

Emissions of Greenhouse Gases in the United States 2001

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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 tenth 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.

The estimates of greenhouse gas emissions contained in this report are based on energy consumption data from the Energy Information Administration’s (EIA’s) *Annual Energy Review 2001 (AER2001)*. The *AER2001* is the first EIA publication that contains revised electricity and fuel data from 1989 to 2000. As a result, EIA has revised its estimates for the years 1989 through 2000 for energy-related carbon dioxide emissions, total greenhouse gas emissions, sector-specific emissions, and emissions by fuel type. Last year’s emissions report was based primarily on EIA’s July 2001 *Monthly Energy Review* (see text box on page 27).

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Executive Summary

Overview

U.S. Anthropogenic Greenhouse Gas Emissions, 1990-2001

| | Carbon Equivalent |
|---|-------------------|
| Estimated 2001 Emissions (Million Metric Tons) | 1,883.3 |
| Change Compared to 2000 (Million Metric Tons) | -23.7 |
| Change from 2000 (Percent) | -1.2% |
| Change Compared to 1990 (Million Metric Tons) | 200.8 |
| Change from 1990 (Percent) | 11.9% |
| Average Annual Increase, 1990-2001 (Percent) | 1.0% |

U.S. emissions of greenhouse gases in 2001 totaled 1,883 million metric tons carbon equivalent, 1.2 percent less than in 2000 (1,907 million metric tons carbon equivalent). The 1.2-percent decrease from 2000 to 2001 is the largest percentage annual decline in total U.S. greenhouse gas emissions during the 1990 to 2001 time frame. The only other year since 1990 in which total emissions have declined is 1991, when emissions fell by 0.8 percent. U.S. greenhouse gas emissions have averaged 1.0-percent annual growth since 1990. The decline in

U.S. greenhouse gas emissions can be attributed to the combination of the following factors: a reduction in overall economic growth from 3.8 percent in 2000 to 0.3 percent in 2001; a 4.4-percent reduction in manufacturing output that lowered industrial emissions; warmer winter weather that decreased the demand for heating fuels; and a drop in electricity demand and coal-fired power generation that reduced emissions from electricity generation.

U.S. greenhouse gas emissions in 2001 were 11.9 percent higher than 1990 emissions (1,683 million metric tons carbon 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 (1.9 percent), or gross domestic product (2.9 percent).

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 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

Table ES1. Summary of Estimated U.S. Emissions of Greenhouse Gases, 1990-2001
(Million Metric Tons of Gas)

| Gas | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Carbon Dioxide ^R | 5,002.8 | 4,960.6 | 5,063.9 | 5,175.4 | 5,260.2 | 5,320.9 | 5,505.0 | 5,573.0 | 5,596.4 | 5,672.8 | 5,855.1 | 5,788.5 |
| Methane | 31.7 | 31.9 | 31.9 | 31.0 | 31.1 | 31.1 | 29.9 | 29.5 | 29.0 | 28.7 | 28.3 | 28.0 |
| Nitrous Oxide | 1.2 | 1.2 | 1.2 | 1.2 | 1.3 | 1.3 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| HFCs, PFCs, and SF ₆ | * | * | * | * | * | * | * | * | * | * | * | * |

^REstimates of energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data. See text box on page 27 for detailed explanation.

*Less than 0.05 million metric tons of gas.

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001).

Source: Estimates presented in this report.

¹See “Units for Measuring Greenhouse Gases” on page 2, 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).

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Gas | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Carbon Dioxide ^R | 1,364 | 1,353 | 1,381 | 1,411 | 1,435 | 1,451 | 1,501 | 1,520 | 1,526 | 1,547 | 1,597 | 1,579 |
| Methane. | 199 | 200 | 200 | 194 | 195 | 195 | 188 | 185 | 182 | 180 | 178 | 176 |
| Nitrous Oxide. | 94 | 96 | 98 | 99 | 106 | 102 | 101 | 99 | 99 | 100 | 98 | 97 |
| HFCs, PFCs, and SF ₆ | 25 | 23 | 24 | 25 | 25 | 27 | 31 | 32 | 35 | 34 | 34 | 31 |
| Total | 1,683 | 1,673 | 1,703 | 1,730 | 1,760 | 1,775 | 1,821 | 1,836 | 1,842 | 1,861 | 1,907 | 1,883 |

^REstimates of energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data and sectoral allocations.

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2000).

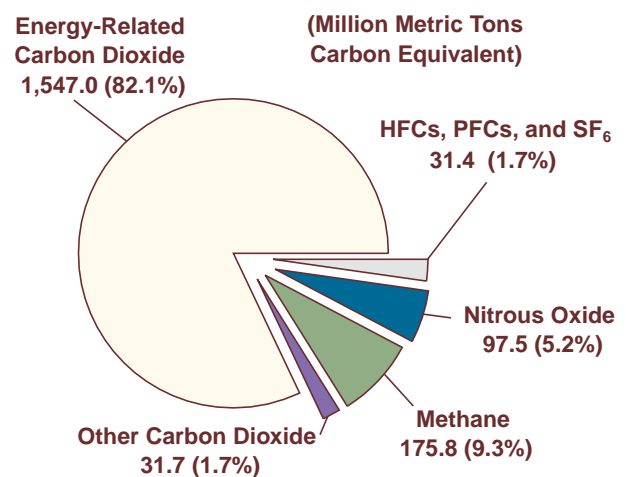
Sources: **Emissions:** Estimates presented in this report. **Global Warming Potentials:** Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 38 and 388-389.

appeared in the IPCC's Second Assessment Report.³ The GWPs published in the Third Assessment Report were used for the calculation of carbon-equivalent emissions for this report. For a discussion of GWPs and a comparison of U.S. carbon-equivalent emissions calculated using the GWPs from the IPCC's Third and Second Assessment Reports, see Chapter 1, page 12. Generally, total U.S. carbon equivalent emissions are 0.8 percent higher when the GWPs from the Third Assessment Report are used.

During 2001, 82.1 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 2001 U.S. greenhouse gas emissions include carbon dioxide from non-combustion sources (1.7 percent of total U.S. greenhouse gas emissions), methane (9.3 percent), nitrous oxide (5.2 percent), and other gases (1.7 percent) (Figure ES1). Methane and nitrous oxide emissions are caused by the biological decomposition of various waste streams and fertilizer, fugitive emissions from chemical processes, fossil fuel production 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.

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 2001



Source: Table ES2 and Table 4 in this report.

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

Carbon Dioxide

The preliminary estimate of U.S. carbon dioxide emissions from both energy consumption and industrial processes in 2001 is 1,579 million metric tons carbon equivalent, which is 1.1 percent lower than in 2000 and accounts for 84 percent of total U.S. greenhouse gas emissions. The 1.1-percent decrease in carbon dioxide emissions in 2001 is the largest annual decline of the 1990 to 2001 period. A 0.8-percent decline in 1991 was the only other annual decrease in carbon dioxide emissions during the period. U.S. carbon dioxide emissions have

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

grown by an average of 1.3 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).

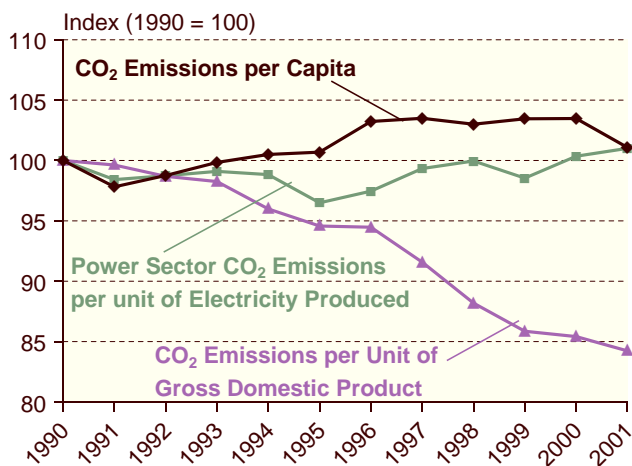
Figure ES2 shows recent trends in some common indexes used to measure the carbon intensity of the U.S. economy. Carbon dioxide emissions per unit of GDP have continued to fall relative to 1990; this measure is now 15.8 percent lower than in 1990. Carbon dioxide emissions per capita, after rising to 3.5 percent above the 1990 level in 1999 and 2000, fell in 2001 to 1.1 percent above the 1990 level. The combination of increasing population growth and rising carbon dioxide emissions per capita resulted in increased aggregate carbon dioxide emissions per year from 1990 through 2000 (a total increase of 17.0 percent). The drop in per capita emissions in 2001 brought the increase since 1990 down to 15.7 percent. Carbon dioxide emissions per unit of net electricity generation increased by 0.6 percent in 2001 from the 2000 level. Although coal-fired generation fell more than other sources of fossil-fuel-generated electric power, increases in emissions from oil- and natural-gas-fired generators offset the decrease. Because oil-fired generators often are less efficient than those that use other fuels, they produce more emissions per unit of

electricity produced. Declines in two of these indexes reflect an economy that was less carbon-intensive in 2001 than in 2000.

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 2001 are estimated at 611.7 million metric tons carbon equivalent, 1.5 percent lower than the 2000 level of 621.2 million metric tons carbon equivalent.⁴ The 2001 decrease can be attributed largely to a 2.2-percent drop in total electricity generation. A 2.6-percent decline in carbon dioxide emissions from coal combustion indicates that the most carbon-intensive form of power generation fell even more than total generation. Also contributing to the decline was a 2.0-percent increase in generation from nuclear fuel, which produces no carbon dioxide emissions.

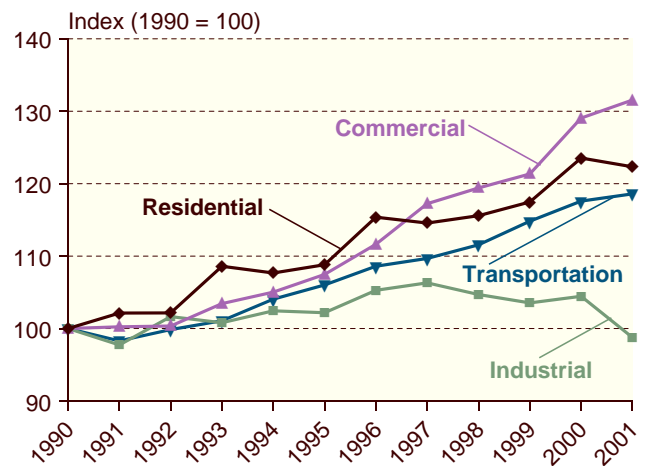
Figure ES3 illustrates trends in carbon dioxide emissions by energy consumption sector. In general, with the exception of the industrial sector, emissions have increased steadily at the sectoral level since 1990. An exception to the general upward trend was 1990-1991, when economic recession and higher oil prices following the Iraqi invasion of Kuwait led to downturns in both the transportation and industrial sectors that were enough to produce a 0.9-percent decrease in national energy-related carbon dioxide emissions in 1991. Average annual growth rates in carbon dioxide emissions by sector during the 1990-2001 period were 2.5 percent for the commercial sector, 1.8 percent for the residential

Figure ES2. Carbon Dioxide Emissions Intensity of U.S. Gross Domestic Product, Population, and Electricity Production, 1990-2001



Sources: Estimates presented in this report.

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1990-2001



Sources: Estimates presented in this report.

⁴As described in detail in Chapter 2, the Energy Information Administration (EIA) has recently completed a reorganization of its electric power data systems to provide better accounting of fuel use, electricity generation, emissions, and other information from the U.S. electric power industry, which has undergone significant structural changes over the past decade. The data reorganization has led to revisions in EIA’s historical data on fuel use for electricity generation, with corresponding revisions in the 1990-2000 estimates of energy-related carbon dioxide emissions, total greenhouse gas emissions, sector-specific emissions, and emissions by fuel type.

sector, and 1.6 percent for the transportation sector. For the industrial sector, however, carbon dioxide emissions have dipped below their 1990 level. Industrial sector carbon dioxide emissions, which are relatively sensitive to economic fluctuations, declined by 2.3 percent in 1991 during the economic recession, dipped again in 1998 in the wake of the Asian economic slowdown, and once again fell in 2001 as industrial output fell by 4.4 percent.

In the residential sector, total carbon dioxide emissions were down by 1.0 percent, from 318.1 million metric tons carbon equivalent in 2000 to 314.9 million metric tons in 2001. The decrease is attributed mainly to a 3.5-percent drop in natural gas use due to warmer weather that reduced heating degree-days by 5.9 percent. Emissions attributable to purchased electricity also fell by 0.1 percent, which also contributed to the overall decline in residential carbon dioxide emissions. Since 1990, residential carbon dioxide emissions have grown by an average of 1.8 percent annually.

Carbon dioxide emissions in the commercial sector increased by 1.9 percent, from 274.4 million metric tons carbon equivalent in 2000 to 279.7 million metric tons in 2001. Emissions attributable to purchased electricity increased by 2.3 percent, from 210.5 million metric tons in 2000 to 215.4 million metric tons in 2001. Carbon dioxide emissions from the combustion of fossil fuels in the commercial sector, primarily natural gas, rose from 63.9 million metric tons in 2000 to 64.3 million metric tons in 2001, a 0.7-percent increase. The commercial sector increase in emissions was driven by strong commercial development in 2001; however, the 1.9-percent growth in emissions during 2001 was less than the 2.5-percent average annual growth in emissions from the commercial sector since 1990.

Energy-related carbon dioxide emissions in the industrial sector in 2001 are estimated at 452.4 million metric tons carbon equivalent, which is approximately equal to the level of emissions in 1991 and 1992. 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 2001 is a case in point: industrial emissions fell by 5.4 percent, from 478.4 million metric tons in 2000 to 452.4 million metric tons in 2001, coinciding with a 4.4-percent decrease in manufacturing output.

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. In all six of the 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, output declined in 2001. The greatest declines were in Primary Metals (-11.4 percent), followed by Pulp and Paper (-5.1 percent) and Stone, Clay and Glass Products (-2.4 percent). Smaller declines in output were seen for the other energy-intensive industries: Food (-0.8 percent), Chemicals (-0.8 percent), and Petroleum (-0.6 percent). By fuel type, industrial sector carbon dioxide emissions from purchased electricity fell by 7.4 percent, emissions from natural gas by 7.4 percent, and emissions from coal by 5.7 percent. Emissions from petroleum use in the industrial sector increased by 2.0 percent in 2001 (a net increase of 1.9 million metric tons carbon equivalent); although carbon dioxide emissions from industrial petroleum consumption were lower by 5.5 million metric tons carbon equivalent, an offsetting increase of 7.4 million metric tons carbon equivalent resulted from a 7-percent decline in nonfuel uses of petroleum in the sector.

