | 94 | 89 | 91 |
| Wood | 45 | 48 | 51 | 54 | 54 | 54 | 58 | 57 | 56 | 61 | 62 | 48 | 48 |
| Total | 346 | 339 | 335 | 326 | 328 | 322 | 335 | 330 | 300 | 311 | 329 | 309 | 311 |
| Industrial | | | | | | | | | | | | | |
| Coal | 1,131 | 1,064 | 1,030 | 1,023 | 1,028 | 1,020 | 995 | 977 | 914 | 893 | 906 | 929 | 872 |
| Fuel Oil ^a | 1,478 | 1,426 | 1,532 | 1,503 | 1,572 | 1,538 | 1,617 | 1,659 | 1,628 | 1,678 | 1,629 | 1,647 | 1,667 |
| Natural Gas | 242 | 245 | 255 | 259 | 261 | 274 | 283 | 283 | 279 | 268 | 271 | 247 | 242 |
| Wood | 1,680 | 1,643 | 1,702 | 1,729 | 1,841 | 1,924 | 1,961 | 2,017 | 1,867 | 1,887 | 1,906 | 1,681 | 1,753 |
| Total | 2,851 | 2,736 | 2,817 | 2,785 | 2,860 | 2,832 | 2,895 | 2,920 | 2,820 | 2,839 | 2,806 | 2,823 | 2,781 |
| Electric Power | | | | | | | | | | | | | |
| Coal | 6,770 | 6,772 | 6,862 | 7,166 | 7,193 | 7,278 | 7,680 | 7,878 | 8,008 | 8,034 | 8,426 | 8,205 | 8,328 |
| Fuel Oil ^a | 228 | 214 | 177 | 201 | 189 | 135 | 146 | 166 | 233 | 216 | 204 | 229 | 162 |
| Natural Gas | 94 | 97 | 100 | 101 | 114 | 123 | 110 | 118 | 133 | 140 | 151 | 153 | 161 |
| Wood | 150 | 147 | 163 | 175 | 177 | 146 | 161 | 160 | 160 | 161 | 156 | 147 | 157 |
| Total | 7,242 | 7,229 | 7,302 | 7,642 | 7,673 | 7,682 | 8,097 | 8,321 | 8,534 | 8,551 | 8,937 | 8,733 | 8,809 |
| Fuel Totals | | | | | | | | | | | | | |
| Coal | 7,965 | 7,895 | 7,951 | 8,248 | 8,278 | 8,354 | 8,733 | 8,916 | 8,965 | 8,976 | 9,375 | 9,179 | 9,245 |
| Fuel Oil^a | 2,128 | 2,051 | 2,117 | 2,102 | 2,155 | 2,051 | 2,163 | 2,205 | 2,214 | 2,275 | 2,247 | 2,282 | 2,232 |
| Natural Gas | 541 | 555 | 575 | 589 | 601 | 627 | 638 | 640 | 633 | 634 | 661 | 629 | 638 |
| Wood | 2,552 | 2,551 | 2,668 | 2,595 | 2,697 | 2,818 | 2,873 | 2,738 | 2,534 | 2,591 | 2,628 | 2,350 | 2,366 |
| Total | 13,187 | 13,051 | 13,310 | 13,534 | 13,731 | 13,850 | 14,406 | 14,499 | 14,345 | 14,476 | 14,911 | 14,441 | 14,482 |

*Less than 500 metric tons nitrous oxide.

P = preliminary data.

^aFuel oil use in the residential sector consists of distillate fuel only. In the other sectors it includes both distillate and residual fuel oil.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 2002); and *Monthly Energy Review*, DOE/EIA-0035(2003/08) (Washington, DC, August 2003).

Table 26. U.S. Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils, 1990-2002
(Thousand Metric Tons Nitrous Oxide)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Thousand Metric Tons Nitrous Oxide | | | | | | | | | | | | | |
| Direct Emissions | | | | | | | | | | | | | |
| Nitrogen Fertilizers | 179 | 182 | 183 | 193 | 195 | 173 | 159 | 159 | 161 | 161 | 154 | 150 | 153 |
| Animal Manure | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Crop Residues | 94 | 91 | 105 | 86 | 113 | 94 | 106 | 114 | 117 | 113 | 116 | 116 | 110 |
| Soil Mineralization | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 11 | 11 | 11 | 11 |
| Biological Fixation in Crops | 171 | 174 | 173 | 165 | 187 | 179 | 178 | 187 | 194 | 193 | 191 | 195 | 181 |
| Sewage Sludge | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| Total Direct Emissions | 459 | 462 | 476 | 458 | 510 | 461 | 459 | 475 | 486 | 482 | 476 | 476 | 459 |
| Indirect Emissions | | | | | | | | | | | | | |
| Soil Leaching | 123 | 125 | 126 | 132 | 134 | 119 | 109 | 110 | 110 | 111 | 106 | 103 | 105 |
| Atmospheric Deposition | 22 | 22 | 22 | 23 | 24 | 21 | 20 | 20 | 20 | 20 | 19 | 18 | 19 |
| Total Indirect Emissions | 144 | 147 | 148 | 155 | 157 | 140 | 129 | 129 | 130 | 130 | 125 | 122 | 124 |
| Total | 604 | 609 | 624 | 613 | 667 | 601 | 587 | 604 | 616 | 613 | 601 | 598 | 583 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Direct Emissions | | | | | | | | | | | | | |
| Nitrogen Fertilizers | 53 | 54 | 54 | 57 | 58 | 51 | 47 | 47 | 48 | 48 | 46 | 44 | 45 |
| Animal Manure | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Crop Residues | 28 | 27 | 31 | 25 | 33 | 28 | 31 | 34 | 35 | 33 | 34 | 34 | 33 |
| Soil Mineralization | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Biological Fixation in Crops | 51 | 51 | 51 | 49 | 55 | 53 | 53 | 55 | 57 | 57 | 56 | 58 | 54 |
| Sewage Sludge | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Total Direct Emissions | 136 | 137 | 141 | 136 | 151 | 137 | 136 | 141 | 144 | 143 | 141 | 141 | 136 |
| Indirect Emissions | | | | | | | | | | | | | |
| Soil Leaching | 36 | 37 | 37 | 39 | 40 | 35 | 32 | 32 | 33 | 33 | 31 | 31 | 31 |
| Atmospheric Deposition | 6 | 7 | 7 | 7 | 7 | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 6 |
| Total Indirect Emissions | 43 | 43 | 44 | 46 | 47 | 41 | 38 | 38 | 38 | 39 | 37 | 36 | 37 |
| Total | 179 | 180 | 185 | 182 | 197 | 178 | 174 | 179 | 182 | 181 | 178 | 177 | 173 |

*Less than 0.5 million 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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). 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 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

Table 27. U.S. Nitrous Oxide Emissions from Solid Waste of Domesticated Animals, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Thousand Metric Tons Nitrous Oxide | | | | | | | | | | | | | |
| Cattle..... | 194 | 196 | 198 | 200 | 204 | 206 | 205 | 200 | 197 | 195 | 194 | 192 | 192 |
| Swine..... | 5 | 5 | 5 | 5 | 6 | 5 | 5 | 6 | 6 | 6 | 5 | 6 | 5 |
| Poultry..... | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Sheep..... | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| Goats..... | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Horses..... | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 |
| Total..... | 209 | 211 | 214 | 216 | 220 | 222 | 220 | 216 | 213 | 211 | 209 | 208 | 207 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Cattle..... | 58 | 58 | 59 | 59 | 60 | 61 | 61 | 59 | 58 | 58 | 57 | 57 | 57 |
| Swine..... | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Poultry..... | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Sheep..... | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Goats..... | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Horses..... | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Total..... | 62 | 62 | 63 | 64 | 65 | 66 | 65 | 64 | 63 | 62 | 62 | 61 | 61 |

*Less than 0.5 million metric tons carbon dioxide equivalent.

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 28. U.S. Nitrous Oxide Emissions from Industrial Sources, 1990-2002

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--|-----------|-----------|-----------|------------|------------|------------|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Thousand Metric Tons Nitrous Oxide | | | | | | | | | | | | | |
| Adipic Acid | | | | | | | | | | | | | |
| Controlled Sources..... | 3 | 4 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 |
| Uncontrolled Sources..... | 54 | 56 | 52 | 56 | 63 | 63 | 66 | 22 | 7 | 8 | 9 | 7 | 8 |
| Total..... | 57 | 60 | 55 | 59 | 67 | 67 | 70 | 27 | 12 | 14 | 14 | 12 | 13 |
| Nitric Acid..... | 40 | 40 | 41 | 41 | 43 | 44 | 46 | 47 | 46 | 45 | 43 | 35 | 37 |
| Total Known Industrial Sources..... | 96 | 99 | 95 | 100 | 110 | 111 | 116 | 74 | 58 | 58 | 57 | 47 | 50 |
| Million Metric Tons Carbon Dioxide Equivalent | | | | | | | | | | | | | |
| Adipic Acid | | | | | | | | | | | | | |
| Controlled Sources..... | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 |
| Uncontrolled Sources..... | 16 | 17 | 15 | 17 | 19 | 19 | 20 | 6 | 2 | 2 | 3 | 2 | 2 |
| Total..... | 17 | 18 | 16 | 18 | 20 | 20 | 21 | 8 | 3 | 4 | 4 | 4 | 4 |
| Nitric Acid..... | 12 | 12 | 12 | 12 | 13 | 13 | 14 | 14 | 14 | 13 | 13 | 10 | 11 |
| Total Known Industrial Sources..... | 29 | 29 | 28 | 30 | 33 | 33 | 34 | 22 | 17 | 17 | 17 | 14 | 15 |

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 2001*, DOE/EIA-0573(2001) (Washington, DC, December 2002). Totals may not equal sum of components due to independent rounding.

Sources: Data sources and methods documented in Energy Information Administration, *Documentation: Emissions of Greenhouse Gases in the United States 2002* (to be published).

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

Overview

Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2002

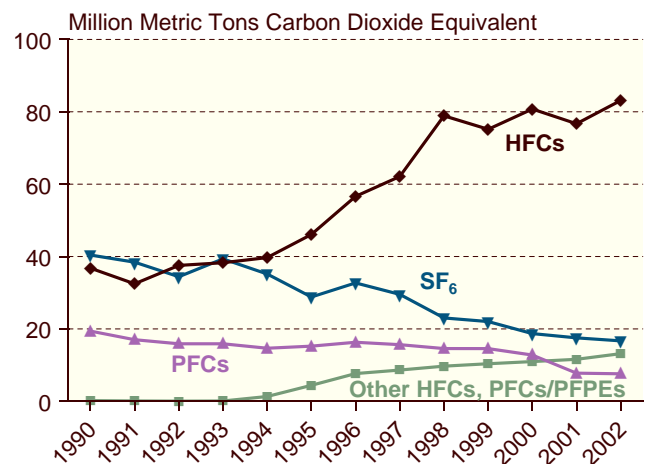
| | |
|--|-------|
| Estimated 2002 Emissions (Million Metric Tons Carbon Dioxide Equivalent) | 120.6 |
| Change Compared to 2001 (Million Metric Tons Carbon Dioxide Equivalent) | 7.0 |
| Change from 2001 (Percent) | 6.2% |
| Change Compared to 1990 (Million Metric Tons Carbon Dioxide Equivalent) | 23.8 |
| Change from 1990 (Percent) | 24.6% |

In addition to the three principal greenhouse gases (carbon dioxide, methane, and nitrous oxide), there are other gases that account for 1.8 percent of total U.S. greenhouse gas emissions when weighted by 100-year global warming potential (GWP).⁷⁵ The U.S. Environmental Protection Agency (EPA) estimates total emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) in 2002 at 120.6 million metric tons carbon dioxide equivalent—a 6.2-percent increase over 2001 emissions and a 24.6-percent increase over 1990 emissions. Table 29 summarizes U.S. emissions of HFCs, PFCs, and SF₆ from 1990 to 2002, and Table 30 shows the corresponding emissions in metric tons carbon dioxide equivalent.

In summary, revised EPA data for 1990-2001 and new estimates for 2002 show that emissions of HFCs have risen overall; annual emissions of PFCs declined overall

from 1990 through 2000 and then dropped more significantly in 2001 and 2002; and SF₆ emissions have declined overall, falling to less than one-half their 1990 level by 2002 (Figure 5). 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.⁷⁶ The trend in HFC emissions is expected to accelerate 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 SF₆ have declined overall in the magnesium and utility sectors since 1990, despite an increase in use in the semiconductor industry.

Figure 5. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2002



Source: Estimates presented in this chapter.

⁷⁵Preliminary data estimates received by EIA from the U.S. Environmental Protection Agency (EPA), Office of Air and Radiation, August 2003. 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.

⁷⁶In previous years, this chapter included emissions estimates and accompanying discussions for a variety of ozone-depleting substances, such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and bromofluorocarbons (halons) and criteria pollutants, such as carbon monoxide (CO), nitrogen oxides (NO_x), and nonmethane volatile organic compounds (NMVOCs), which have indirect effects on climate through their effects on atmospheric concentrations of greenhouse gases. Although no longer included in the main body of this report, emissions estimates for ozone-depleting substances and criteria pollutants are included in Energy Information Administration, *Documentation: Emissions of Greenhouse Gases in the United States 2002* (to be published).

The Intergovernmental Panel on Climate Change (IPCC) defines three classes of “other gases” to be included in estimating emissions: HFCs, PFCs, and SF₆. This chapter describes emissions sources and gives emissions estimates for these engineered chemicals, which occur on a very limited basis in nature.⁷⁷ Although they are much more potent when measured by their high GWPs than are the principal greenhouse gases, they are emitted in such small quantities that their overall impact is currently small.

The small quantities of HFCs, PFCs, and SF₆ that are emitted have disproportionate effects on overall emissions because of their large GWPs. PFCs and SF₆ have particularly high GWPs because of their scarcity, stability, strong infrared absorption in the atmosphere, and long atmospheric lifetimes.⁷⁸ SF₆ is the most potent of the greenhouse gases, with a GWP of 22,200. PFCs, with 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 10,000.⁷⁹

The emissions estimates in Table 29 are taken from data supplied by the EPA’s Office of Air and Radiation.⁸⁰ The estimates in Table 30 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 EIA, using GWP values from the IPCC’s 2001 Third Assessment Report. The 2002 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)

Since 1990, HFC emissions have accounted for a growing share (68.9 percent in 2002) of total carbon dioxide equivalent emissions of HFCs, PFCs, and SF₆ combined. The EPA estimates U.S. emissions of all HFCs in 2002 at

U.S. Emissions of Hydrofluorocarbons, 1990-2002

| | |
|--|--------|
| Estimated 2002 Emissions (Million Metric Tons Carbon Dioxide Equivalent) | 83.1 |
| Change Compared to 2001 (Million Metric Tons Carbon Dioxide Equivalent) | 6.4 |
| Change from 2001 (Percent) | 8.4% |
| Change Compared to 1990 (Million Metric Tons Carbon Dioxide Equivalent) | 46.3 |
| Change from 1990 (Percent) | 126.0% |

83.1 million metric tons carbon dioxide equivalent, an 8.4-percent increase from 2001 emissions and a 126.0-percent increase from 1990.⁸¹ The largest portion of HFC emissions, 75.4 percent, is attributed to their use as replacements for ozone-depleting substances, which has increased 84-fold since 1990.

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.⁸² 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.⁸³

⁷⁷See Chapter 1, Table 1. Naturally occurring (pre-industrial) emissions of perfluoromethane (CF₄) were 40 parts per trillion. Their concentration had doubled by 1998.

⁷⁸See discussion of relative forcing effects of gases in Chapter 1.

⁷⁹Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

⁸⁰Preliminary data estimates received by EIA from the EPA’s Office of Air and Radiation, August 2003.

⁸¹Preliminary data estimates received by EIA from the EPA’s Office of Air and Radiation, August 2003. 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.

⁸²European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/others/firefighting/main_appli/main.htm.

⁸³European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/insulation/main_appli/main.htm.