Carbon dioxide emissions in the transportation sector, at 512.0 million metric tons carbon equivalent, were 0.8 percent higher in 2001 than in 2000. Emissions of carbon dioxide from gasoline consumption (60.2 percent of transportation sector emissions) grew by 2.1 percent, but emissions from jet fuel use for air travel and residual fuel consumption by ships fell by 4.3 percent and 5.8 percent, respectively, as air travel disruptions and an economic downturn at the end of the year affected both airlines and shipping. Transportation sector carbon dioxide emissions have grown by an average of 1.6 percent annually since 1990.

Methane

U.S. emissions of methane in 2001 were 1.1 percent lower than in 2000, at 28.0 million metric tons of methane or 175.8 million metric tons carbon equivalent (9.3 percent of total U.S. greenhouse gas emissions). Total U.S. methane emissions in 2000 were 28.3 million metric tons of methane. The 2001 decline resulted primarily from decreases in methane emissions from natural gas systems and coal mining, which more than offset small increases in emissions from waste management (primarily landfills) and agricultural sources.

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 37.8, 32.8, and 29.0 percent, respectively, of total 2001 U.S. emissions of methane, or approximately 9.3 percent of the Nation's total carbon-equivalent greenhouse gas emissions. 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 11.1 million metric tons of methane in 2000 to 10.6 million metric tons of methane in 2001, representing a 4.3-percent reduction in emissions from energy sources. Methane emissions from energy sources have fallen by 11.3 percent since 1990. The drop in 2001 was the result of reductions in emissions associated with withdrawals of natural gas from underground storage and in emissions from gassy underground coal mines.

Methane emissions from agricultural sources increased by 0.7 percent, from 9.1 million metric tons in 2000 to 9.2 million metric tons in 2001. 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. In 2001, methane emissions from enteric fermentation and animal waste increased by 0.5 and 0.3 percent, respectively. Agricultural emissions have increased by 11.3 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 increased by 1.4 percent, from 8.0 million metric tons in 2000 to 8.1 million metric tons in 2001. Contributing to the increase was a 1.4-percent increase in emissions from landfills that resulted from an increase in the amount of municipal solid waste landfilled and a leveling off of methane recovery for energy use and flaring. Emissions of methane from waste management have declined by 28.4 percent since 1990 as a result of an increase in the amount of methane recovered (3.9 million metric tons more in 2001

than in 1990) that would otherwise have been emitted to the atmosphere.

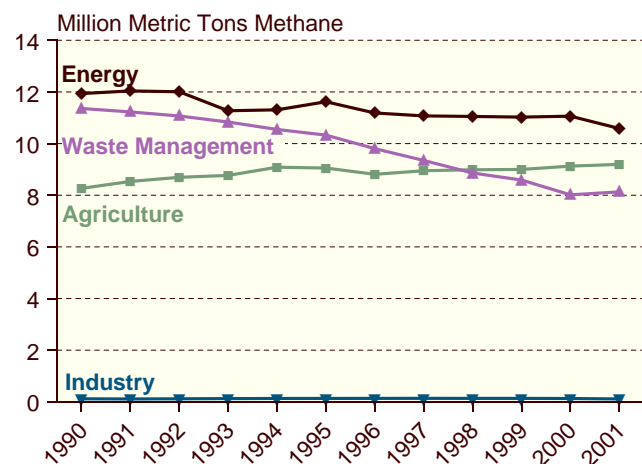
The estimates for methane emissions are more uncertain than those for carbon dioxide. U.S. methane emissions do not necessarily increase with growth in energy consumption or the economy. Energy-related methane emissions are strongly influenced by coal production from a relatively restricted number of 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 1.0 percent from 2000 to 2001, to 1.2 million metric tons of nitrous oxide or 97.5 million metric tons carbon equivalent (5.2 percent of total U.S. greenhouse gas emissions). The 2001 decline in nitrous oxide emissions resulted primarily from decreases in emissions from agricultural sources and industrial processes. Since 1990, U.S. nitrous oxide emissions have grown by 3.2 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 vehicles, a significant number of assumptions are required for the derivation of emissions estimates.

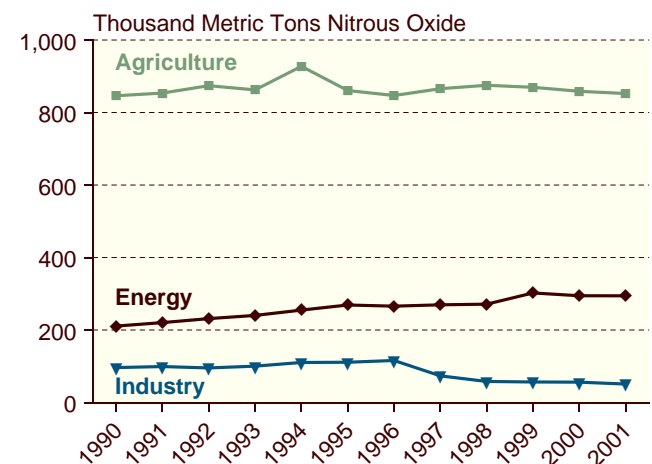
U.S. nitrous oxide emissions include two large categories of sources, agriculture and energy use, and two smaller categories, industrial processes and waste management (Figure ES5). Agricultural sources, at 852.5

Figure ES4. U.S. Emissions of Methane by Source, 1990-2001



Source: Estimates presented in this report.

Figure ES5. U.S. Emissions of Nitrous Oxide by Source, 1990-2001



Source: Estimates presented in this chapter.

thousand metric tons of nitrous oxide, account for about 70.6 percent of total U.S. nitrous oxide emissions. Emissions associated with nitrogen fertilization of soils, at 620.5 thousand metric tons, account for 72.8 percent of nitrous oxide emissions from agriculture. Emissions from the solid waste of animals, at 230.1 thousand metric tons, make up 27.0 percent of agricultural nitrous oxide emissions. Nitrous oxide emissions from agriculture have increased by 0.7 percent since 1990.

U.S. nitrous oxide emissions associated with fossil fuel combustion in 2001 were about 0.3 million metric tons of nitrous oxide, or 23.5 percent of total nitrous oxide emissions. Of these energy-related emissions, 82.7 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 34.7 percent since 1990.

Industrial processes and wastewater treatment facilities are responsible for 5.8 percent of total nitrous oxide emissions. Industrial process emissions fell from 56.2 thousand metric tons in 2000 to 51.0 thousand metric tons in 2001. This continues a trend that since 1996 has produced a 56.0-percent decrease as a result of reductions in emissions from the production of adipic acid. Emissions from wastewater treatment facilities were unchanged from 2000 at 19.8 thousand metric tons in 2001.

Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

HFCs, PFCs, and SF₆ are three classes of engineered gases that account for 1.7 percent of U.S. GWP-weighted emissions of greenhouse gases. At 31.4 million metric tons carbon equivalent in 2001, their emissions were 7.7 percent lower than in 2000. The 2000 to 2001 decrease in emissions of the engineered gases was caused by across-the-board reductions in emissions of HFCs (5.0 percent), PFCs (36.1 percent), and SF₆ (6.7 percent). At 21.0 million metric tons carbon equivalent, emissions of HFCs make up the majority of this category, followed by SF₆ at 4.7 million metric tons and PFCs at 2.4 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 2001, their combined emissions totaled 3.3 million metric tons carbon equivalent. Emissions in this “other” group in 2001 were 6.0 percent higher than in 2000 and orders of magnitude higher than in 1990, when emissions were miniscule (less than 50,000 metric tons carbon equivalent). Since 1990, HFC emissions from U.S. sources have increased by 109.4 percent, PFC emissions have decreased by 53.9 percent, and SF₆ emissions have decreased by 50.8 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, 4310, 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. According to U.S. Forest Service researchers, U.S. forest land absorbs about 246 million metric tons of carbon annually, equivalent to 15.6 percent of U.S. carbon dioxide emissions. 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.

Over the past several years there has been increasing interest in the United States regarding carbon sequestration in agricultural soils through changes in agricultural practices. Proponents suggest that changes in tillage practices can cause agricultural soils to move from being net sources to net sinks of carbon dioxide, and that the amounts of carbon that might be absorbed by these changes could be significant at the national level. Although EIA’s previous emissions inventory reports did not include estimates of carbon sequestration in agricultural soils, they are included in this year’s inventory (see Chapter 6, “Land Use Issues”).

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 ninth annual update, covering national emissions over the period 1990-2000, with preliminary estimates of emissions for 2001. 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 carbon equivalent; estimates for other gases are reported in metric tons of gas (see "Units for Measuring Greenhouse Gases," page 2). Total national emissions estimates measured in carbon equivalents 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 keep the Earth at its present temperature, scientists began to postulate that increasing concentrations of greenhouse gases would make the Earth warmer.

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 has not yet "entered into force," which 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. The United States, at UNFCCC negotiations at 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.

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

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.

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 is reported in carbon units, defined as the weight of the carbon content of carbon dioxide (i.e., just the “C” in CO₂). Carbon dioxide units at full molecular weight can be converted into carbon units by dividing by 44/12, or 3.6667. This approach has been adopted for two reasons:

- Carbon dioxide is most commonly measured in carbon units in the scientific community. Scientists

argue that not all carbon from combustion is, in fact, emitted in the form of carbon dioxide. Because combustion is never perfect, some portion of the emissions consists of carbon monoxide, methane, other volatile organic compounds, and particulates. These other gases (particularly carbon monoxide) eventually decay into carbon dioxide, but it is not strictly accurate to talk about “tons of carbon dioxide” emitted.

- Carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration. Because most fossil fuels are 75 percent to 90 percent carbon by weight, it is easy and convenient to compare the weight of carbon emissions (in carbon units) with the weight of the fuel burned. Similarly, carbon sequestration in forests and soils is always measured in tons of carbon, and the use of carbon units makes it simple to compare sequestration with emissions.

While carbon dioxide emissions can be measured in tons of carbon, emissions of other 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). GWPs are discussed later in this chapter and delineated in Table 3. For comparability, carbon dioxide equivalent units can be converted to “carbon equivalent” by multiplying by 12/44 (as in Table ES2) to provide a measure of the relative effects of various gases on climate.

most recent report of the 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 find some mechanism for limiting the risk of climate change and ameliorating possible consequences. To date, efforts have focused 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 counterbalancing 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

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/>.

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

Chapter 2

- There has been a major realignment of EIA data regarding electricity generation, going back to 1989. These changes have been implemented to better reflect the electric power industry that has resulted from restructuring over the past several years. Also, in the course of this work, EIA determined that natural gas consumption by independent power producers would be more accurately estimated from data derived directly from surveys of independent power producers, rather than from natural gas supplier surveys as was done previously. Data have been revised back to 1993, changing the estimates of total natural gas consumption and consumption by sector. Thus, both the sector shares and absolute levels of energy-related carbon dioxide emissions have been revised (for example, emissions in 2000 are 1.1 percent higher than previously estimated). Readers should consult Chapter 2 for details of the changes.

Chapter 3

- Estimates of methane recovery from coal mines have been lowered for the period 1998 through 2000, to reflect new data collected by the U.S. Environmental Protection Agency (EPA) Coalbed Methane Outreach Program. The effect of this revision was to raise estimates of net emissions from coal mines by about 100,000 metric tons of methane in each of those three years.

Chapter 5

- The data presented in Chapter 5 for other gases (HFCs, PFCs, and SF₆) are provided by the EPA. Much of the EPA's estimation methodology is based on sectoral models. Revisions to the models and subsequent changes in historical emissions estimates are explained below:
 - Data reported in 1999 and 2000 to the EPA's Voluntary SF₆ Emissions Reduction Partnership and new information on world sales of SF₆ to electric power systems from 1990 to 1999 (RAND Corporation), has changed the emissions trajectory from previously estimated trends in both magnitude and direction, with emissions now near steady for 1990-1994 and decreasing for 1995-2001.
 - Estimates of SF₆ emissions from the magnesium industry have been revised for 1993-1999, due to changes in estimated emissions factors for

different segments of the magnesium industry. These revisions resulted in a total decrease in SF₆ emissions of 1.6 percent from 1993 through 1999.

- New information on aluminum production (smelters) and anode effects from the Voluntary Aluminum Industrial Partnership Program have led to revisions of 1990-1999 estimates for PFC emissions. The revisions show an average 2.8-percent annual decrease in CF₄ and C₂F₆ emissions.
- The methodology for estimating emissions from semiconductor manufacturing has been changed to one based on total annual emissions reported by participants in the PFC Emission Reduction Partnership for the Semiconductor Industry. The revisions result in an average 1.5-percent decrease in annual HFC, PFC, and SF₆ emissions from semiconductor manufacturing for 1990-1999.
- For substitutes to replace ozone-depleting substances (ODS), revisions to chemical substitution trends and new information from industry representatives have led to revised assumptions for the EPA's Vintaging Model, particularly in the areas of cleaning solvents, stationary refrigeration, and fire extinguishing equipment. The revisions result in an average 10.6-percent decrease in annual emissions of HFCs, PFCs, and SF₆ from their use as ODS substitutes for 1994-1999.
- Correction of an error by the EPA in the conversion of gigagrams (Gg) of HFC-23 to teragrams (Tg) of carbon dioxide equivalent have affected estimates of HFC-23 emissions from HCFC-22 production for 1990-1998. This revision results in an average decrease of less than 0.1 percent in annual HFC-23 emissions from the production of HCFC-22.

Chapter 6

- The data presented in Chapter 6 for carbon dioxide sequestration through land use and forestry activities are based on carbon stock estimates developed by the U.S. Forest Service. In previous reports, EIA has presented carbon sequestration estimates only for U.S. forest and harvested wood components. This year's report includes carbon sequestration estimates for urban trees, agricultural soils, and landfilled yard trimmings to supplement the updated data on forest carbon stocks.

(continued on page 5)

What's New in This Report (Continued)

Appendix B

- Carbon emission coefficients for coal by sector and rank have been revised to reflect a new analysis of 6,588 coal samples from the U.S. Geological Survey (USGS) Coal Quality Database. The samples were taken between 1973 and 1989 and were drawn largely from State geological surveys. The USGS database replaces the EIA Coal Analysis File used previously, which was based on a much older set of coal samples. The resulting changes in carbon emission factors are less than 1 percent across all coal ranks and end-use sectors.