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 2002, incorporating a number of revisions to the estimates of HFC, PFC, and SF₆ emissions for 2001 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 primary change in the methodology for calculating emissions from electrical transmission and distribution is an increase in the assumed emission rate from equipment manufacturers. Previously, the emission rate was assumed to be 3 percent of the SF₆ charged into new equipment. The revised 2001 estimate bases the quantity of SF₆ charged into new equipment on statistics compiled by the National Electrical Manufacturers Association. The revised 10-percent emission rate is the average of the “ideal” and “realistic” manufacturing emission rates (4 percent and 17 percent, respectively), as identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE).^b This revision resulted in an

average annual increase of 3.7 percent in SF₆ emissions for the period 1990 through 2000.

- *Magnesium Production and Processing.* The emissions estimates in this report were revised to reflect new activity data for magnesium production and processing, which affected the emission factor for die casting. The new, lower emission factor was adjusted to account for lower emission rates reported by participants in EPA’s SF₆ Emission Reduction Partnership for the Magnesium Industry, including nearly 100 percent of all die casting operations in the United States. The combination of these changes and the methodological revision described above resulted in an average annual decrease of about 1.9 percent in SF₆ emissions for the period 1990 through 2000.
- *Substitution of Ozone-Depleting Substances.* The EPA updated assumptions for its Vintaging Model in the fire-extinguishing sector. These changes resulted in an average annual decrease of 0.7 percent in HFC and PFC emissions for the period 1994 through 2000.
- *Aluminum Production.* In cooperation with the EPA’s Voluntary Aluminum Industrial Partnership program, participants provided additional smelter-specific information on aluminum production and the frequency and duration of anode effects. The new information resulted in a decrease of 0.3 percent in PFC emissions for 2000.

^aThe information presented in this text box was obtained from 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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

^bP. O’Connell, F. Heil, J. Henriot, G. Mauthe, H. Morrison, L. Neimeyer, M. Pittroff, R. Probst, and J.P. Tailebois, *SF₆ in the Electric Industry, Status 2000* (CIGRE, February 2002).

Trifluoromethane (HFC-23)

The EPA estimates 2002 emissions of HFC-23 at 1,754 metric tons of gas.⁸⁴ Annual emissions have fluctuated since 1990, showing an overall decline of 41.6 percent by 2002. Although emissions of HFC-23 are relatively small, its high GWP (12,000)⁸⁵ gives it a substantial potential climatic effect. Nearly all HFC-23 emissions (96.4 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 continues to grow, emissions of HFC-23 from this source have declined, because the emission rate of HFC-23 (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined significantly since 1990.⁸⁶

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

⁸⁴Preliminary data estimates received by EIA from the EPA’s Office of Air and Radiation, August 2003.

⁸⁵Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

⁸⁶U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.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, reducing the uncertainty of model inputs, such as equipment characteristics and sales figures.

^aU.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

household (central) air conditioners, and 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.⁸⁷

Tetrafluoroethane (HFC-134a)

According to EPA estimates, emissions of HFC-134a, which has a GWP of 1,300,⁸⁸ have grown from 564 metric tons in 1990 to 33,963 metric tons in 2002.⁸⁹ HFC-134a accounts for the largest share of all HFC emissions (53.1 percent in terms of carbon dioxide equivalent), and the single largest share of any one gas for all HFC, PFC, and SF₆ emissions combined (36.6 percent). The 2002 estimate is 7.6 percent higher than that for 2001. Emissions of HFC-134a have increased more than 59-fold since 1990, more rapidly than emissions of any other single greenhouse gas.

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 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

⁸⁷U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

⁸⁸Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

⁸⁹Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003.

pharmaceuticals, such as taxol for breast cancer treatment, nutraceuticals, flavors, and fragrances.⁹⁰ According to the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), worldwide sales of HFC-134a jumped almost fourfold between 1992 and 1993, doubled again in 1994, and continued growing steadily to 131,969 metric tons of gas in 2001.⁹¹

A number of HFC-134a producers are undertaking modest capacity expansion projects, including DuPont, INEOSFluor (formerly ICI Klea), and Honeywell (formerly AlliedSignal). More significant additions of new capacity are likely to be needed, however, given that capacity is increasing by only 2 to 3 percent per year, while global demand is growing by 10 percent.⁹² Anticipating and planning for this growth has proven to be a difficult challenge for producers, who must manage as best they can an unprecedented transition from an established product (CFC-12), which is being phased out under a global treaty, to a new product (HFC-134a).

Other HFCs

Other hydrofluorocarbons 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.⁹³ The EPA estimates emissions of HFC-125 (pentafluoroethane) at 236 metric tons of gas in 1992, increasing to 2,283 metric tons in 2002.⁹⁴ The estimate for 2002 is 22.1 percent higher than the estimate for 2001. 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 phaseout of HCFC-22 begins to gain momentum, producers expect a rapid increase in the demand for R-410A.⁹⁵ HFC-125 can also be used as a firefighting agent.

The EPA estimates 1993 emissions of HFC-143a (trifluoroethane) at 12 metric tons of gas, increasing to 1,413 metric tons in 2002.⁹⁶ The estimate for 2002 is 23.8 percent higher than the estimate for 2001. 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.

The EPA estimates 1997 emissions of HFC-236fa (hexafluoropropane) at 15 metric tons of gas, increasing to 435 metric tons in 2002.⁹⁷ The estimate for 2002 is 17.7 percent higher than the estimate for 2001. HFC-236fa is also used as a refrigerant, in particular by the U.S. Navy for shipboard applications.⁹⁸ 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-431mee, with 100-year GWPs of 120, 3,500, 950, and 1,500, respectively.⁹⁹ The EPA estimates total emissions of this group of "other HFCs" at 13.2 million metric tons carbon dioxide equivalent in 2002, representing 10.9 percent of all emissions of HFCs, PFCs, and SF₆ reported.¹⁰⁰ 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" have increased by 13.5 percent since 2001 and by more than 72-fold since 1990.

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

⁹⁰European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/solvents/main_appli/main.htm.

⁹¹Alternative Fluorocarbons Environmental Acceptability Study, Production, Sales and Atmospheric Release, web site www.afeas.org/prodsales_download.html.

⁹²J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

⁹³Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

⁹⁴Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003.

⁹⁵J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

⁹⁶Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003.

⁹⁷Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003.

⁹⁸E-mail correspondence with the Office of Policy, U.S. Department of Energy, October 18, 2000.

⁹⁹Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

¹⁰⁰Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003. 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.

optimal operating temperature range; hence, the refrigerant best suited for use in ice cream freezers will differ from the best choice for milk coolers.¹⁰¹

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.¹⁰² Demand for Honeywell's insulating foam agent Enovate™ 3000 (HFC-245fa) is so strong that the company is building a new plant in Geismar, Louisiana, which began commercial operation in early August 2002.¹⁰³ Honeywell is also developing blends that combine HFC-245fa with other materials to enhance its cost/performance ratio. For some applications, non-fluorochemical alternatives (e.g., hydrocarbons) have been identified.¹⁰⁴

Perfluorocarbons (PFCs)

U.S. Emissions of Perfluorocarbons, 1990-2002

| | |
|--|--------|
| Estimated 2002 Emissions (Million Metric Tons Carbon Dioxide Equivalent) | 7.6 |
| Change Compared to 2001 (Million Metric Tons Carbon Dioxide Equivalent) | -0.2 |
| Change from 2001 (Percent) | -2.2% |
| Change Compared to 1990 (Million Metric Tons Carbon Dioxide Equivalent) | -11.8 |
| Change from 1990 (Percent) | -60.8% |

The EPA estimates 2002 emissions of PFCs at 7.6 million metric tons carbon dioxide equivalent, accounting for 6.3 percent of all emissions of HFCs, PFCs, and SF₆ combined. The estimate for 2002 is 2.2 percent lower than the estimate for 2001 and 60.8 percent lower than

1990 emissions (Table 30).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. PFC emissions are not regulated, although their high GWPs (5,700 for perfluoromethane [CF₄] and 11,900 for perfluoroethane [C₂F₆])¹⁰⁶ have drawn attention. 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 531 metric tons of perfluoromethane and 56 metric tons of perfluoroethane in 2002.¹⁰⁷ 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 78.2 percent and 77.3 percent, respectively, since 1990.