- Appendix B has been expanded substantially, to include documentation of the development of emission coefficients for coal by rank and end-use sector, natural gas sold via pipeline and flared, and all major petroleum products. This improves on previous editions that captured only changes in the annual emissions coefficients.

Appendix F

- The conversion factors provided by EIA have been streamlined and reorganized to provide a more useful and intuitive tool for readers.

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 Carbon Equivalent) ^a | 210,000 | 6,300 | 216,300 | 213,100 | 3,200 |
| 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 210,000 million metric tons carbon equivalent, based on balanced flux of 120,000 million metric tons carbon equivalent between land and atmosphere and 90,000 million metric tons carbon equivalent 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 6,300 million metric tons carbon equivalent and distribution of those emissions (atmospheric absorption 3,200 million metric tons carbon equivalent, ocean absorption 1,700 million metric tons carbon equivalent, and land absorption 1,400 million metric tons carbon equivalent), 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).

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 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 (90 billion metric tons carbon equivalent per year) and land (120 billion metric tons carbon equivalent annually), including 60 billion metric tons carbon equivalent from plant respiration, 55 billion metric tons carbon equivalent from non-plant respiration (bacteria, fungi, and herbivores) and 4 billion metric tons carbon equivalent from combustion of natural and human-made fires.⁹ Known anthropogenic sources (including deforestation) were estimated to account for about 7.9 billion metric tons of carbon 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 3.1 to 3.3 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 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

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.

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.

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 0.032 million metric tons in 1996.¹⁶ 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.

Another new class of engineered halocarbons are 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.

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.¹⁸

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

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.

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.

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, 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 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

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.

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.

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.

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

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.

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.

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 halocarbons, such as 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

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.

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

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 continue until the UNFCCC reporting rules are changed. Therefore, the U.S. Environmental Protection Agency (EPA), in its *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000* (April 2002), compiled the official U.S. emissions inventory for submission to the UNFCCC based on the GWPs published in the Second Assessment Report. In its next inventory report, the EPA will present aggregate emissions calculated with

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).

GWPs from the Third Assessment report for informational purposes.

The table below shows 2001 U.S. carbon-equivalent greenhouse gas emissions calculated using the IPCC's 1996 and 2001 GWPs. The estimate for total U.S. emissions in 2000 is 0.8 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-equivalent methane emissions are 10 percent higher, and carbon-equivalent nitrous oxide emissions are 4 percent lower. Carbon-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 | IPCC GWP | | Annual GWP-Weighted Emissions (Million Metric Tons Carbon Equivalent) | | | | | | | | |
|---|----------|------|--|--------------|-------------------|--------------|--------------|-------------------|--------------|--------------|-------------------|
| | 1996 | 2001 | 1990 | | | 2000 | | | 2001 | | |
| | | | 1996 GWP | 2001 GWP | Percent Change | 1996 GWP | 2001 GWP | Percent Change | 1996 GWP | 2001 GWP | Percent Change |
| Carbon Dioxide | 1 | 1 | 1,364 | 1,364 | 0.0 | 1,597 | 1,597 | 0.0 | 1,579 | 1,579 | 0.0 |
| Methane | 21 | 23 | 181 | 199 | 9.5 | 162 | 178 | 9.5 | 160 | 176 | 10.0 |
| Nitrous Oxide | 310 | 296 | 99 | 94 | -4.5 | 103 | 98 | -4.5 | 102 | 97 | -4.0 |
| HFCs, PFCs, and SF ₆ | — | — | 26 | 25 | -3.8 | 31 | 34 | 9.7 | 28 | 31 | 10.7 |
| Total | — | — | 1,670 | 1,682 | 0.7 | 1,891 | 1,907 | 0.8 | 1,868 | 1,883 | 0.8 |

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

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

From the Framework Convention to the Kyoto Protocol

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

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.

³⁵The 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, United States of America. Belarus initially participated in the Framework Convention but did not join the Kyoto Protocol. Turkey initially joined the Convention but subsequently asked to withdraw from Annex I status and did not join the Kyoto Protocol. Kazakhstan applied for Annex I status in June 1999 but withdrew its application in June 2000.

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

The Framework Convention divided its signatories into two groups: the countries listed in Annex I to the Protocol, and all others. The Annex I countries include the 24 original members of the Organization for Economic Cooperation and Development (OECD) (including the United States), the European Union, and 14 countries with economies in transition (Russia, Ukraine, and Eastern Europe).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 Both the European Union (EU) and the individual members of the EU signed the Protocol 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 Annex I emissions “have deposited their instruments of ratification, acceptance, approval, or accession.” As of December 18, 2002, 100 countries had ratified the Protocol. The Annex I nations that had ratified the Protocol represented 43.7 percent of total Annex I carbon dioxide emissions in 1990.³⁸

The Kyoto Protocol and the United States

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

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 (see box on page 14). 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

³⁷Several Eastern European states have been permitted to use emissions from the late 1980s, rather than 1990, as their baseline. All signatories may elect to use 1995 emissions of HFCs, PFCs, and sulfur hexafluoride as the baseline rather than 1990 emissions.

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).

Historical and Projected U.S. Carbon and Total Greenhouse Gas Intensity

On February 14, 2002, President Bush announced the Administration’s Global Climate Change Initiative. A key goal of the Climate Change Initiative is to reduce U.S. greenhouse gas intensity by 18 percent between 2002 and 2012. As indicated in the table below, the projected baseline reduction is 13.8 percent over the 10-year period. For the purposes of the initiative, total greenhouse gas (GHG) intensity is defined as the ratio of total U.S. greenhouse gas emissions to economic output.

Historical and Projected Growth Rates for U.S. Carbon Intensity

| Decade | Overall Change in Intensity (Percent) | | Average Annual Change in Intensity (Percent) | |
|--------------------|---------------------------------------|-------|--|------|
| | Carbon | GHG | Carbon | GHG |
| History | | | | |
| 1950-1960 | -12.9 | — | -1.4 | — |
| 1960-1970 | -3.1 | — | -0.3 | — |
| 1970-1980 | -18.1 | — | -2.0 | — |
| 1980-1990 | -22.9 | — | -2.6 | — |
| 1990-2000 | -15.6 | -17.5 | -1.7 | -1.9 |
| Projections | | | | |
| 2002-2012 | -12.5 | -13.8 | -1.3 | -1.5 |
| 2000-2020 | -26.3 | -26.4 | -1.5 | -1.5 |
| 2000-2025 | -31.1 | — | -1.5 | — |

Sources: **History:** Estimates presented in Appendix E of this report. **Projections:** Based on Energy Information Administration, “Early Release of the Annual Energy Outlook 2003” (November 2002), web site www.eia.doe.gov/oiaf/aeo/index.html; and U.S. Department of State, *U.S. Climate Action Report 2002* (Washington, DC, May 2002), Chapter 5, “Projected Greenhouse Gas Emissions,” pp. 70-80, web site www.epa.gov.

The carbon intensity and greenhouse gas intensity of the U.S. economy move in lockstep (see figure at right), 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 and projected trends in U.S. carbon intensity (energy-related carbon dioxide emissions per unit of economic output) are described below.

The carbon intensity of the U.S. economy has been falling steadily, with a few brief exceptions, since 1949, the earliest year for which EIA has data (see figure on opposite page). In terms of decades, as shown in the table above, changes in carbon intensity were fairly

modest for the 1950s (-12.9 percent) and 1960s (-3.1 percent), accelerated in the 1970s (-18.1 percent) and 1980s (-22.9 percent), and fell back slightly in the 1990s (-15.6 percent). These declines can be analyzed in terms of trends in energy intensity and the carbon intensity of energy supply.

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:

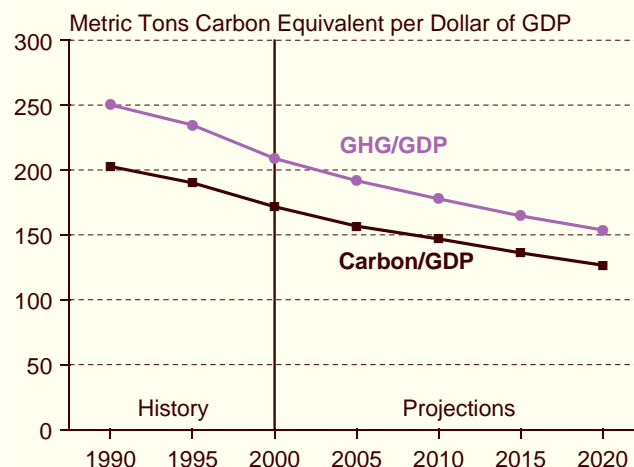
$$\text{Energy Intensity} \times \text{Carbon Intensity of Energy Supply} = \text{Carbon Intensity of the Economy}$$

or, algebraically,

$$(\text{Energy/GDP}) \times (\text{Carbon Emissions/Energy}) = (\text{Carbon Emissions/GDP})$$

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
(continued on page 15)

Intensity Ratios: GHG/GDP and Carbon/GDP



Sources: **History:** Estimates presented in this report. **Projections:** Based on Energy Information Administration, “Early Release of the Annual Energy Outlook 2003” (November 2002), web site www.eia.doe.gov/oiaf/aeo/index.html; and U.S. Department of State, *U.S. Climate Action Report 2002* (Washington, DC, May 2002), Chapter 5, “Projected Greenhouse Gas Emissions,” pp. 70-80, web site www.epa.gov.

Historical and Projected U.S. Carbon and Total Greenhouse Gas Intensity (Continued)

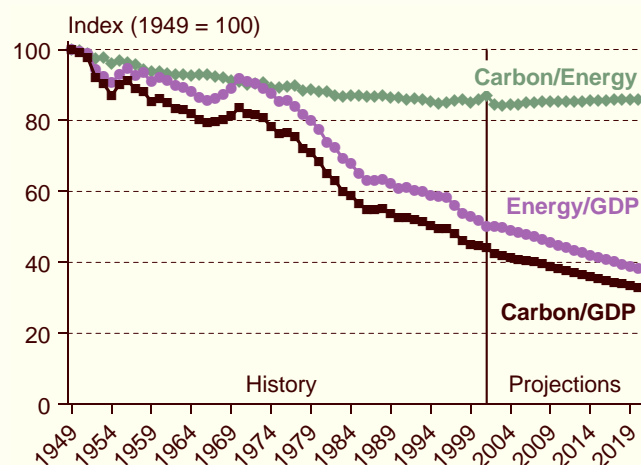
meant that over the second half of the 20th century economic growth was less tied to growth in energy demand than it was during the period of industrialization in the 19th and early 20th century. Other factors contributing to decreases in energy intensity include:

- 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

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



Sources: **History:** Estimates presented in Appendix E of this report. **Projections:** Based on Energy Information Administration, "Early Release of the Annual Energy Outlook 2003" (November 2002), web site www.eia.doe.gov/oiaf/aeo/index.html; and U.S. Department of State, *U.S. Climate Action Report 2002* (Washington, DC, May 2002), Chapter 5, "Projected Greenhouse Gas Emissions," pp. 70-80, web site www.epa.gov.

relatively unchanged. The primary reason 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 peak in 2006, this trend is expected to stabilize. Other factors that have decreased the carbon intensity of the energy supply include:

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

Unlike the expectation of future reductions in energy intensity, it is less clear, absent a change in policy, that carbon intensity of energy supply will decrease dramatically in the near future. Both nuclear electricity generation and hydropower generating capacity are expected to peak in 2006. Additionally, rising natural gas prices may make coal a more viable economic alternative for future electricity generation. If these trends continue, any decline in the carbon intensity of the economy will come from decreasing energy intensity rather than decreasing carbon intensity of the energy supply.

There are, however, several possibilities for continued reductions in the carbon intensity of energy supply:

- Renewable energy other than hydropower could make gains in the electric power sector, providing a source of carbon-free energy.
- Increased use of less carbon-intensive transportation fuels could further reduce overall carbon intensity.
- Distributed generation technologies using renewable energy sources such as solar photovoltaics could provide carbon-free energy at the source of demand.
- A resurgence of the nuclear power industry could result in a growing contribution to the energy mix.

Between 1990 and 2000, there were relatively easy methods to reduce gases other than carbon dioxide—e.g. methane capture at landfills—that kept emissions of greenhouse gases relatively stable while the economy grew. As a result, GHG intensity declined slightly more than carbon intensity (1.9 percent per year versus 1.7 percent per year). Between 2000 and 2020 GHG intensity is expected to decline by 26.4 percent, about the same as carbon intensity (26.3 percent).

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}

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.⁴⁴ 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.⁴⁵

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 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.⁴⁶ COP-8 met from October 23 to November 1, 2002, in New Delhi, India.⁴⁷ 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 2003 in Italy.

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.climatechange.gov/Library/climateletter.htm (September 9, 2002).

⁴⁴See U.N. Framework Convention on Climate Change, web site <http://cop6.unfccc.int/media/press.html>.

⁴⁵“U.N. Conference Fails to Reach Accord on Global Warming,” *New York Times* (November 26, 2000).

⁴⁶Pew 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.

⁴⁷United 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>.

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.

2. Carbon Dioxide Emissions

Overview

| U.S. Anthropogenic Carbon Dioxide Emissions, 1990-2001 | | |
|--|----------------|-------------------|
| | Carbon Dioxide | Carbon Equivalent |
| Estimated 2001 Emissions (Million Metric Tons) | 5,789.0 | 1,578.7 |
| Change Compared to 2000 (Million Metric Tons) | -66.6 | -18.2 |
| Change from 2000 (Percent) | -1.1% | -1.1% |
| Change Compared to 1990 (Million Metric Tons) | 852.4 | 214.3 |
| Change from 1990 (Percent) | 15.7% | 15.7% |
| Average Annual Increase, 1990-2001 (Percent) | 1.3% | 1.3% |

Total emissions of carbon dioxide in the United States and its territories were 1,578.7 million metric tons carbon equivalent in 2001, 18.2 million metric tons carbon equivalent (1.1 percent) less than the 2000 total (Table 4). The decrease in emissions from 2000 to 2001 was the first since 1991, when a slumping economy led to a decline of 0.8 percent from 1990. The decline in carbon dioxide emissions in 2001 can be attributed in large part to a reduction in overall U.S. economic growth from 3.8 percent in 2000 to 0.3 percent in 2001; a 4.4-percent reduction in manufacturing output that lowered industrial emissions (Table 5); warmer winter weather that decreased the demand for heating fuels; and a drop in electricity demand and coal-fired power generation that reduced the growth in emissions from electricity generation. The decline in emissions from 2000 to 2001 follows an increase of 3.2 percent, or 49.7 million metric tons, from 1999 to 2000 (Figure 1). Since 1990, total U.S. carbon dioxide emissions have increased by an average of about 1.3 percent per year.

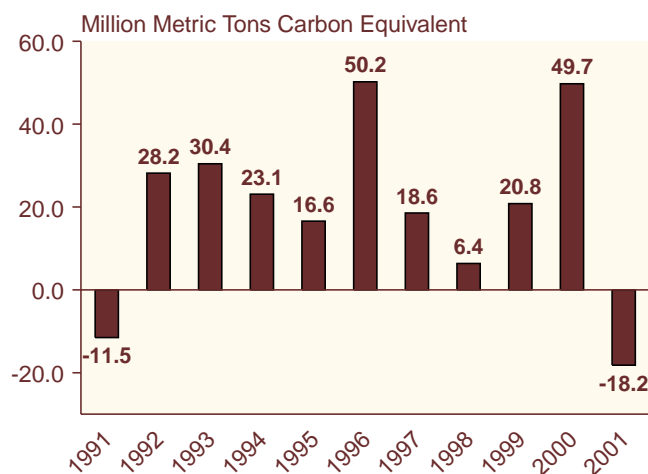
In the United States, most carbon dioxide (98 percent) is emitted as the result of the combustion of fossil fuels; consequently, carbon dioxide emissions and energy use are highly correlated. Historically, economic growth, the weather, the carbon and energy intensity of the economy, and movements in energy prices have caused

year-to-year fluctuations in energy consumption and resulting carbon dioxide emissions. Warmer-than-normal winter weather in 2001 was an important factor in reducing residential and commercial energy consumption and carbon dioxide emissions below the levels that would have been expected under normal conditions.

The decreased demand for heating fuels can be seen in the residential and commercial sectors, 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 declined by 1.0 percent, from 318.1 million metric tons carbon equivalent in 2000 to 314.9 million metric tons carbon equivalent in 2001. In the commercial sector (Table 7), emissions increased by 1.9 percent (from 274.4 million metric tons in 2000 to 279.7 million metric tons in 2001). Most of the economic growth in the commercial sector in 2001 was in service industries. In addition, weather conditions have a smaller effect on energy use and carbon dioxide emissions in the commercial sector than in the residential sector.

Industrial production and related energy consumption declined in 2001; the total industrial production index was down by 3.9 percent for the year. Manufacturing activity was down by 4.4 percent. The drop in the manufacturing index was the largest in recent years, even surpassing the 2.4-percent decline during the recession of

Figure 1. Annual Change in U.S. Carbon Dioxide Emissions, 1990-2001



Source: Estimates presented in this chapter.

1991. In all six of the energy-intensive industry groups, which traditionally account for about 65 to 70 percent of total industrial carbon dioxide emissions, output declined in 2001. The greatest declines were in Primary Metals (-11.4 percent), followed by Pulp and Paper (-5.1 percent) and Stone, Clay and Glass Products (-2.4 percent). Smaller declines in output were seen for the other energy-intensive industries: Food (-0.8 percent), Chemicals (-0.8 percent), and Petroleum (-0.6 percent). Preliminary results indicate that industrial emissions (Table 8) were down by 5.4 percent (from 478.4 million metric tons carbon equivalent in 2000 to 452.4 million metric tons in 2001), primarily because of the decline in industrial output.

Estimates for 2001 indicate that carbon dioxide emissions in the transportation sector (Table 9) increased by 0.8 percent, from 507.3 million metric tons carbon equivalent in 2000 to 511.6 million metric tons in 2001. The modest increase can be attributed largely to the economic slowdown late in the year that dampened demand for transportation services. Transportation sector energy demand usually is affected less by an

economic downturn than is demand for energy services in other sectors (in particular, manufacturing).

Net generation of electricity decreased by 2.2 percent from 2000 to 2001, and total carbon dioxide emissions from the electric power sector decreased by 1.5 percent, from 621.2 million metric tons carbon equivalent in 2000 to 611.7 million metric tons in 2001 (Table 10). 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.⁴⁸

Evolution of EIA Emissions Estimates for the Electric Power Sector

EIA's *Emissions of Greenhouse Gases in the United States 1999*, published in October 2000, included a table that showed emissions based on electricity generation in the industrial sector and in the traditional electric power sector (electric utilities only). Emissions from the two sources were summed to provide a more complete estimate of total electric power emissions. However, in the end-use sector tables, only the electric utility emissions were shared out—as had been the case in all previous EIA emissions inventory reports. This created some confusion for readers who could not add the electricity totals across sectors and arrive at the values in the standalone table for the electric power sector.

Emissions of Greenhouse Gases in the United States 2000, published in November 2001, included a table that showed total emissions for both utility and nonutility generators in the electric power sector. Unlike the previous year, it was not a standalone table, and the emissions total was shared out to the four end-use sectors. Because none of EIA's other multi-fuel publications allocated energy consumption in quite the same way, however, the data could not be recreated by using the energy consumption data from EIA's integrated multi-fuel publications. In this and future EIA

greenhouse gas emissions inventories, estimates of electric power sector emissions will be based on data published in EIA's integrated multi-fuel publications.

The *Annual Energy Review 2001 (AER2001)*, published in October 2002, was the first of EIA's annual multi-fuel publications that used the revised data for electricity sector fuel consumption. In *AER2001*, the electric power sector data include all plants whose primary business is to sell electricity (North American Industrial Classification System—NAICS—code 22). The *AER2001* consumption tables (e.g., Table 6.5 for natural gas) include the fuel used by NAICS 22 CHP plants to produce thermal energy.

In assigning emissions to end-use sectors for the greenhouse gas inventory, all the emissions related to fuel consumed for electricity-only or CHP plants remain in the commercial and industrial sector unless they are categorized as being primarily in the business of selling electricity (NAICS 22), in which case they are included in the electric power sector. The electric power sector's emissions are shared out to the end-use sectors according to the electricity consumption data in the *AER2001* end-use consumption tables.

⁴⁸As described in detail later in this chapter, the Energy Information Administration (EIA) has recently completed a reorganization of its electric power data systems to provide better accounting of fuel use, electricity generation, emissions, and other information from the U.S. electric power industry, which has undergone significant structural changes over the past decade. The data reorganization has led to revisions in EIA's historical data on fuel use for electricity generation, with corresponding revisions in the 1990-2000 estimates of energy-related carbon dioxide emissions, total greenhouse gas emissions, sector-specific emissions, and emissions by fuel type.

Nonfuel uses of fossil fuels, principally petroleum, sequestered 81.0 million metric tons carbon equivalent in 2001, down by 5.7 million metric tons (6.6 percent) from 2000 (Table 11). 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 sequestered in the form of plastic, about 6.1 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 2000. The 2000 estimate of 6.1 million metric tons is used in this report as an estimate for 2001 emissions 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—declined by 0.9 percent, from 32.0 million metric tons carbon equivalent in 2000 to 31.7 million metric tons in 2001 (Table 4). Although emissions from most sources were nearly unchanged, a decline in emissions from industrial processes resulted in a net decline for the “other sources” category.

Energy Consumption

Energy End-Use Sector Sources of U.S. Carbon Dioxide Emissions, 1990-2001

| Sector | Million Metric Tons Carbon Equivalent | | Percent Change | |
|----------------|---------------------------------------|-------|----------------|-----------|
| | 1990 | 2001 | 1990-2001 | 2000-2001 |
| Residential | 257.5 | 314.9 | 22.3% | -1.0% |
| Commercial | 212.6 | 279.7 | 31.5% | 1.9% |
| Industrial | 458.0 | 452.4 | -1.2% | -5.4% |
| Transportation | 431.4 | 511.6 | 18.6% | 0.8% |

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 2001 U.S. carbon dioxide emissions (adjusting for U.S. Territories and bunker fuels), 98 percent, or 1,547.0 million metric tons carbon equivalent, resulted from the combustion of fossil fuels. This figure

represents a 1.1-percent decrease from 2000 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 314.9 million metric tons carbon equivalent, residential carbon dioxide emissions represented 20.2 percent of U.S. energy-related carbon dioxide emissions in 2001. The residential sector's pro-rated share of electric power sector emissions accounts for about two-thirds of that amount (216.3 million metric tons).⁴⁹ Petroleum (mainly distillate fuel oil) accounted for 8.6 percent and natural gas 22.6 percent. Since 1990, residential electricity-related emissions have grown by 2.3 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 decreased by 1.0 percent in 2001 (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 6.0 percent relative to 1995. In 1997, emissions declined by 0.7 percent due to warmer winter weather. The warmer winter in 2001, relative to 2000,

⁴⁹Sectoral (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. 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.

was a major contributor to the 2001 decline in residential sector emissions.

Since 1990, the growth in carbon dioxide emissions attributable to the residential sector has averaged 1.8 percent per year. Residential sector emissions in 2001 were 57.5 million metric tons carbon equivalent higher than in 1990, representing 28.9 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 279.7 million metric tons carbon equivalent, account for about 17.9 percent of total energy-related carbon dioxide emissions, of which 77.0 percent (215.4 million metric tons) is the sector's pro-rated share of electricity-related emissions. Petroleum contributes 5.0 percent and natural gas 17.1 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 increased by 2.3 percent in 2001, while emissions from the direct combustion of fuels (dominated by natural gas, as in the residential sector) increased by 0.7 percent. Overall, carbon dioxide emissions related to commercial sector activity increased by 1.9 percent—from 274.4 to 279.7 million metric tons carbon equivalent—between 2000 and 2001 (Table 7). Since 1990, commercial emissions growth has averaged 2.5 percent per year, the largest growth of any end-use sector. Commercial sector carbon dioxide emissions have risen by 67.1 million metric tons carbon

equivalent since 1990, accounting for 33.7 percent of the total increase in U.S. energy-related carbon dioxide emissions.

Industrial Sector

Industrial sector emissions, at 452.4 million metric tons carbon equivalent, accounted for about 29 percent of total U.S. energy-related carbon dioxide emissions in 2001. In terms of fuel shares, electricity consumption was responsible for 39.6 percent of total industrial sector emissions (179.0 million metric tons), natural gas for 27.3 percent (123.4 million metric tons), petroleum for 21.6 percent (97.9 million metric tons), and coal for 11.3 percent (51.0 million metric tons).

Estimated 2001 energy-related carbon dioxide emissions in the industrial sector, at 452.4 million metric tons carbon equivalent (Table 8), were 5.4 percent lower than the 2000 emissions level of 478.4 million metric tons. Carbon dioxide emissions attributable to industrial sector energy consumption have declined by an average of 0.1 percent per year since 1990. As a result, total energy-related industrial emissions in 2001 were 1.2 percent (5.6 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 26.1 million short tons in 2001. Other industrial coal consumption has declined from 76.3 million short tons in 1990 to 63.4 million short tons in 2001. Energy-intensive industries have been replaced by others that are less energy-intensive, such as computer chip and electronic component manufacturing.

Transportation Sector

Transportation sector emissions, at 511.6 million metric tons carbon equivalent, accounted for one-third of total energy-related carbon dioxide emissions in 2001. Almost all (98 percent) of transportation sector emissions result from the consumption of petroleum products: motor gasoline, at 60 percent of total transportation sector emissions; middle distillates (diesel fuel) at 21 percent; jet fuel at 13 percent of the total; and residual oil (i.e., heavy fuel oil, largely for maritime use) at 3 percent of the sector's total emissions. Motor gasoline is used primarily in automobiles and light trucks, and middle distillates are used in heavy trucks, locomotives, and ships.

Emissions attributable to the transportation sector increased by 0.8 percent in 2001, from 507.3 to 511.6 million metric tons carbon equivalent (Table 9). The

Energy-Related Carbon Dioxide Emissions in Manufacturing

Manufacturing is the single largest source of carbon dioxide emissions in the U.S. industrial sector. This industrial subsector, which excludes agriculture, mining, and construction, accounts for 85 percent of industrial energy-related carbon dioxide emissions and also accounts for approximately 84 percent of industrial energy consumption. The table below shows the latest estimates of energy-related carbon dioxide emissions from the manufacturing subsector, based on energy consumption statistics from EIA's 1998 Manufacturing Energy Consumption Survey (MECS).

Of the 405.2 million metric tons carbon equivalent emitted by manufacturers in 1998, about 43 percent (174.4 million metric tons carbon equivalent) was emitted by two industry groups: Petroleum and Coal Products (21.6 percent) and Chemicals (21.5 percent). Four other groups account for roughly 37 percent of the subsector total: Primary Metals (16.9 percent), Paper (8.0 percent), Food (6.1 percent), and Stone, Clay and Glass (5.6 percent). The Other Manufacturing group, consisting of 14 industries that range from apparel to fabricated metals to computer manufacturing, accounts for the remaining 20 percent; none of those 14 industry groups separately accounts for more than 3 percent of total energy-related carbon dioxide emissions from the manufacturing subsector.

The mix and quantity of manufacturers' demand for fuel and nonfuel uses of energy affects the subsector's carbon intensity of energy use—i.e., the ratio of carbon emitted per unit of energy used (see box in Chapter 1, page 14). Overall, manufacturing industries had carbon intensities of 12.67 and 12.17 million metric tons carbon equivalent per quadrillion Btu in 1991 and 1998,

respectively; however, the carbon intensities of the various industry groups differed markedly.

Both the petroleum industry and the chemical industry transform energy sources into products, such as petrochemical feedstocks, asphalt, and plastics. Only a part of the carbon content of energy inputs is emitted to the atmosphere; the remainder is sequestered in the products (see Table A2 in Appendix A).^a Because both the petroleum and chemical industries use energy for nonfuel purposes, both have lower carbon intensities than the manufacturing average: 12.14 and 11.35 million metric tons carbon equivalent per quadrillion Btu for the petroleum industry in 1991 and 1998, respectively; and 11.61 and 11.15 million metric tons carbon equivalent per quadrillion Btu for the chemicals industry.

The paper industry uses wood byproducts extensively, yielding carbon intensities of 9.55 and 9.17 million metric tons carbon equivalent per quadrillion Btu in 1991 and 1998, respectively. Carbon dioxide emissions from wood consumption are considered to be zero, because the carbon emitted has been recently sequestered and the regrowing of trees will re-sequester the emitted carbon. The primary metals industry, however, is a heavy user of energy sources with high carbon content, such as coal. As a result, the overall carbon intensity for the primary metals industry was 16.12 million metric tons carbon equivalent per quadrillion Btu in 1991 and 16.11 in 1998.