Aluminum smelting companies that participate in EPA's Voluntary Aluminum Industry Partnership (VAIP) program have achieved many 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 in 2002 as a result of cutbacks in smelter production, which in turn were caused by increased energy costs in various parts of the country.

Another source of PFC emissions is semiconductor manufacturing. For 2002, the EPA estimates emissions of perfluoromethane and perfluoroethane from semiconductor manufacturing at 175 metric tons and 244 metric tons of gas, respectively.¹⁰⁸ Both estimates reflect the rapid growth of the semiconductor industry in the

¹⁰¹C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

¹⁰²C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

¹⁰³Honeywell, "Honeywell Prepares for First Shipments of Commercially Produced Enovate™ 3000 Blowing Agent," Press Release (August 22, 2002), web site www.enovate3000.com/pdfs/PressRelease8-16.pdf.

¹⁰⁴J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

¹⁰⁵Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003. 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.

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

¹⁰⁷Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003.

¹⁰⁸Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003.

1990s, which resulted in increases of 52.2 percent and 52.6 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 (C₃F₈, with a GWP of 8,600), perfluorobutane (C₄F₁₀, GWP 8,600), perfluorohexane (C₆F₁₄, GWP 9,000), and nitrogen trifluoride (NF₃).¹⁰⁹ 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 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.¹¹⁰

Sulfur Hexafluoride (SF₆)

U.S. Emissions of Sulfur Hexafluoride, 1990-2002

| | |
|--|--------|
| Estimated 2002 Emissions (Million Metric Tons Carbon Dioxide Equivalent) | 16.7 |
| Change Compared to 2001 (Million Metric Tons Carbon Dioxide Equivalent) | -0.8 |
| Change from 2001 (Percent) | -4.7% |
| Change Compared to 1990 (Million Metric Tons Carbon Dioxide Equivalent) | -23.7 |
| Change from 1990 (Percent) | -58.7% |

The EPA estimates 2002 emissions of SF₆ at 752 metric tons of gas, accounting for 13.8 percent of all HFC, PFC, and SF₆ emissions combined in 2002.¹¹¹ The estimate for 2002 is 58.7 percent lower than the estimate for 1990. The decrease is the result of industry efforts to reduce emissions from electrical power systems, the rising cost of SF₆, and the closure of a major U.S. magnesium production facility. In contrast, emissions of SF₆ from uses in the semiconductor manufacturing industry have increased overall by 30.5 percent since 1990.

SF₆ is used primarily in electrical applications and magnesium metal casting processes. SF₆ is an excellent dielectric gas for high-voltage applications, because it is chemically inert, gaseous at low temperatures, nonflammable, nontoxic, and noncorrosive.¹¹² In electrical transmission and distribution systems, SF₆ 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.¹¹³

Other applications that produce SF₆ emissions include magnesium metal casting processes that employ SF₆ to replace toxic and corrosive materials, such as salt fluxes and sulfur dioxide (SO₂). Another important use of SF₆ is as a cover gas during magnesium production and processing to prevent excessive oxidation of molten magnesium in the presence of air. Pre-treating aluminum melt with SF₆ (or an inert gas mixture) prevents porosity and therefore weakening of the metal. It also removes oxides and solid impurities. In addition, mixtures of SF₆ and O₂ are used as feed gases for plasma etching of semiconductor devices.¹¹⁴ Because of its extremely low atmospheric concentration, SF₆ 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.¹¹⁵

¹⁰⁹Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

¹¹⁰U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), Annex J, web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹¹¹Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, August 2003.

¹¹²European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?chfamilies/SF6/prod_main/prod.htm.

¹¹³U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹¹⁴European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/electri_appli/main_appli/main.htm.

¹¹⁵Historically, emissions of SF₆ 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.

Other Gases

In compiling its estimates, the EPA receives data from participants in the SF₆ Emission Reduction Partnership for Electric Power Systems and the SF₆ Emissions Reduction Partnership for the Magnesium Industry. The uncertainty associated with SF₆ emissions in the electric power industry is noteworthy, because the data

reported cover only 1999, 2000, and 2001, and a model was necessary to “backcast” emissions for 1990 to 1998, as well as for those utilities not reporting to the program. A major model assumption made regarding magnesium processing, that SF₆ neither reacts nor decomposes, adds an element of uncertainty to the estimates.¹¹⁶

¹¹⁶U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

Table 29. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2002
(Thousand Metric Tons of Gas)

| Gas | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Hydrofluorocarbons | | | | | | | | | | | | | |
| HFC-23 | 3.0 | 2.6 | 3.0 | 2.7 | 2.7 | 2.3 | 2.7 | 2.6 | 3.5 | 2.7 | 2.6 | 1.7 | 1.8 |
| HFC-125 | * | * | 0.2 | 0.5 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.6 | 1.9 | 2.3 |
| HFC-134a | 0.6 | 0.6 | 0.6 | 2.9 | 4.5 | 12.2 | 16.2 | 20.2 | 23.1 | 26.1 | 28.9 | 31.6 | 34.0 |
| HFC-143a | * | * | * | * | 0.1 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 | 1.4 |
| HFC-236fa | * | * | * | * | * | * | * | * | 0.1 | 0.2 | 0.3 | 0.4 | 0.4 |
| Perfluorocarbons | | | | | | | | | | | | | |
| CF ₄ | 2.6 | 2.2 | 2.1 | 2.0 | 1.8 | 1.8 | 1.9 | 1.8 | 1.5 | 1.5 | 1.4 | 0.8 | 0.7 |
| C ₂ F ₆ | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.4 | 0.3 | 0.3 |
| C ₄ F ₁₀ | * | * | * | * | * | * | * | * | * | * | * | * | * |
| PFCs/PFPEs | W | W | W | W | W | W | W | W | W | W | W | W | W |
| Other HFCs, PFCs/PFPEs | M | M | M | M | M | M | M | M | M | M | M | M | M |
| Sulfur Hexafluoride | 1.8 | 1.7 | 1.6 | 1.8 | 1.6 | 1.3 | 1.5 | 1.3 | 1.0 | 1.0 | 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, August 2003).

Table 30. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2002
(Million Metric Tons Carbon Dioxide Equivalent)

| Gas | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | P2002 |
|--------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Hydrofluorocarbons | | | | | | | | | | | | | |
| HFC-23 | 36.1 | 31.7 | 35.9 | 32.9 | 32.7 | 28.1 | 32.4 | 31.3 | 41.9 | 31.9 | 31.2 | 20.9 | 21.0 |
| HFC-125 | * | * | 0.8 | 1.6 | 1.0 | 1.6 | 2.3 | 3.0 | 3.8 | 4.4 | 5.3 | 6.4 | 7.8 |
| HFC-134a | 0.7 | 0.7 | 0.8 | 3.8 | 5.8 | 15.9 | 21.1 | 26.2 | 30.0 | 33.9 | 37.6 | 41.0 | 44.2 |
| HFC-143a | * | * | * | 0.1 | 0.2 | 0.5 | 0.9 | 1.4 | 2.1 | 2.9 | 3.9 | 4.9 | 6.1 |
| HFC-236fa | * | * | * | * | * | * | * | 0.1 | 1.1 | 2.0 | 2.8 | 3.5 | 4.1 |
| Total HFCs | 36.8 | 32.5 | 37.6 | 38.3 | 39.7 | 46.1 | 56.6 | 62.1 | 78.9 | 75.2 | 80.8 | 76.7 | 83.1 |
| Perfluorocarbons | | | | | | | | | | | | | |
| CF ₄ | 14.5 | 12.6 | 11.7 | 11.4 | 10.2 | 10.3 | 11.0 | 10.0 | 8.7 | 8.6 | 7.9 | 4.3 | 4.0 |
| C ₂ F ₆ | 4.9 | 4.4 | 4.2 | 4.4 | 4.4 | 4.9 | 5.3 | 5.6 | 5.9 | 5.9 | 4.9 | 3.5 | 3.6 |
| C ₄ F ₁₀ | * | * | * | * | * | * | * | * | * | * | * | * | * |
| Total PFCs | 19.4 | 17.0 | 15.9 | 15.9 | 14.7 | 15.2 | 16.3 | 15.6 | 14.6 | 14.6 | 12.8 | 7.8 | 7.6 |
| Other HFCs, PFCs/PFPEs | 0.2 | 0.1 | 0.0 | 0.1 | 1.3 | 4.4 | 7.7 | 8.6 | 9.7 | 10.4 | 11.0 | 11.6 | 13.2 |
| Sulfur Hexafluoride | 40.4 | 38.4 | 34.4 | 39.4 | 35.2 | 28.8 | 32.7 | 29.5 | 23.0 | 22.0 | 18.7 | 17.5 | 16.7 |
| Total Emissions | 96.8 | 88.0 | 87.9 | 93.6 | 90.9 | 94.6 | 113.3 | 116.0 | 126.2 | 122.1 | 123.2 | 113.6 | 120.6 |

*Less than 0.05 million metric tons carbon dioxide equivalent.

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, August 2003).

6. Land Use Issues

Overview

Land use change 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.¹¹⁷ The U.S. Environmental Protection Agency (EPA) estimates annual U.S. carbon sequestration for the year 2001 at 838.1 million metric tons carbon dioxide equivalent, a decline of approximately 21.9 percent from the 1,072.8 million metric tons carbon dioxide equivalent sequestered in 1990 (Table 31). In 1990 land use change and forestry practices represented an offset of 17.4 percent of total U.S. anthropogenic carbon dioxide emissions, but by 2001 that amount had declined to 12.3 percent.

Land Use Change and Forestry Carbon Sequestration

The EPA’s estimates for carbon sequestration from land use change and forestry in 2001 include four main components: (1) changes in forest carbon stocks (759 million metric tons carbon dioxide equivalent or 90.6 percent of the total), (2) changes in agricultural soil carbon stocks (15.2 million metric tons carbon dioxide equivalent or 1.8 percent of the total), (3) changes in carbon stocks in

Table 31. Net Carbon Dioxide Sequestration from U.S. Land Use Change and Forestry, 1990 and 1995-2001
(Million Metric Tons Carbon Dioxide Equivalent)

| Component | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
|-------------------------------------|----------------------------|----------------------------|----------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Forests | 982.7 ^a | 979.0 ^a | 979.0 ^a | 759.0 ^b | 751.7 ^b | 762.7 ^b | 755.3 ^b | 759.0 ^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 | 13.3 ^a | 14.9 ^a | 13.6 ^a | 13.9 ^b | 11.5 ^b | 11.9 ^b | 13.8 ^b | 15.2 ^b |
| Landfilled Yard Trimmings | 18.2 ^a | 11.6 ^a | 9.7 ^a | 9.0 ^a | 8.7 ^a | 7.8 ^a | 6.9 ^a | 5.3 ^b |
| Total | 1,072.8^a | 1,064.2^a | 1,061.0^a | 840.6^b | 830.5^b | 841.1^b | 834.6^b | 838.1^b |

^aEstimate based on historical data.

^bEstimate 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-03-004 (Washington, DC, April 2003), web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹¹⁷Intergovernmental 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.

urban trees (58.7 million metric tons carbon dioxide equivalent or 7.0 percent of the total), and (4) changes in carbon stocks in landfilled yard trimmings (5.3 million metric tons carbon dioxide equivalent or 0.6 percent of the total).¹¹⁸

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 are based on the EPA's own method of examining life-cycle greenhouse gas emissions and sinks associated with solid waste management.¹¹⁹

The EPA's carbon flux estimates, with the exception of those from wood products, urban trees, and liming, are based on surveys of U.S. forest lands and soils carried out at 5- or 10-year intervals by the U.S. Forest Service. The resulting annual averages are applied to years between surveys. Annual estimates of carbon fluxes

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 7 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.

^aThe Cooperative Research Centre for Greenhouse Accounting, "Good Practice for Land Use, Land-Use Change, and Forestry," web site www.greenhouse.crc.org.au/goodpractice/ (2003).

^bG.-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), web site http://www.ipcc-nggip.iges.or.jp/SBSTA18/LULUCF_SBSTA18_side-event.htm.

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 on the second draft document was completed at the end of June 2003. The IPCC author teams are currently in the process of revising the second draft in response to comments received. A final draft of the *Good Practice Guidance* for LULUCF will be provided to governments in October 2003 for final comment, before their anticipated acceptance at the COP-9 meeting in December 2003.^{a, b}

¹¹⁸U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹¹⁹U.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.

between survey years are interpolated and, therefore, change little from year to year, except when a new assessment is made. For landfilled yard trimmings, periodic solid waste survey data are interpolated to derive annual storage estimates. The most current national forest and soil surveys were completed for the year 1997; thus, carbon flux estimates from forests 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.¹²⁰

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.¹²¹ 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:

- 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.

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 seven forest components or “forest pools” to a “product pool.” 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.¹²²

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 the atmosphere. The size of wood product landfills has increased over the past century.¹²³

According to the EPA (Table 32), between 1990 and 2001, U.S. forest and harvested wood components accounted for an average annual net sequestration of 887 million metric tons carbon dioxide equivalent, resulting from domestic forest growth and increases in forested land area. Over the same period, however, increasing harvests and land-use changes have resulted in a decrease of approximately 23 percent in annual sequestration.

¹²⁰U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹²¹U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹²²U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, EPA-430-R-02-003 (Washington, DC, April 2002), web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2002.html>.

¹²³U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, EPA-430-R-02-003 (Washington, DC, April 2002), p. 129, web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2002.html>.

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,¹²⁴ based on data collected from 1990 through 2001. Net carbon dioxide flux from urban trees is estimated at 58.7 million metric tons carbon dioxide equivalent annually from 1990 through 2001 (Table 31).¹²⁵

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 33), is divided into three categories of land use and land management activities: (1) agricultural land use and land management activities on mineral soils; (2) agricultural land use and land management activities on organic soils; 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 2001. Net carbon dioxide flux from agricultural soils is estimated at 15.2 million metric tons carbon dioxide equivalent in 2001.¹²⁶

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—

Changes in Landfilled Yard Trimming Carbon Stocks

Carbon stored in landfilled yard trimmings can remain indefinitely. In the United States, yard trimmings (grass clippings, leaves, and branches) make up a considerable portion of the municipal waste stream, and significant amounts of the yard trimmings collected are discarded

Table 32. Net Carbon Dioxide Sequestration in U.S. Forests, 1990 and 1995-2001
(Million Metric Tons Carbon Dioxide Equivalent)

| Description | 1990 ^a | 1995 ^a | 1996 ^a | 1997 ^b | 1998 ^b | 1999 ^b | 2000 ^b | 2001 ^b |
|---|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Forest Carbon Stocks | 773.7 | 773.7 | 773.7 | 546.3 | 546.3 | 546.3 | 546.3 | 546.3 |
| Trees | 469.3 | 469.3 | 469.3 | 447.3 | 447.3 | 447.3 | 447.3 | 447.3 |
| Understory | 11.0 | 11.0 | 11.0 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 |
| Forest Floor | 25.7 | 25.7 | 25.7 | -29.3 | -29.3 | -29.3 | -29.3 | -29.3 |
| Down Dead Wood | 55.0 | 55.0 | 55.0 | 58.7 | 58.7 | 58.7 | 58.7 | 58.7 |
| Forest Soils | 212.7 | 212.7 | 212.7 | 55.0 | 55.0 | 55.0 | 55.0 | 55.0 |
| Harvested Wood Carbon Stocks . . | 209.0 | 205.3 | 205.3 | 212.7 | 205.3 | 216.3 | 209.0 | 212.7 |
| Wood Products | 47.7 | 55.0 | 55.0 | 58.7 | 51.3 | 62.3 | 58.7 | 58.7 |
| Landfilled Wood | 161.3 | 150.3 | 150.3 | 154.0 | 154.0 | 154.0 | 150.3 | 154.0 |
| Total | 982.7 | 979.0 | 979.0 | 759.0 | 751.7 | 762.7 | 755.3 | 759.0 |

^aEstimates based on historical data.