The 1991 MECS estimated consumption that yielded carbon dioxide emissions from the manufacturing
(continued on page 24)

Carbon Dioxide Emissions from Manufacturing by Industry Group, 1998

| Industry Group | SIC Code | Carbon Dioxide Emissions (Million Metric Tons Carbon Equivalent) | Share of Total Manufacturing Emissions (Percent) | Carbon Intensity of Energy Use (Million Metric Tons Carbon Equivalent per Quadrillion Btu Consumed) |
|-------------------------------|----------|--|--|--|
| Petroleum | 29 | 87.4 | 21.6 | 11.35 |
| Chemicals | 28 | 87.1 | 21.5 | 11.15 |
| Metals | 33 | 68.4 | 16.9 | 16.11 |
| Paper | 26 | 32.3 | 8.0 | 9.17 |
| Food | 20 | 24.6 | 6.1 | 13.58 |
| Glass | 32 | 22.6 | 5.6 | 16.32 |
| Other Manufacturing | | 82.8 | 20.4 | 12.15 |
| Total | | 405.2 | 100.0 | 12.17 |

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

^aAppendixes for this report are available on web site www.eia.doe.gov/oiaf/1605/ggrrpt/index.html.

Carbon Dioxide Emissions

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 308.0 million metric tons carbon equivalent, grew by 2.1 percent. Since 1990, carbon dioxide emissions related to the transportation sector have increased at an average annual rate of 1.6 percent. The growth since 1990 has meant that transportation emissions have increased by a total of 80.2 million metric tons, representing 40.3 percent of the growth in energy-related carbon dioxide emissions from all sectors. Transportation is the largest contributing 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 39.2 percent of total U.S. energy-related carbon dioxide emissions. The electric power sector includes traditional regulated utilities, as well as independent power producers whose primary business is the generation and sale of electricity. The industrial sector and, to a much lesser extent, the commercial sector also include establishments that generate electricity; however, their primary business is not electricity generation, and so their electricity-related

Electric Power Sector Carbon Dioxide Emissions by Fuel Input, 1990-2001

| Fuel | Million Metric Tons Carbon Equivalent | | Percent Change | |
|-------------|---------------------------------------|-------|----------------|-----------|
| | 1990 | 2001 | 1990-2001 | 2000-2001 |
| Petroleum | 27.0 | 27.5 | 1.7% | 11.9% |
| Natural Gas | 47.8 | 77.7 | 62.5% | 1.5% |
| Coal | 417.3 | 506.4 | 21.3% | -2.6% |
| Total | 492.3 | 611.7 | 24.3% | -1.5% |

emissions are included in the totals for those sectors, not in the electric power sector.

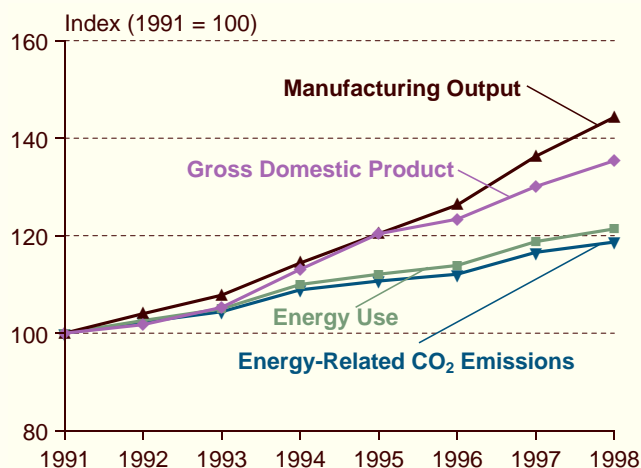
Preliminary estimates indicate that carbon dioxide emissions from the electric power sector decreased by 1.5 percent (9.6 million metric tons carbon equivalent), from 621.2 million metric tons in 2000 to 611.7 million metric tons in 2001 (Table 10). Emissions from natural-gas-fired generation increased by 1.5 percent, emissions from coal-fired generation decreased by 2.6 percent, and emissions from petroleum-fired generation increased by

Energy-Related Carbon Dioxide Emissions in Manufacturing (Continued)

subsector as a whole totaling 341.3 million metric tons carbon equivalent. The corresponding estimate for 1998 is 405.2 million metric tons—an increase of 63.9 million metric tons or 18.7 percent. Over the same interval, manufacturing output increased by 44.3 percent, and gross domestic product (GDP) increased by 35.4 percent (in constant 1996 dollars). Thus, the MECS data suggest more efficiency in manufacturing energy consumption relative to output, with production increasing on average by 5.4 percent per year and energy consumption by only 3.1 percent per year from 1991 to 1998 (see figure). As a result, manufacturing output was more than 40 percent higher in 1998 than in 1991, but energy-related carbon dioxide emissions were only 20 percent higher.

From 1994 to 1998, carbon dioxide emissions associated with electricity use by manufacturing industries increased by 22.1 million metric tons carbon equivalent (17 percent), and emissions associated with natural gas use increased by 8.7 million metric tons carbon equivalent (9 percent). Electricity use continues to account for the largest share of manufacturers' carbon dioxide emissions—35 percent (131.1 million metric tons) and 38 percent (153.2 million metric tons) in 1994 and 1998, respectively (see table on page 25). Smaller changes,

Energy and Emissions Trends in the U.S. Manufacturing Sector, 1991-1998



Source: Energy Information Administration, Federal Reserve Board, and Bureau of Economic Analysis. Values for 1992, 1993, 1995, 1996, and 1997 are interpolated.

which are not statistically significant, are estimated for emissions associated with manufacturing use of coal (a slight decrease) and petroleum and other fuels (a slight increase).

(continued on page 25)

Energy-Related Carbon Dioxide Emissions in Manufacturing (Continued)

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

| Fuel Type | SIC Code | | | | | | Other Mfg. | Total |
|---|-------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|
| | 29 | 28 | 33 | 26 | 20 | 32 | | |
| 1991 | | | | | | | | |
| CO ₂ Emissions (Million Metric Tons Carbon Equivalent) | | | | | | | | |
| Petroleum | 40.9 | 11.5 | 0.9 | 3.7 | 1.0 | 1.7 | 2.8 | 62.6 |
| Natural Gas | 12.1 | 27.9 | 10.2 | 7.9 | 7.4 | 5.5 | 12.6 | 83.6 |
| Coal | 0.4 | 6.9 | 22.7 | 7.7 | 3.9 | 7.6 | 3.5 | 52.7 |
| Electricity | 5.4 | 22.7 | 25.7 | 10.4 | 8.7 | 5.4 | 43.9 | 122.1 |
| Other | 16.6 | 2.6 | 0.8 | 0.1 | 0.0 | 0.0 | 0.1 | 20.3 |
| Total | 75.4 | 71.6 | 60.4 | 29.8 | 21.0 | 20.3 | 63.0 | 341.3 |
| Share of Total Manufacturing Energy Use (Percent) | 23.0 | 22.9 | 13.9 | 11.6 | 5.5 | 4.5 | 18.7 | 100.0 |
| Share of Total Manufacturing CO ₂ Emissions (Percent) | 22.1 | 21.0 | 17.7 | 8.7 | 6.2 | 5.9 | 18.4 | 100.0 |
| Carbon Intensity of Energy Use (Million Metric Tons Carbon Equivalent per Quadrillion Btu Consumed) | 12.14 | 11.61 | 16.12 | 9.55 | 14.26 | 16.87 | 12.51 | 12.67 |
| 1994 | | | | | | | | |
| CO ₂ Emissions (Million Metric Tons Carbon Equivalent) | | | | | | | | |
| Petroleum | 47.7 | 11.5 | 1.3 | 4.3 | 1.2 | 2.0 | 2.7 | 70.7 |
| Natural Gas | 11.7 | 32.1 | 11.7 | 8.3 | 9.1 | 6.2 | 14.5 | 93.5 |
| Coal | 0.0 | 7.8 | 26.2 | 7.8 | 4.3 | 7.2 | 3.5 | 56.8 |
| Electricity | 6.0 | 25.7 | 24.3 | 11.0 | 9.8 | 6.1 | 48.3 | 131.1 |
| Other | 16.5 | 1.2 | 0.9 | 0.3 | 0.1 | 0.1 | 0.4 | 19.6 |
| Total | 81.8 | 78.3 | 64.5 | 31.6 | 24.4 | 21.6 | 69.4 | 371.7 |
| Share of Total Manufacturing Energy Use (Percent) | 22.6 | 23.2 | 13.3 | 11.2 | 6.0 | 4.4 | 19.2 | 100.0 |
| Share of Total Manufacturing CO ₂ Emissions (Percent) | 22.0 | 21.1 | 17.4 | 8.5 | 6.6 | 5.8 | 18.7 | 100.0 |
| Carbon Intensity of Energy Use (Million Metric Tons Carbon Equivalent per Quadrillion Btu Consumed) | 12.21 | 11.35 | 16.32 | 9.48 | 13.61 | 16.39 | 12.21 | 12.52 |
| 1998 | | | | | | | | |
| CO ₂ Emissions (Million Metric Tons Carbon Equivalent) | | | | | | | | |
| Petroleum | 47.7 | 15.4 | 1.0 | 4.1 | 0.8 | 1.8 | 2.8 | 73.7 |
| Natural Gas | 14.5 | 34.8 | 13.1 | 8.5 | 8.7 | 6.4 | 16.3 | 102.2 |
| Coal | 0.0 | 7.3 | 25.7 | 7.0 | 3.7 | 7.6 | 2.7 | 54.1 |
| Electricity | 6.2 | 28.2 | 27.8 | 12.4 | 11.4 | 6.6 | 60.5 | 153.2 |
| Other | 19.0 | 1.3 | 0.9 | 0.2 | 0.0 | 0.2 | 0.4 | 22.1 |
| Total | 87.4 | 87.1 | 68.4 | 32.3 | 24.6 | 22.6 | 82.8 | 405.2 |
| Share of Total Manufacturing Energy Use (Percent) | 23.1 | 23.4 | 12.8 | 10.6 | 5.5 | 4.2 | 20.5 | 100.0 |
| Share of Total Manufacturing CO ₂ Emissions (Percent) | 21.6 | 21.5 | 16.9 | 8.0 | 6.1 | 5.6 | 20.4 | 100.0 |
| Carbon Intensity of Energy Use (Million Metric Tons Carbon Equivalent per Quadrillion Btu Consumed) | 11.35 | 11.15 | 16.11 | 9.17 | 13.58 | 16.32 | 12.15 | 12.17 |

Note: To calculate carbon intensity and percent of Btu, 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).

11.9 percent. Carbon dioxide emissions from the electric power industry have grown by 24.3 percent since 1990, while total carbon dioxide emissions have grown by 14.6 percent. The 2001 decrease can be attributed largely to a 2.2-percent drop in total electricity generation and a 2.6-percent decline in emissions from coal-fired power plants, which are the predominant and most carbon-intensive source of power generation. Contributing to the overall decline in emissions from the electric power sector in 2001 was a 2.0-percent increase in generation from nuclear fuel, which produces no carbon dioxide emissions.

EIA has recently completed a reorganization of its electricity data to reflect the changes in ownership and generation patterns that have taken place in the electric power sector since the early 1990s. This report makes use of those data. Carbon dioxide emissions from nonutility power producers, including independent power producers that produce only electricity, as well as those combined heat and power (CHP) producers (also known as cogenerators) whose primary business is the production of electricity, are included with carbon dioxide emissions from traditional electric utilities in the electric power sector (Table 10). Carbon dioxide emissions from CHP producers that generate electricity primarily for their own use are included in industrial or commercial sector carbon dioxide emissions, depending on the classification of each producer's primary business. Thus, the electricity-related emissions that are shared out to the end-use sectors are based only on purchased electricity from the electric power sector. The box on page 27 describes the changes that have been made in EIA's electricity data systems and their effects on the EIA estimates of carbon dioxide emissions related to energy consumption.

Nonfuel Use of Energy Inputs

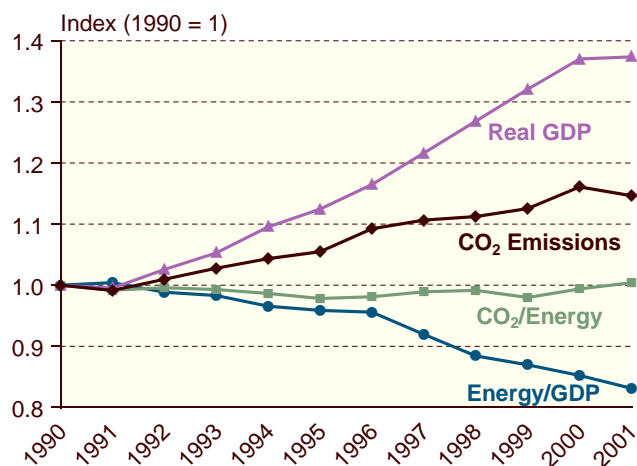
In 2001, 81.0 million metric tons carbon equivalent was sequestered through nonfuel uses of fossil fuels (Table 11). The vast majority of this sequestered carbon was in petroleum-based products (75.9 million metric tons), with smaller amounts in natural-gas-based products (4.6 million metric tons) and coal-based products (less than 0.5 million metric tons carbon equivalent). 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 2001 was 6.6 percent lower than in 2000, when 86.7 million metric tons carbon equivalent was sequestered. Since 1990, the annual sequestration of carbon in this manner has increased by 12.3 million metric tons or 18.0 percent. This translates to an average annual growth rate of 1.5 percent.

Carbon Dioxide Emissions and Economic Growth

Between 1990 and 2001, U.S. economic growth averaged 2.9 percent per year. Energy-related carbon dioxide emissions, however, grew by an average of 1.3 percent annually. As shown in Figure 2, U.S. energy intensity (energy consumed per dollar of GDP) fell by an average of 1.7 percent per year from 1990 to 2001. The carbon dioxide intensity of energy use (carbon-equivalent 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

Figure 2. Growth in U.S. Carbon Dioxide Emissions and GDP, Energy Intensity of GDP, and Carbon Dioxide Intensity of Energy Use, 1990-2001



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

EIA Changes to Electric Power Sector and Fossil Fuel Data

EIA has comprehensively reviewed and revised how it collects, estimates, and reports fuel use for facilities producing electricity. The review addressed both inconsistent reporting of the fuels used for electric power across historical years and changes in the electric power marketplace that have been inconsistently represented in various EIA survey forms and publications.