^bEstimates 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. 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 1990-2001*, EPA-430-R-03-004 (Washington, DC, April 2003), web site <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹²⁴D.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.

¹²⁵U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹²⁶U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

in landfills. Both the amount of yard trimmings collected annually and the percentage of trimmings landfilled have declined over the past decade, and net carbon dioxide sequestration in landfilled yard trimmings has declined accordingly (Table 31). Since 1990, programs limiting disposal of yard trimmings have led to an increase in backyard composting and the use of mulching mowers. 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.¹²⁷

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

Table 33. Net Carbon Dioxide Sequestration in U.S. Agricultural Soils, 1990 and 1995-2001
(Million Metric Tons Carbon Dioxide Equivalent)

| Description | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
|---------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Mineral Soils | 57.1 | 58.6 | 57.3 | 57.4 | 55.8 | 55.7 | 57.3 | 59.1 |
| Organic Soils | -34.3 | -34.8 | -34.8 | -34.8 | -34.8 | -34.8 | -34.8 | -34.8 |
| Liming of Soils | -9.5 | -8.9 | -8.9 | -8.7 | -9.6 | -9.1 | -8.8 | -9.1 |
| Total | 13.3 | 14.9 | 13.6 | 13.9 | 11.5 | 11.9 | 13.8 | 15.2 |

^aEstimates based on historical data.

^bEstimates 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 1990-2000*, EPA-430-R-02-003 (Washington, DC, April 2002), web site www.epa.gov.

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 four 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, processing residues from primary timber mills, and logging 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 the four sources in 2001 were as follows: (1) 9.6 million tons from MSW, (2) 18.1 million tons from construction and demolition debris, (3) 1.9 million tons from primary timber processing, and (4) 74.5 million tons from logging residues.

Logging residues represent the largest fraction 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.

^aD. McKeever, "Taking Inventory of Woody Residuals," *BioCycle*, Vol. 44, No. 7 (July 2003), pp. 31-35.

¹²⁷U.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.

USDA Agriculture and Forestry Greenhouse Gas Inventory

The U.S. Department of Agriculture (USDA) Global Change Program Office is currently compiling an Agriculture and Forestry Greenhouse Gas Inventory for the United States. The USDA inventory is intended to provide a comprehensive assessment of the contribution of agriculture and forestry to nationwide greenhouse gas emissions. The document was prepared to support and expand on information provided in the U.S. Environmental Protection Agency's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. The USDA inventory provides detailed data on trends in agriculture and forestry greenhouse gas emissions and sinks, including information by source and sink at State and regional levels. The report is structured primarily from a land use perspective. It contains a chapter on forests, which details carbon sequestration in forests, soils, urban trees, and wood products for the year 2002. The USDA inventory is currently in draft form; however, EIA plans to publish the 2002 sequestration values in next year's report.

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,¹²⁸ 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?

¹²⁸G. 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/global-warming-in-depth/all_reports/land_use_and_climate_change/index.cfm.

¹²⁹U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

¹³⁰U.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/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html>.

- 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.

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 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).¹²⁹

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 forested lands 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.¹³⁰

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.¹³¹ 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 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.¹³² 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.

New 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.¹³³

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 and accepting as fact 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.

¹³¹G. 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/global-warming-in-depth/all_reports/land_use_and_climate_change/index.cfm

¹³²W.H. Schlesinger and J. Lichter, "Limited Carbon Storage in Soil and Litter of Experimental Forest Plots Under Increased Atmospheric CO₂," *Nature*, Vol. 411 (2001), pp. 466-469.

¹³³F. 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

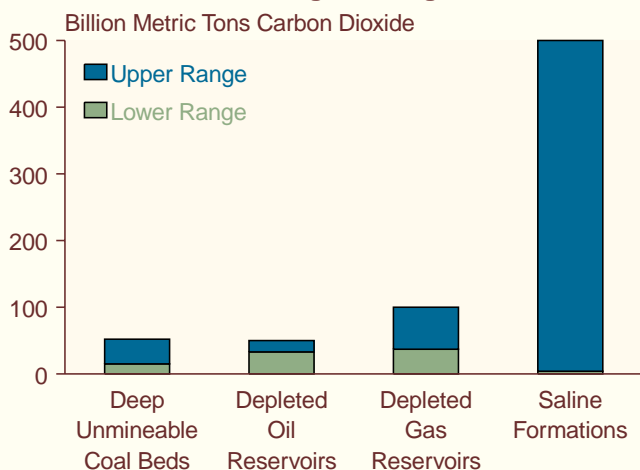
The capture and permanent storage of carbon dioxide in geologic formations has gained increasing attention as an option for sequestering carbon dioxide emissions from industrial processes and coal-fired power generation. As part of the February 2002 introduction of the Global Climate Change Initiative, 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 regional partnerships 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 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 below show the estimated capacity range of each domestic geologic storage option in the United States and potential locations for geologic storage.

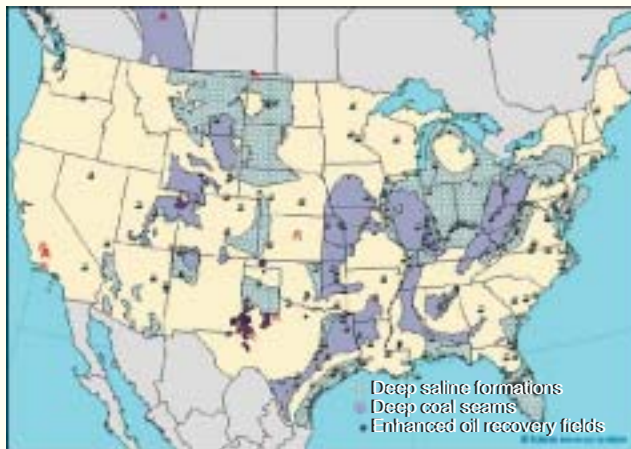
(continued on page 81)

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 CO₂ Capture and Storage Working Group, NCCTI Energy Technologies Group, Office of Fossil Energy, U.S. Department of Energy, *CO₂ 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.

^aCO₂ Capture and Storage Working Group, NCCTI Energy Technologies Group, Office of Fossil Energy, U.S. Department of Energy, *CO₂ 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.

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 82)

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 |
| <ul style="list-style-type: none"> • Chemical absorption with liquid amine solution • Oxygen-fired combustion • Pre-combustion decarbonization (e.g., through gasification) | <ul style="list-style-type: none"> • Carbon dioxide pipeline • Shipping • Trucking^a | <ul style="list-style-type: none"> • Enhanced oil, gas, and coalbed methane recovery • Food processing and carbonation, and synthesis of chemicals | <ul style="list-style-type: none"> • Deep saline formations • Deep, unmineable coal seams • Depleted oil and gas reservoirs • Shales |

Sample Applications

| | | | |
|--|--|---|--|
| A new 600 MW 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-km 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 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 MMTC 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 | 100 km via pipeline: 1-3 | NA ^f | Sample storage sites: ^g 4-19 |
| Ultra-supercritical PC: 42.4 | 500 km via tanker: 2 | | |
| NGCC: 60.4 | Trucking: NA | | |

IGCC = integrated gasification combined cycle; NA = not available; NGCC = natural gas combined cycle; PC = pulverized coal.

^aA.F.B. Wildenborg and L.G.H. van der Meer, "The Use of Oil, Gas and Coal Fields as CO₂ 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.

^bScience Applications International Corporation, calculations based on data from K. Thambimuthu, J. Davison, and M. Gupta, "CO₂ 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.

^cU.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/program_plans/03/.

^dElectric Power Research Institute, *Updated Cost and Performance Estimates for Fossil Fuel Power Plants with CO₂ Removal*, Interim report (Palo Alto, CA, December 2002), web site www.netl.doe.gov/coalpower/gasification/pubs/pdf/1004483.pdf.

^eInternational 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.

^fNo estimates are available on the added cost benefits of resource enhancement and the impact on total injection and storage cost.

^gDue 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.