The goal of EIA's comprehensive review was to improve the quality and consistency of its electric power data throughout all data and analysis products. Because power facilities operate in all sectors of the economy (e.g., in commercial buildings, such as hospitals and college campuses, and industrial facilities, such as paper mills and refineries) and use many fuels, any change to electric power data affects data series in nearly all fuel areas and causes changes in a wide variety of EIA publications.

As a result of the comprehensive review, the following changes have been made:

- EIA has adjusted all presentations of data on electric power to a consistent format and defined the electric power sector to include electricity-only and CHP plants^a whose primary business is to sell electricity, or electricity and heat, to the public.
- EIA is providing detail on fuel used by CHP plants in the electric power, commercial, and industrial sectors.
- EIA has changed the source of data on fuel used by components of the electric power sector: all tabulations and publications will use data obtained from EIA's surveys of electric power generators. This change in data source affects the reporting of EIA's historical data for total fuel consumption of natural gas. The revisions contribute to changes in EIA's electricity series as well as the fuel-use series.

As a result of these changes, EIA has revised its estimates for the years 1990 through 2000 for energy-related carbon dioxide emissions, total greenhouse gas emissions, sector-specific emissions, and emissions by fuel type. EIA's *Annual Energy Review 2001 (AER2001)* was the first of its annual reports in which the revised electricity and fuel data were

published. The emissions reported in this publication are based largely on the data published in *AER2001*.

Summary of Changes in Greenhouse Gas Emissions Estimates

This report assigns all energy-consumption-related carbon dioxide emissions to one of four end-use sectors: residential, commercial, industrial, and transportation. A sector's emissions consist of the fuels directly burned in that sector (e.g., natural gas consumed to heat homes), as well as the sector's share of emissions resulting from electricity generation, based on its market share of purchased electricity. Emissions attributable to the electric power sector (which includes entities other than utilities) are shared out to the end-use sectors. The electric power sector includes electricity-only plants (utilities and independent power producers) and CHP plants that are primarily in the business of selling electricity.

In EIA's earlier emissions inventories (1990-1999), only emissions attributable to conventional electric utilities were shared out to the end-use sectors (see box on page 20); all emissions from nonutility generators were assigned to the industrial sector, even though some of those emissions were associated with electricity sold into the electricity grid and consumed in the residential and commercial sectors. In last year's inventory report (for data year 2000), nonutility emissions were reallocated to the energy end-use sectors.^b For this year's inventory, the allocation of electricity sector emissions to the end-use sectors is based on energy data presented in EIA's multi-fuel publications and is not unique to this report.

Changes to Fossil Fuel Inputs

In addition to changes in data for the electric power sector, the review of EIA data resulted in changes to primary fossil fuel inputs that affect both the sectoral allocation of those fuels and total energy consumption and therefore affect the estimates of total energy-related carbon dioxide emissions. The changes principally affect the natural gas data series, but there are also smaller changes in historical data for the other fossil fuels. As a result, this report includes revised
(continued on page 28)

^aCombined heat and power (CHP) plants produce both electricity and useful thermal output. EIA formerly referred to these plants as cogenerators, but has determined that CHP better describes the facilities because some of the plants included in EIA's data do not produce heat and power in a sequential fashion, and as a result do not meet the legal definition of cogeneration specified in the Public Utilities Regulatory Policy Act (PURPA).

^bThe method used for the reallocation is described in Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001), p. 20.

EIA Changes to Electric Power Sector and Fossil Fuel Data (Continued)

1990-2000 estimates for carbon dioxide emissions by sector (see table below) and by fuel (see table on page 29).

Natural Gas Consumption

In past EIA data publications, natural gas consumption was presented for the residential, commercial, industrial, transportation, and electric utility sectors. Deliveries of natural gas to independent power producers (called “other nonutility power producers” on EIA survey forms) were included in the data reported for the industrial sector, and the measures were collected through natural gas survey forms submitted by gas delivery agents (local distribution companies and pipelines).

As with the other data, beginning with *AER2001*, the definition of industrial sector gas consumption for 1993-2001 no longer includes independent power producers. The new definition of the electric power sector includes independent power producers, utilities, and other electricity generators whose primary business is

selling electricity. The data reported for the electric power sector are derived entirely from data submitted on EIA’s electricity data collection forms, including Forms EIA-759, “Monthly Power Plant Report,” and EIA-860B, “Annual Electric Generator Report—Non-utility,” through 2000 and Form EIA-906, “Power Plant Report,” for 2001.

In comparison with past energy data publications, the impact of the definitional change for the industrial sector is to reduce measured natural gas consumption in the sector. For example, in *AER2000* EIA showed 9.39 trillion cubic feet delivered to industrial facilities in 2000. In *AER2001*, the comparable figure (under the “other industrial” heading) for 2000 is 8.25 trillion cubic feet. However, total estimated carbon dioxide emissions in the industrial sector are higher because last year’s report reallocated all electricity-related emissions from the industrial sector to the electric power sector (see box on page 20). This year’s report is based on data that include energy for companies whose primary business is the production of electricity
(continued on page 29)

Revisions to EIA Estimates of U.S. Carbon Dioxide Emissions from Energy Consumption by End-Use Sector, 1990-2000
(Million Metric Tons Carbon Equivalent)

| End-Use Sector | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| CO₂ Emissions Estimates, This Report | | | | | | | | | | | |
| Residential | 257.5 | 263.0 | 263.0 | 279.6 | 277.2 | 280.1 | 297.0 | 295.0 | 297.6 | 302.5 | 318.1 |
| Commercial | 212.6 | 213.2 | 213.4 | 220.0 | 223.4 | 228.5 | 237.4 | 249.3 | 253.9 | 258.0 | 274.4 |
| Industrial | 458.0 | 447.6 | 465.6 | 461.7 | 469.2 | 468.0 | 482.2 | 486.9 | 479.5 | 474.2 | 478.4 |
| Transportation | 431.4 | 424.1 | 430.8 | 436.1 | 448.9 | 457.4 | 468.5 | 473.2 | 481.3 | 495.3 | 507.3 |
| Total | 1,359.5 | 1,347.8 | 1,372.8 | 1,397.3 | 1,418.7 | 1,434.1 | 1,485.2 | 1,504.3 | 1,512.3 | 1,530.1 | 1,578.3 |
| Electric Power | 492.3 | 492.2 | 495.7 | 515.9 | 522.5 | 526.8 | 546.5 | 564.8 | 589.2 | 592.8 | 621.2 |
| <i>Electric Power Percent of Total</i> | <i>36.2%</i> | <i>36.5%</i> | <i>36.1%</i> | <i>36.9%</i> | <i>36.8%</i> | <i>36.7%</i> | <i>36.8%</i> | <i>37.5%</i> | <i>39.0%</i> | <i>38.7%</i> | <i>39.4%</i> |
| CO₂ Emissions Estimates, Last Year’s Report | | | | | | | | | | | |
| Residential | 257.0 | 261.6 | 261.8 | 278.4 | 275.8 | 277.9 | 293.9 | 292.8 | 293.7 | 298.8 | 313.4 |
| Commercial | 210.3 | 210.4 | 210.8 | 217.2 | 220.4 | 224.6 | 233.1 | 245.4 | 250.4 | 253.1 | 267.8 |
| Industrial | 452.7 | 439.8 | 455.1 | 452.9 | 463.3 | 461.1 | 476.1 | 481.5 | 469.5 | 465.8 | 465.7 |
| Transportation | 431.8 | 424.2 | 431.1 | 436.4 | 449.3 | 457.8 | 468.9 | 473.6 | 481.5 | 499.4 | 514.8 |
| Total | 1,351.7 | 1,336.0 | 1,358.7 | 1,384.8 | 1,408.8 | 1,421.3 | 1,471.9 | 1,493.3 | 1,495.2 | 1,517.1 | 1,561.7 |
| Electric Power | 507.0 | 506.0 | 512.0 | 532.4 | 540.7 | 542.5 | 562.1 | 583.1 | 607.2 | 612.6 | 641.6 |
| <i>Electric Power Percent of Total</i> | <i>37.5%</i> | <i>37.9%</i> | <i>37.7%</i> | <i>38.4%</i> | <i>38.4%</i> | <i>38.2%</i> | <i>38.2%</i> | <i>39.0%</i> | <i>40.6%</i> | <i>40.4%</i> | <i>41.1%</i> |
| Changes from Last Year’s Report to This Report | | | | | | | | | | | |
| Residential | 0.4 | 1.3 | 1.2 | 1.3 | 1.4 | 2.3 | 3.1 | 2.2 | 3.9 | 3.7 | 4.7 |
| Commercial | 2.4 | 2.8 | 2.6 | 2.7 | 3.0 | 3.9 | 4.3 | 3.9 | 3.5 | 5.0 | 6.6 |
| Industrial | 5.4 | 7.8 | 10.5 | 8.8 | 6.0 | 7.0 | 6.1 | 5.4 | 10.0 | 8.5 | 12.7 |
| Transportation | -0.4 | -0.2 | -0.3 | -0.3 | -0.4 | -0.4 | -0.3 | -0.5 | -0.3 | -4.1 | -7.5 |
| Total | 7.8 | 11.8 | 14.1 | 12.5 | 9.9 | 12.8 | 13.3 | 11.0 | 17.1 | 13.0 | 16.6 |
| Electric Power | -14.7 | -13.8 | -16.3 | -16.6 | -18.2 | -15.7 | -15.6 | -18.3 | -18.0 | -19.8 | -20.4 |
| <i>Electric Power Percent of Total</i> | <i>-1.3</i> | <i>-1.4</i> | <i>-1.6</i> | <i>-1.5</i> | <i>-1.5</i> | <i>-1.4</i> | <i>-1.4</i> | <i>-1.5</i> | <i>-1.7</i> | <i>-1.6</i> | <i>-1.7</i> |

Sources: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001), and estimates presented in this chapter.

EIA Changes to Electric Power Sector and Fossil Fuel Data (Continued)

in the electric power sector. Energy consumption and related emissions from other industrial electricity producers are included in the industrial sector, even if some of that electricity is sold to other sectors. This change is a result of the change in the operational definition of deliveries to the industrial sector.

In comparison with past publications, the impact of the definitional change and the new data sources for the electric power sector is to increase measured natural gas consumption. As a result of the changes in data sources (predominantly new electric power data sources), total natural gas consumption is higher than previously published. Total natural gas consumption in the electric power sector for 1998, 1999, and 2000 has been revised upward by 5 percent, 3 percent, and 3 percent, respectively.

Also beginning with the publication of *AER2001* and following with the *Natural Gas Annual*, new detail is available about natural gas consumption in the commercial, industrial, and electric power sectors that distinguishes deliveries of natural gas to CHP plants from deliveries to other facilities. "Deliveries to industrial consumers" includes deliveries to industrial consumers that are CHP plants (such as those at paper mills) and to other industrial users. Included with the CHP

plant data are a small number of industrial firms that report using natural gas only to generate electricity (most likely for their own use). "Deliveries to commercial consumers" also include deliveries to CHP plants, such as those at hospitals. Similarly, a small number of plants that report natural gas use only for electricity generation are included with the data on commercial CHP plants. The sources for total commercial and industrial sector data are natural gas survey forms, and the sources for the subcomponent CHP data series are electric power survey forms. The sources of all electric power data series, including the CHP subcomponent, are electric power survey forms.

As shown in the table below, when adjusted for nonfuel uses, estimated carbon dioxide emissions from natural gas for 1990-2000 are higher than the estimates in last year's report. In percentage terms, the increase ranges from 2.4 percent (6.4 million metric tons carbon equivalent) in 1990 to 4.4 percent (13.6 million metric tons) in 1998.

Petroleum and Coal Emissions

There were also some changes to coal emissions and to a lesser extent petroleum. The changes to petroleum
(continued on page 30)

Revisions to EIA Estimates of U.S. Carbon Dioxide Emissions from Energy Consumption by Fuel, 1990-2000

(Million Metric Tons Carbon Equivalent)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|--|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| CO₂ Emissions Estimates, This Report | | | | | | | | | | | |
| Petroleum | 590.5 | 576.2 | 586.9 | 588.3 | 600.9 | 597.0 | 619.4 | 625.3 | 635.6 | 650.3 | 658.8 |
| Coal | 489.3 | 485.6 | 489.5 | 505.6 | 508.5 | 514.0 | 536.7 | 548.4 | 552.6 | 553.7 | 578.7 |
| Natural Gas | 279.7 | 285.9 | 296.3 | 303.3 | 309.2 | 323.0 | 329.0 | 330.5 | 324.0 | 325.9 | 340.7 |
| Total Fossil Fuels | 1,359.4 | 1,347.7 | 1,372.7 | 1,397.2 | 1,418.6 | 1,434.0 | 1,485.1 | 1,504.2 | 1,512.2 | 1,530.0 | 1,578.2 |
| CO₂ Emissions Estimates, Last Year's Report | | | | | | | | | | | |
| Petroleum | 590.4 | 576.1 | 586.6 | 587.7 | 600.3 | 596.3 | 618.7 | 624.6 | 634.4 | 649.3 | 657.7 |
| Coal | 487.9 | 482.0 | 486.0 | 501.9 | 507.1 | 510.3 | 532.6 | 547.4 | 550.4 | 552.6 | 572.8 |
| Natural Gas | 273.2 | 278.1 | 286.3 | 295.5 | 301.5 | 314.5 | 320.4 | 321.5 | 310.5 | 315.3 | 331.2 |
| Total Fossil Fuels | 1,351.6 | 1,336.1 | 1,358.9 | 1,385.0 | 1,408.9 | 1,421.1 | 1,471.7 | 1,493.4 | 1,495.4 | 1,517.2 | 1,561.7 |
| Changes from Last Year's Report to This Report | | | | | | | | | | | |
| Petroleum | 0.1 | 0.1 | 0.2 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 1.2 | 1.0 | 1.0 |
| Coal | 1.3 | 3.6 | 3.5 | 3.8 | 1.4 | 3.6 | 4.1 | 1.1 | 2.1 | 1.2 | 5.9 |
| Natural Gas | 6.4 | 7.8 | 10.0 | 7.8 | 7.7 | 8.5 | 8.6 | 9.0 | 13.6 | 10.6 | 9.5 |
| Total Fossil Fuels | 7.8 | 11.6 | 13.7 | 12.2 | 9.7 | 12.9 | 13.4 | 10.8 | 16.9 | 12.8 | 16.5 |
| Percentage Changes from Last Year's Report to This Report | | | | | | | | | | | |
| Petroleum | 0.0% | 0.0% | 0.0% | 0.1% | 0.1% | 0.1% | 0.1% | 0.1% | 0.2% | 0.2% | 0.2% |
| Coal | 0.3% | 0.8% | 0.7% | 0.8% | 0.3% | 0.7% | 0.8% | 0.2% | 0.4% | 0.2% | 1.0% |
| Natural Gas | 2.4% | 2.8% | 3.5% | 2.7% | 2.5% | 2.7% | 2.7% | 2.8% | 4.4% | 3.3% | 2.9% |
| Total Fossil Fuels | 0.6% | 0.9% | 1.0% | 0.9% | 0.7% | 0.9% | 0.9% | 0.7% | 1.1% | 0.8% | 1.1% |

Sources: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001), and estimates presented in this chapter.