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 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.^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 costs and contributing to atmospheric emissions. The estimated "energy penalty" of installing capture technology at a power plant ranges from 13 to 25 percent, depending on the type of combustion technology used.^c

As shown in the table on page 81, the cost of capturing carbon dioxide from integrated gasification combined cycle (IGCC), new pulverized coal (PC), and natural gas combined cycle (NGCC) power plants range from \$17 to \$61 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. Thus, current research to improve the feasibility of capture and storage is focused on methods to decrease costs and energy use, as well as demonstrating that geologic sequestration is safe and environmentally sound.

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.

^bU.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/program_plans/03/.

^cInternational 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.

^dJ. 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*. New York, NY: Industrial Press, 1974.
- 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/internationalinks.
- Baldwin, R.L., Thornley, J.H.M., and Beaver, 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.

References

- 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.
- Burdick, D.L., and Leffler, W.L. *Petrochemicals in Non-technical 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.
- 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.
- 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.
- 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. *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.

References

- 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. 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.
- "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/>.
- 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. "CO₂ 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.
- Holzappel-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 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.ch/pub/guide.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.
- 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 CO₂ 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., Frohling, 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.

References

- 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*, Pew Center on Global Climate Change (June 2000), p. v. Web site www.pewclimate.org/global-warming-in-depth/all_reports/land_use_and_climate_change/index.cfm
- Marland, G., et al. *Estimates of CO₂ 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.
- 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.
- Myneni, R., et al. "Forests Storing 700 Million Tons of Carbon per Year." *UniSci Daily University Science News*. December 12, 2001.
- Nagy, B., and Columbo, U., eds. *Fundamental Aspects of Petroleum Chemistry*. New York, NY: Elsevier Publishing, 1967.
- 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.
- Oak Ridge National Laboratory. *Transportation Energy Data Book*. Oak Ridge, TN, various years. Web site www-cta.ornl.gov/publications/tebd.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.
- Parson, E.A., and Greene, O. "The Complex Chemistry of the International Ozone Agreements." *Environment* 37. March 1995.
- "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.

- 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 N₂O 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.
- 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.
- 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.
- Stuedler, P.A., et al. "Influence of Nitrogen Fertilization on Methane Uptake in Temperate Forest Soils." *Nature* 341. September 28, 1989.

References

- 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: SF₅CF₃." *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., Fingfinger, 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, 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. *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.

References

- 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/Resource_Center_Publications_GHG_Emissions_US_EmissionsInventory2003.html.
- U.S. Environmental Protection Agency, *Land Use, Land Use Change, and Forestry* (2000). Web site www.epa.gov.
- 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, 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.

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'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/.

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.
Renewable Energy: www.caddet-re.org
Energy Efficiency: www.caddet-ee.org
- Center for Renewable Energy and Sustainable Technology.
<http://solstice.crest.org/index.shtml>
- 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/env/ghg.html
- Environmental Defense Fund.
www.edf.org
- Global Change.
www.globalchange.org
- 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, Environmental Quality.
www.energy.gov/environ/
- U.S. Department of Energy, Climate Challenge Program.
www.eren.doe.gov/climatechallenge/
- U.S. Department of State, Climate Change Homepage.
<http://www.state.gov/g/oes/climate/>

Related Links

U.S. Environmental Protection Agency,
Global Warming Homepage.
www.epa.gov/globalwarming/

U.S. Geological Survey, Global Change Research.
<http://geochange.er.usgs.gov>

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](http://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/peh/

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/climate/

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 = $(141.5/\text{sp.gr.}60 \text{ deg.F}/60 \text{ deg.F}) - 131.5$.

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 cut-back 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).

BOD₅: 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 (CO₂): 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 2,700°F.

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): $(\text{CH}_3)_3\text{COC}_2\text{H}$: 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 earth's 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 ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), 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 anti-knock 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 glass, 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 (SO₂): 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 (SF₆): 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 (SO₂) and sulfur trioxide (SO₃).

Tertiary amyl methyl ether ((CH₃)₂(C₂H₅)COCH₃): 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) | = | $4,407 \text{ m}^2$ |
| 1 hectare | = | $10,000 \text{ m}^2$ | = | 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, 1949-2002
(Million Metric Tons of Carbon Dioxide)

| Year | Residential | | | | | Commercial | | | | |
|--------|-------------|-----------|-------|-------------|--------|-------------|-----------|-------|-------------|--------|
| | 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 | 123.0 | 5.7 | 523.9 | 908.9 | 140.7 | 95.5 | 8.3 | 407.9 | 652.5 |
| 1981 | 245.6 | 108.4 | 6.7 | 517.0 | 877.7 | 136.1 | 80.5 | 9.2 | 426.5 | 652.2 |
| 1982 | 250.8 | 101.1 | 7.1 | 513.1 | 872.1 | 141.0 | 74.5 | 10.6 | 428.1 | 654.1 |
| 1983 | 238.3 | 94.8 | 7.1 | 526.0 | 866.3 | 132.2 | 82.4 | 11.0 | 434.8 | 660.5 |
| 1984 | 247.3 | 93.6 | 7.7 | 537.1 | 885.7 | 136.9 | 87.4 | 11.9 | 457.4 | 693.6 |
| 1985 | 241.0 | 103.8 | 6.5 | 548.2 | 899.6 | 132.2 | 75.7 | 10.1 | 476.2 | 694.0 |
| 1986 | 234.0 | 101.9 | 6.5 | 552.7 | 895.1 | 125.8 | 80.3 | 10.0 | 482.7 | 698.8 |
| 1987 | 234.2 | 105.3 | 6.2 | 576.1 | 921.8 | 131.9 | 78.7 | 9.4 | 504.6 | 724.6 |
| 1988 | 251.2 | 109.3 | 6.2 | 602.9 | 969.5 | 144.8 | 75.7 | 9.6 | 529.9 | 760.0 |
| 1989 | 260.2 | 108.7 | 2.6 | 618.1 | 989.6 | 147.9 | 70.8 | 11.1 | 554.1 | 784.0 |
| 1990 | 238.8 | 97.9 | 2.4 | 611.7 | 950.8 | 142.6 | 69.4 | 12.1 | 555.4 | 779.5 |
| 1991 | 248.0 | 96.6 | 2.2 | 620.0 | 966.7 | 148.5 | 65.9 | 11.1 | 555.5 | 781.0 |
| 1992 | 255.2 | 99.2 | 2.3 | 611.0 | 967.7 | 152.6 | 62.0 | 11.2 | 555.3 | 781.1 |
| 1993 | 269.0 | 100.5 | 2.3 | 654.9 | 1026.7 | 155.3 | 56.6 | 11.2 | 583.1 | 806.2 |
| 1994 | 263.3 | 98.6 | 2.0 | 656.1 | 1020.0 | 157.3 | 57.2 | 11.1 | 594.0 | 819.6 |
| 1995 | 263.0 | 95.8 | 1.6 | 665.4 | 1025.7 | 164.3 | 53.0 | 11.0 | 608.3 | 836.7 |
| 1996 | 284.2 | 102.6 | 1.6 | 696.9 | 1085.3 | 171.3 | 54.2 | 11.5 | 630.9 | 867.9 |
| 1997 | 270.2 | 98.4 | 1.5 | 706.5 | 1076.6 | 174.3 | 50.6 | 12.2 | 674.1 | 911.2 |
| 1998 | 246.5 | 90.4 | 1.2 | 758.1 | 1096.2 | 163.5 | 47.4 | 8.7 | 702.8 | 922.4 |
| 1999 | 256.5 | 100.8 | 1.3 | 765.3 | 1123.9 | 165.2 | 47.2 | 9.7 | 711.4 | 933.5 |
| 2000 | 270.3 | 107.1 | 1.1 | 790.8 | 1169.4 | 174.3 | 54.1 | 8.6 | 768.9 | 1005.9 |
| 2001 | 259.5 | 105.6 | 1.1 | 794.6 | 1160.8 | 165.0 | 53.0 | 9.2 | 791.1 | 1018.3 |
| 2002 P | 267.2 | 104.0 | 1.1 | 820.7 | 1193.0 | 169.4 | 52.6 | 9.2 | 781.8 | 1012.9 |

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, 1949-2002

(Million Metric Tons of Carbon Dioxide)

| Year | Industrial | | | | | Transportation | | | | |
|--------|-------------|-----------|-------|-------------|---------|----------------|-----------|-------|-------------|--------|
| | 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 | 477.2 | 284.6 | 594.9 | 1787.4 | 34.3 | 1349.6 | 0.0 | 2.3 | 1386.2 |
| 1981 | 426.4 | 413.6 | 284.5 | 590.9 | 1714.0 | 34.8 | 1334.6 | 0.0 | 2.3 | 1371.7 |
| 1982 | 367.1 | 387.3 | 230.6 | 523.7 | 1506.7 | 32.4 | 1305.8 | 0.0 | 2.2 | 1340.5 |
| 1983 | 349.1 | 349.5 | 225.8 | 543.4 | 1466.4 | 26.7 | 1316.4 | 0.0 | 2.2 | 1345.3 |
| 1984 | 381.7 | 396.7 | 258.5 | 576.6 | 1612.3 | 28.8 | 1358.4 | 0.0 | 2.4 | 1389.6 |
| 1985 | 362.5 | 375.2 | 253.3 | 577.6 | 1567.4 | 27.5 | 1378.8 | 0.0 | 2.6 | 1408.9 |
| 1986 | 341.5 | 381.0 | 242.1 | 560.2 | 1523.2 | 26.5 | 1433.8 | 0.0 | 2.6 | 1462.9 |
| 1987 | 373.2 | 385.9 | 244.1 | 581.3 | 1585.4 | 28.4 | 1476.0 | 0.0 | 2.5 | 1506.9 |
| 1988 | 392.1 | 398.7 | 259.4 | 605.3 | 1659.1 | 33.4 | 1530.6 | 0.0 | 2.7 | 1566.8 |
| 1989 | 412.7 | 375.4 | 254.3 | 631.8 | 1677.0 | 34.3 | 1547.3 | 0.0 | 2.7 | 1584.3 |
| 1990 | 432.9 | 380.3 | 249.5 | 625.7 | 1688.8 | 35.9 | 1530.9 | 0.0 | 2.7 | 1569.5 |
| 1991 | 439.8 | 354.3 | 234.8 | 614.1 | 1643.9 | 32.7 | 1514.0 | 0.0 | 2.6 | 1549.4 |
| 1992 | 459.9 | 399.8 | 225.7 | 634.8 | 1723.5 | 32.1 | 1535.8 | 0.0 | 2.6 | 1570.5 |
| 1993 | 465.9 | 368.9 | 224.8 | 643.0 | 1705.1 | 34.0 | 1554.1 | 0.0 | 2.5 | 1590.6 |
| 1994 | 464.6 | 381.9 | 226.1 | 655.5 | 1733.5 | 37.4 | 1591.0 | 0.0 | 3.3 | 1631.7 |
| 1995 | 490.5 | 365.5 | 224.3 | 646.0 | 1732.0 | 38.2 | 1620.1 | 0.0 | 3.2 | 1661.4 |
| 1996 | 506.9 | 393.0 | 219.0 | 663.0 | 1785.2 | 38.9 | 1663.3 | 0.0 | 3.2 | 1705.3 |
| 1997 | 507.3 | 394.7 | 215.3 | 677.9 | 1800.4 | 41.1 | 1678.4 | 0.0 | 3.2 | 1722.7 |
| 1998 | 495.0 | 387.0 | 201.2 | 685.4 | 1776.0 | 35.1 | 1719.5 | 0.0 | 3.3 | 1757.9 |
| 1999 | 477.7 | 404.3 | 196.6 | 682.0 | 1767.0 | 35.6 | 1767.1 | 0.0 | 3.3 | 1806.0 |
| 2000 | 483.5 | 378.2 | 199.5 | 705.8 | 1774.1 | 35.5 | 1810.2 | 0.0 | 3.6 | 1849.2 |
| 2001 | 441.5 | 410.0 | 192.7 | 637.2 | 1685.3 | 33.9 | 1789.7 | 0.0 | 3.7 | 1827.3 |
| 2002 P | 432.7 | 412.8 | 179.4 | 643.1 | 1673.7 | 35.2 | 1811.2 | 0.0 | 3.4 | 1849.7 |

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, 1949-2002
(Million Metric Tons of Carbon Dioxide)

| Year | End-Use Sector | | | | | Electric Power Sector | | | |
|--------|----------------|------------|------------|----------------|--------|-----------------------|-----------|--------|---------|
| | 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 | 908.9 | 652.5 | 1787.4 | 1386.2 | 4735.0 | 200.8 | 202.8 | 1125.3 | 1529.0 |
| 1981 | 877.7 | 652.2 | 1714.0 | 1371.7 | 4615.6 | 198.4 | 169.6 | 1168.5 | 1536.7 |
| 1982 | 872.1 | 654.1 | 1506.7 | 1340.5 | 4373.4 | 176.1 | 120.8 | 1170.1 | 1467.1 |
| 1983 | 866.3 | 660.5 | 1466.4 | 1345.3 | 4338.5 | 158.0 | 119.0 | 1229.4 | 1506.5 |
| 1984 | 885.7 | 693.6 | 1612.3 | 1389.6 | 4581.3 | 169.7 | 99.1 | 1304.4 | 1573.5 |
| 1985 | 899.6 | 694.0 | 1567.4 | 1408.9 | 4569.9 | 166.7 | 84.0 | 1353.7 | 1604.6 |
| 1986 | 895.1 | 698.8 | 1523.2 | 1462.9 | 4580.0 | 141.9 | 112.0 | 1343.9 | 1598.2 |
| 1987 | 921.8 | 724.6 | 1585.4 | 1506.9 | 4738.6 | 154.9 | 96.9 | 1412.4 | 1664.5 |
| 1988 | 969.5 | 760.0 | 1659.1 | 1566.8 | 4955.5 | 143.0 | 120.6 | 1476.9 | 1740.8 |
| 1989 | 989.6 | 784.0 | 1677.0 | 1584.3 | 5034.8 | 168.5 | 130.4 | 1507.1 | 1806.7 |
| 1990 | 950.8 | 779.5 | 1688.8 | 1569.5 | 4988.6 | 176.0 | 99.2 | 1519.4 | 1795.5 |
| 1991 | 966.7 | 781.0 | 1643.9 | 1549.4 | 4941.0 | 179.4 | 92.6 | 1519.1 | 1792.2 |
| 1992 | 967.7 | 781.1 | 1723.5 | 1570.5 | 5042.7 | 186.6 | 77.1 | 1538.8 | 1803.7 |
| 1993 | 1026.7 | 806.2 | 1705.1 | 1590.6 | 5128.6 | 187.9 | 88.0 | 1606.5 | 1883.6 |
| 1994 | 1020.0 | 819.6 | 1733.5 | 1631.7 | 5204.7 | 211.1 | 82.8 | 1613.8 | 1908.9 |
| 1995 | 1025.7 | 836.7 | 1732.0 | 1661.4 | 5255.8 | 228.4 | 59.5 | 1633.8 | 1922.9 |
| 1996 | 1085.3 | 867.9 | 1785.2 | 1705.3 | 5443.7 | 204.9 | 64.5 | 1723.5 | 1994.0 |
| 1997 | 1076.6 | 911.2 | 1800.4 | 1722.7 | 5510.9 | 218.9 | 73.3 | 1768.3 | 2061.7 |
| 1998 | 1096.2 | 922.4 | 1776.0 | 1757.9 | 5552.5 | 248.0 | 102.9 | 1797.5 | 2149.6 |
| 1999 | 1123.9 | 933.5 | 1767.0 | 1806.0 | 5630.5 | 259.9 | 95.6 | 1805.2 | 2161.9 |
| 2000 | 1169.4 | 1005.9 | 1774.1 | 1849.2 | 5798.6 | 280.7 | 89.9 | 1895.7 | 2269.2 |
| 2001 | 1160.8 | 1018.3 | 1685.3 | 1827.3 | 5691.7 | 289.1 | 99.6 | 1834.9 | 2226.6 |
| 2002 P | 1193.0 | 1012.9 | 1673.7 | 1849.7 | 5729.3 | 299.1 | 72.2 | 1874.7 | 2249.0 |

Notes: Emissions from the electric power sector are apportioned to each end-use sector according to their share of electricity 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*.