EIA Changes to Electric Power Sector and Fossil Fuel Data (Continued)

are all 0.2 percent or less and can be attributed to slight differences in the details of the data series used last year (the *Monthly Energy Review*) and this year (the *Annual Energy Review*). The coal data contain some data revisions (for example, for 2000). Also, the change in categories—for example, moving coal consumption

from the industrial to the electric power sector—entails applying different carbon coefficients that can make the change in emissions differ from the change in underlying consumption values. The changes to coal emissions were all 1 percent or less.

(carbon-equivalent emissions of greenhouse gases per unit of GDP) at an average rate of 1.5 percent per year through 2020.⁵⁰

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 2001, total energy-related carbon dioxide emissions from the U.S. Territories are estimated at 14.8 million metric tons carbon equivalent (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 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 is 2.2 million metric tons carbon equivalent (3.5 percent higher than 2000).⁵¹ In 2001, approximately 26.5 million metric tons was emitted in total from international bunker fuels, including 24.2 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

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:

⁵⁰Energy Information Administration, *Annual Energy Outlook 2003*, DOE/EIA-0383(2003) (Washington, DC, January 2003).

⁵¹Based on early estimates from the U.S. Department of Defense (DoD). The new DoD estimates include adjustments to past values. For example, the 1990 estimate has been revised from 4.9 to 3.7 million metric tons carbon equivalent, and the 1999 estimate has been revised from 2.7 to 2.1 million metric tons (last year's report used 1999 as a proxy for 2000). Final numbers will be published by the U.S. Environmental Protection Agency in April 2003.

U.S. Carbon Dioxide Emissions from Other Sources, 1990-2001

| | |
|---|-------|
| Estimated 2001 Emissions (Million Metric Tons Carbon Equivalent) | 31.7 |
| Change Compared to 2000 (Million Metric Tons Carbon Equivalent) | -0.3 |
| Change from 2000 (Percent) | -0.9% |
| Change Compared to 1990 (Million Metric Tons Carbon Equivalent) | 4.2 |
| Change from 1990 (Percent) | 15.5% |

- 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 2001, about 1.7 million metric tons carbon equivalent 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 5.0 million metric tons carbon equivalent in 2001 (Table 4). Appendix D contains data on additional energy production sources that are excluded from this report.

Industrial Process Emissions

Industrial emissions of carbon dioxide not caused by the combustion of fossil fuels accounted for only 1.2 percent (18.8 million metric tons carbon equivalent) of total U.S. carbon dioxide emissions in 2001 (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 2001 were 2.4 million metric tons carbon equivalent (14.9 percent) higher than in 1990 and 0.5 million metric tons (2.6 percent) lower than in 2000 (Table 12). Sixty 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 2001, the United States manufactured an estimated 89.6 million metric tons of cement, resulting in the direct release of carbon dioxide containing 11.4 million metric tons carbon equivalent into the atmosphere. This calculation is independent of the carbon dioxide released by the production of energy consumed in making cement. This represents an increase in carbon dioxide emissions of 2.3 million metric tons carbon equivalent (25.0 percent) compared with 1990 and an increase of about 0.1 million metric tons (0.9 percent) compared with 2000.

There are numerous other industrial processes in which carbonate minerals are used in ways that release carbon dioxide into the atmosphere, including the use of limestone in the production of lime and in flue gas desulfurization and the manufacture and some uses of soda ash. Carbon dioxide is also released during aluminum smelting, when carbon anodes (with the carbon derived from nonfuel use of fossil fuels) are vaporized in the presence of aluminum oxide. Approximately 7.4 million metric tons carbon equivalent was released in emissions from these other industrial process sources in 2001.

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 6.1 million metric tons carbon equivalent, as calculated by the U.S. EPA, with the most recent estimate being for 2000. The 2000 value has been used as an estimate for 2001.

Carbon Dioxide Emissions

Table 4. U.S. Carbon Dioxide Emissions from Energy and Industry, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Fuel Type or Process | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--------------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Energy Consumption | | | | | | | | | | | | |
| Petroleum | 590.5 | 576.2 | 586.9 | 588.3 | 600.9 | 597.0 | 619.4 | 625.3 | 635.6 | 650.3 | 658.8 | 668.0 |
| Coal | 489.3 | 485.6 | 489.5 | 505.6 | 508.5 | 514.0 | 536.7 | 548.4 | 552.6 | 553.7 | 578.7 | 561.1 |
| Natural Gas..... | 279.7 | 285.9 | 296.3 | 303.3 | 309.2 | 323.0 | 329.0 | 330.5 | 324.0 | 325.9 | 340.7 | 329.4 |
| 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 |
| Energy Subtotal | 1,359.5 | 1,347.8 | 1,372.8 | 1,397.3 | 1,418.7 | 1,434.1 | 1,485.2 | 1,504.3 | 1,512.3 | 1,530.1 | 1,578.3 | 1,558.7 |
| Adjustments to Energy | | | | | | | | | | | | |
| U.S. Territories (+) | 8.4 | 9.7 | 9.7 | 10.8 | 10.9 | 11.4 | 10.2 | 10.9 | 13.0 | 13.6 | 14.3 | 14.8 |
| Military Bunker Fuels (-) | 3.7 | 3.6 | 3.2 | 3.0 | 2.6 | 2.4 | 2.4 | 2.6 | 2.7 | 2.7 | 2.1 | 2.2 |
| International Bunker Fuels (-) .. | 27.3 | 29.1 | 26.7 | 24.2 | 24.1 | 25.1 | 25.4 | 27.3 | 28.6 | 26.6 | 25.5 | 24.2 |
| Total Energy Adjustments .. | -22.6 | -23.0 | -20.2 | -16.3 | -15.8 | -16.1 | -17.6 | -19.0 | -18.3 | -15.6 | -13.4 | -11.7 |
| Adjusted Energy Total | 1,337.0 | 1,324.8 | 1,352.5 | 1,381.0 | 1,402.9 | 1,417.9 | 1,467.5 | 1,485.3 | 1,494.0 | 1,514.5 | 1,564.9 | 1,547.0 |
| Other Sources | | | | | | | | | | | | |
| Gas Flaring | 2.5 | 2.8 | 2.8 | 3.7 | 3.8 | 4.7 | 4.5 | 4.2 | 1.7 | 1.8 | 1.7 | 1.7 |
| CO ₂ in Natural Gas | 3.8 | 4.0 | 4.2 | 4.4 | 4.6 | 4.6 | 4.8 | 4.9 | 4.9 | 4.8 | 4.9 | 5.0 |
| Cement Production | 9.1 | 8.9 | 8.9 | 9.5 | 10.0 | 10.1 | 10.1 | 10.5 | 10.7 | 10.9 | 11.3 | 11.4 |
| Other Industrial | 7.3 | 7.2 | 7.2 | 7.1 | 7.2 | 7.6 | 7.9 | 8.0 | 8.1 | 8.0 | 8.0 | 7.4 |
| Waste Combustion | 4.8 | 5.3 | 5.4 | 5.7 | 6.0 | 6.3 | 6.5 | 7.0 | 6.9 | 7.1 | 6.1 | 6.1 |
| Total Other Sources | 27.4 | 28.0 | 28.5 | 30.5 | 31.7 | 33.2 | 33.8 | 34.6 | 32.3 | 32.6 | 32.0 | 31.7 |
| Total | 1,364.4 | 1,352.9 | 1,381.1 | 1,411.5 | 1,434.6 | 1,451.2 | 1,501.4 | 1,519.9 | 1,526.3 | 1,547.1 | 1,596.8 | 1,578.7 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data and sectoral allocations. 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, 1990-2001
(Million Metric Tons Carbon Equivalent)

| End-Use Sector | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Residential | 257.5 | 263.0 | 263.0 | 279.6 | 277.2 | 280.1 | 297.0 | 295.0 | 297.6 | 302.5 | 318.1 | 314.9 |
| Commercial..... | 212.6 | 213.2 | 213.4 | 220.0 | 223.4 | 228.5 | 237.4 | 249.3 | 253.9 | 258.0 | 274.4 | 279.7 |
| Industrial..... | 458.0 | 447.6 | 465.6 | 461.7 | 469.2 | 468.0 | 482.2 | 486.9 | 479.5 | 474.2 | 478.4 | 452.4 |
| Transportation..... | 431.4 | 424.1 | 430.8 | 436.1 | 448.9 | 457.4 | 468.5 | 473.2 | 481.3 | 495.3 | 507.3 | 511.6 |
| Total | 1,359.5 | 1,347.8 | 1,372.8 | 1,397.3 | 1,418.7 | 1,434.1 | 1,485.2 | 1,504.3 | 1,512.3 | 1,530.1 | 1,578.3 | 1,558.7 |
| Electric Power..... | 492.3 | 492.2 | 495.7 | 515.9 | 522.5 | 526.8 | 546.5 | 564.8 | 589.2 | 592.8 | 621.2 | 611.7 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data and sectoral allocations. 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, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|-------------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Petroleum | | | | | | | | | | | | |
| Liquefied Petroleum Gas | 6.3 | 6.7 | 6.6 | 6.8 | 6.8 | 6.9 | 8.1 | 7.9 | 7.4 | 9.1 | 9.3 | 8.5 |
| Distillate Fuel | 16.5 | 16.4 | 17.1 | 18.0 | 17.2 | 17.3 | 18.3 | 17.7 | 15.4 | 15.9 | 16.2 | 16.6 |
| Kerosene | 1.2 | 1.4 | 1.3 | 1.5 | 1.3 | 1.5 | 1.7 | 1.8 | 2.1 | 2.2 | 2.0 | 2.2 |
| Petroleum Subtotal | 24.0 | 24.5 | 24.9 | 26.3 | 25.3 | 25.7 | 28.1 | 27.4 | 24.9 | 27.2 | 27.5 | 27.2 |
| Coal | 0.7 | 0.6 | 0.6 | 0.6 | 0.5 | 0.4 | 0.4 | 0.4 | 0.3 | 0.4 | 0.3 | 0.3 |
| Natural Gas | 65.1 | 67.6 | 69.6 | 73.4 | 71.8 | 71.7 | 77.5 | 73.7 | 67.2 | 69.9 | 73.7 | 71.1 |
| Electricity ^a | 167.7 | 170.3 | 167.9 | 179.3 | 179.6 | 182.3 | 191.0 | 193.5 | 205.1 | 204.9 | 216.5 | 216.3 |
| Total | 257.5 | 263.0 | 263.0 | 279.6 | 277.2 | 280.1 | 297.0 | 295.0 | 297.6 | 302.5 | 318.1 | 314.9 |

^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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data and sectoral allocations. 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, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|-------------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Petroleum | | | | | | | | | | | | |
| Motor Gasoline | 2.1 | 1.6 | 1.5 | 0.6 | 0.5 | 0.3 | 0.5 | 0.8 | 0.8 | 0.9 | 0.9 | 0.9 |
| Liquefied Petroleum Gas | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.4 | 1.4 | 1.3 | 1.6 | 1.6 | 1.5 |
| Distillate Fuel | 9.6 | 9.5 | 9.1 | 9.1 | 9.1 | 9.0 | 9.4 | 8.8 | 8.3 | 8.2 | 9.1 | 9.3 |
| Residual Fuel | 5.1 | 4.5 | 4.0 | 3.7 | 3.7 | 3.0 | 2.9 | 2.4 | 1.8 | 1.6 | 1.9 | 1.8 |
| Kerosene | 0.2 | 0.2 | 0.2 | 0.3 | 0.4 | 0.4 | 0.4 | 0.5 | 0.6 | 0.5 | 0.5 | 0.5 |
| Petroleum Subtotal | 18.2 | 17.1 | 16.1 | 14.9 | 14.8 | 14.0 | 14.6 | 13.8 | 12.9 | 12.8 | 14.0 | 14.0 |
| Coal | 3.3 | 3.1 | 3.1 | 3.1 | 3.1 | 3.0 | 3.1 | 3.3 | 2.4 | 2.7 | 2.3 | 2.3 |
| Natural Gas | 38.9 | 40.5 | 41.6 | 42.4 | 42.9 | 44.8 | 46.7 | 47.5 | 44.6 | 45.1 | 47.5 | 48.0 |
| Electricity ^a | 152.2 | 152.5 | 152.6 | 159.7 | 162.6 | 166.6 | 172.9 | 184.6 | 194.1 | 197.6 | 210.5 | 215.4 |
| Total | 212.6 | 213.2 | 213.4 | 220.0 | 223.4 | 228.5 | 237.4 | 249.3 | 253.9 | 258.0 | 274.4 | 279.7 |

^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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data and sectoral allocations. Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Carbon Dioxide Emissions

Table 8. U.S. Carbon Dioxide Emissions from Industrial Sector Energy Consumption, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Petroleum | | | | | | | | | | | | |
| Motor Gasoline | 3.6 | 3.7 | 3.7 | 3.5 | 3.7 | 3.8 | 3.8 | 4.1 | 3.8 | 2.9 | 2.9 | 3.0 |
| Liquefied Petroleum Gas | 12.0 | 12.1 | 12.7 | 12.1 | 12.9 | 12.7 | 13.0 | 13.5 | 13.0 | 13.7 | 13.7 | 12.5 |
| Distillate Fuel | 23.2 | 22.4 | 22.5 | 21.6 | 21.7 | 21.0 | 22.1 | 22.2 | 21.9 | 21.1 | 22.3 | 22.8 |
| Residual Fuel | 8.2 | 6.4 | 7.6 | 8.9 | 8.4 | 6.6 | 6.6 | 5.6 | 4.3 | 3.8 | 4.5 | 4.2 |
| Asphalt and Road Oil | * | * | * | * | * | * | * | * | * | * | * | * |
| Lubricants | 1.9 | 1.7 | 1.7 | 1.7 | 1.8 | 1.8 | 1.7 | 1.8 | 1.9 | 1.9 | 1.9 | 1.7 |
| Kerosene | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 | 0.2 | 0.2 |
| Other Petroleum | 51.4 | 48.3 | 55.1 | 48.9 | 51.5 | 48.6 | 54.4 | 55.5 | 53.5 | 55.8 | 50.4 | 53.4 |
| Petroleum Subtotal | 100.5 | 94.9 | 103.5 | 97.0 | 100.4 | 94.9 | 102.0 | 103.0 | 98.9 | 99.5 | 96.0 | 97.9 |
| Coal | 67.8 | 63.9 | 61.2 | 60.8 | 61.2 | 60.8 | 59.3 | 58.3 | 54.5 | 53.3 | 54.0 | 51.0 |
| Coal Coke Net Imports | 0.1 | 0.3 | 0.9 | 0.7 | 1.5 | 1.5 | 0.9 | 1.4 | 2.0 | 1.8 | 2.0 | 1.1 |
| Natural Gas | 118.1 | 119.9 | 125.4 | 127.1 | 126.7 | 133.8 | 138.3 | 138.4 | 135.0 | 130.3 | 133.2 | 123.4 |
| Electricity^a | 171.6 | 168.7 | 174.5 | 176.2 | 179.5 | 177.1 | 181.8 | 185.8 | 189.1 | 189.4 | 193.2 | 179.0 |
| Total | 458.0 | 447.6 | 465.6 | 461.7 | 469.2 | 468.0 | 482.2 | 486.9 | 479.5 | 474.2 | 478.4 | 452.4 |

*Less than 50,000 metric tons carbon equivalent.

^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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data and sectoral allocations. 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, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Petroleum | | | | | | | | | | | | |
| Motor Gasoline | 260.5 | 259.2 | 263.0 | 268.9 | 273.3 | 279.0 | 284.0 | 286.5 | 292.5 | 299.7 | 301.5 | 308.0 |
| Liquefied Petroleum Gas | 0.4 | 0.3 | 0.3 | 0.3 | 0.6 | 0.3 | 0.3 | 0.2 | 0.3 | 0.2 | 0.2 | 0.2 |
| Jet Fuel | 60.1 | 58.1 | 57.6 | 58.1 | 60.4 | 60.0 | 62.7 | 63.3 | 64.2 | 66.3 | 68.5 | 65.6 |
| Distillate Fuel | 75.6 | 72.6 | 75.2 | 77.2 | 82.3 | 85.1 | 89.7 | 93.4 | 97.0 | 101.9 | 105.0 | 107.5 |
| Residual Fuel | 21.6 | 21.8 | 22.8 | 19.2 | 18.8 | 19.4 | 18.1 | 15.1 | 14.3 | 14.2 | 18.9 | 17.8 |
| Lubricants | 1.8 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 | 1.6 | 1.7 | 1.8 | 1.8 | 1.8 | 1.6 |
| Aviation Gasoline | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Petroleum Subtotal | 420.9 | 414.4 | 421.3 | 426.1 | 437.8 | 446.1 | 457.1 | 461.1 | 470.8 | 484.7 | 496.7 | 501.4 |
| Coal | * | * | * | * | * | * | * | * | * | * | * | * |
| Natural Gas | 9.8 | 8.9 | 8.8 | 9.3 | 10.2 | 10.4 | 10.6 | 11.2 | 9.6 | 9.7 | 9.7 | 9.2 |
| Electricity^a | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 |
| Total | 431.4 | 424.1 | 430.8 | 436.1 | 448.9 | 457.4 | 468.5 | 473.2 | 481.3 | 495.3 | 507.3 | 511.6 |

*Less than 50,000 metric tons carbon equivalent.

^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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data and sectoral allocations. 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, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Generator Type and Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Total Emissions from Fuel Use | | | | | | | | | | | | |
| Petroleum | | | | | | | | | | | | |
| Heavy Fuel Oil | 24.3 | 22.9 | 18.4 | 20.2 | 18.3 | 11.9 | 13.2 | 15.1 | 22.1 | 20.2 | 18.4 | 20.9 |
| Light Fuel Oil | 1.9 | 1.7 | 1.5 | 1.7 | 2.4 | 2.1 | 2.2 | 2.2 | 2.7 | 2.8 | 3.5 | 3.5 |
| Petroleum Coke | 0.8 | 0.8 | 1.2 | 2.2 | 1.9 | 2.2 | 2.2 | 2.8 | 3.4 | 3.1 | 2.7 | 3.0 |
| Petroleum Subtotal | 27.0 | 25.3 | 21.1 | 24.1 | 22.6 | 16.3 | 17.6 | 20.0 | 28.2 | 26.1 | 24.5 | 27.5 |
| Coal | 417.3 | 417.8 | 423.7 | 440.4 | 442.2 | 448.2 | 472.9 | 484.9 | 493.3 | 495.7 | 520.1 | 506.4 |
| Natural Gas | 47.8 | 48.9 | 50.9 | 51.3 | 57.6 | 62.3 | 55.9 | 59.7 | 67.6 | 70.9 | 76.5 | 77.7 |
| 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 |
| Total | 492.3 | 492.2 | 495.7 | 515.9 | 522.5 | 526.8 | 546.5 | 564.8 | 589.2 | 592.8 | 621.2 | 611.7 |
| Emissions from Fuel Use for Electricity Generation | | | | | | | | | | | | |
| Petroleum | | | | | | | | | | | | |
| Heavy Fuel Oil | 24.1 | 22.7 | 18.2 | 20.1 | 18.2 | 11.8 | 13.1 | 14.9 | 22.0 | 20.1 | 18.3 | 20.8 |
| Light Fuel Oil | 1.9 | 1.6 | 1.4 | 1.7 | 2.3 | 2.1 | 2.1 | 2.1 | 2.7 | 2.7 | 3.4 | 3.5 |
| Petroleum Coke | 0.8 | 0.8 | 1.2 | 2.1 | 1.9 | 2.0 | 2.0 | 2.7 | 3.3 | 3.0 | 2.6 | 2.9 |
| Petroleum Subtotal | 26.8 | 25.2 | 20.9 | 23.9 | 22.4 | 15.9 | 17.3 | 19.7 | 28.0 | 25.9 | 24.3 | 27.2 |
| Coal | 416.8 | 417.1 | 422.8 | 439.5 | 441.1 | 446.9 | 471.6 | 483.7 | 492.0 | 494.1 | 518.4 | 504.7 |
| Natural Gas | 46.4 | 47.5 | 49.1 | 49.4 | 55.5 | 60.2 | 53.7 | 57.3 | 65.1 | 68.3 | 73.7 | 74.4 |
| 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 |
| Total | 490.1 | 489.9 | 492.9 | 512.8 | 519.0 | 523.1 | 542.7 | 560.8 | 585.1 | 588.4 | 616.6 | 606.5 |
| Emissions from Fuel Use for Thermal Energy Production | | | | | | | | | | | | |
| Petroleum | | | | | | | | | | | | |
| Heavy Fuel Oil | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | * |
| Light Fuel Oil | * | * | * | * | * | 0.1 | * | * | * | * | * | 0.1 |
| Petroleum Coke | 0.0 | 0.0 | * | * | * | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Petroleum Subtotal | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.4 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Coal | 0.5 | 0.7 | 0.9 | 1.0 | 1.2 | 1.3 | 1.3 | 1.2 | 1.3 | 1.6 | 1.6 | 1.7 |
| Natural Gas | 1.4 | 1.5 | 1.8 | 1.9 | 2.1 | 2.1 | 2.2 | 2.4 | 2.5 | 2.6 | 2.8 | 3.3 |
| Total | 2.1 | 2.3 | 2.9 | 3.1 | 3.5 | 3.7 | 3.8 | 4.0 | 4.0 | 4.4 | 4.7 | 5.2 |

*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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Energy-related carbon dioxide emissions have been revised as part of an agency-wide adjustment to energy consumption data and sectoral allocations. 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, 1990-2001
(Million Metric Tons Carbon Equivalent)

| End Use and Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Industrial | | | | | | | | | | | | |
| Petroleum | | | | | | | | | | | | |
| Liquefied Petroleum Gases. . . | 16.2 | 18.6 | 18.7 | 18.2 | 20.9 | 21.4 | 22.3 | 22.6 | 21.6 | 24.4 | 25.1 | 22.8 |
| Distillate Fuel | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Residual Fuel | 0.5 | 0.7 | 0.6 | 0.6 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Asphalt and Road Oil | 24.1 | 22.2 | 22.7 | 23.7 | 24.2 | 24.3 | 24.2 | 25.2 | 26.0 | 27.3 | 26.3 | 25.9 |
| Lubricants | 1.9 | 1.7 | 1.7 | 1.8 | 1.8 | 1.8 | 1.7 | 1.8 | 1.9 | 2.0 | 1.9 | 1.8 |
| Other (Subtotal) | 19.7 | 19.2 | 20.3 | 22.0 | 22.7 | 22.7 | 23.2 | 24.7 | 26.2 | 26.9 | 25.3 | 23.0 |
| Pentanes Plus | 1.2 | 0.7 | 0.9 | 4.0 | 3.8 | 4.4 | 4.6 | 4.4 | 3.9 | 4.8 | 4.6 | 3.5 |
| Petrochemical Feed | 12.6 | 12.6 | 13.4 | 13.6 | 14.1 | 13.6 | 13.8 | 15.9 | 16.1 | 15.1 | 15.7 | 13.8 |
| Petroleum Coke | 2.5 | 2.1 | 3.2 | 1.7 | 1.9 | 1.8 | 2.1 | 1.6 | 3.0 | 4.0 | 2.0 | 2.5 |
| Waxes and Miscellaneous .. | 3.4 | 3.7 | 2.7 | 2.7 | 2.9 | 2.7 | 2.7 | 2.8 | 3.2 | 3.0 | 3.0 | 3.2 |
| Coal | 0.4 | 0.4 | 0.8 | 0.6 | 0.5 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Natural Gas | 4.1 | 3.9 | 3.5 | 3.9 | 5.0 | 4.7 | 4.7 | 5.1 | 6.0 | 5.0 | 5.1 | 4.6 |
| Transportation | | | | | | | | | | | | |
| Lubricants | 1.8 | 1.6 | 1.6 | 1.7 | 1.7 | 1.7 | 1.6 | 1.7 | 1.8 | 1.8 | 1.8 | 1.7 |
| Total | 68.7 | 68.2 | 70.0 | 72.4 | 77.5 | 77.8 | 79.1 | 82.4 | 84.8 | 88.7 | 86.7 | 81.0 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Carbon Dioxide Emissions

Table 12. U.S. Carbon Dioxide Emissions from Industrial Processes, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Cement Manufacture | | | | | | | | | | | | |
| Clinker Production | 8.90 | 8.66 | 8.75 | 9.25 | 9.82 | 9.85 | 9.91 | 10.24 | 10.48 | 10.69 | 11.01 | 11.12 |
| Masonry Cement | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 |
| Cement Kiln Dust | 0.18 | 0.17 | 0.18 | 0.19 | 0.20 | 0.20 | 0.20 | 0.20 | 0.21 | 0.21 | 0.22 | 0.22 |
| Cement Subtotal | 9.09 | 8.85 | 8.94 | 9.46 | 10.04 | 10.07 | 10.13 | 10.47 | 10.72 | 10.93 | 11.26 | 11.37 |
| Other Industrial | | | | | | | | | | | | |
| Limestone Consumption | | | | | | | | | | | | |
| Lime Manufacture | 3.39 | 3.36 | 3.47 | 3.58 | 3.73 | 3.96 | 4.11 | 4.22 | 4.30 | 4.22 | 4.20 | 4.00 |
| Iron Smelting | 0.47 | 0.44 | 0.37 | 0.31 | 0.30 | 0.31 | 0.30 | 0.31 | 0.30 | 0.29 | 0.30 | 0.27 |
| Steelmaking | 0.08 | 0.09 | 0.07 | 0.13 | 0.15 | 0.14 | 0.11 | 0.09 | 0.10 | 0.07 | 0.12 | 0.17 |
| Copper Refining | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 |
| Glass Manufacture | 0.03 | 0.03 | 0.04 | 0.05 | 0.08 | 0.09 | 0.05 | 0.02 | 0.05 | 0.05 | 0.05 | 0.05 |
| Flue Gas Desulfurization | 0.18 | 0.19 | 0.19 | 0.18 | 0.19 | 0.24 | 0.26 | 0.28 | 0.27 | 0.29 | 0.32 | 0.32 |
| Dolomite Manufacture | 0.13 | 0.10 | 0.08 | 0.07 | 0.07 | 0.06 | 0.09 | 0.09 | 0.09 | 0.04 | 0.09 | 0.09 |
| Limestone Subtotal | 4.33 | 4.24 | 4.27 | 4.36 | 4.57 | 4.85 | 4.98 | 5.05 | 5.15 | 5.00 | 5.11 | 4.94 |
| Soda Ash Manufacture | 0.92 | 0.92 | 0.94 | 0.91 | 0.92 | 1.04 | 1.03 | 1.08 | 1.04 | 1.00 | 0.99 | 0.97 |
| Soda Ash Consumption | | | | | | | | | | | | |
| Glass Manufacture | * | * | * | * | * | * | * | * | * | * | * | * |
| Flue Gas Desulfurization | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.02 | 0.03 | 0.03 |
| Sodium Silicate | 0.05 | 0.05 | 0.05 | 0.06 | 0.06 | 0.07 | 0.06 | 0.07 | 0.07 | 0.06 | 0.07 | 0.07 |
| Sodium Tripolyphosphate | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 |
| Soda Ash Subtotal | 0.10 | 0.10 | 0.10 | 0.11 | 0.11 | 0.13 | 0.12 | 0.14 | 0.12 | 0.10 | 0.11 | 0.11 |
| Carbon Dioxide Manufacture | 0.24 | 0.25 | 0.26 | 0.26 | 0.27 | 0.29 | 0.30 | 0.31 | 0.32 | 0.34 | 0.35 | 0.37 |
| Aluminum Manufacture | 1.62 | 1.65 | 1.62 | 1.48 | 1.32 | 1.35 | 1.43 | 1.44 | 1.48 | 1.51 | 1.47 | 1.04 |
| Shale Oil Production | 0.05 | * | * | * | * | * | * | * | * | * | * | * |
| Other Industrial Subtotal | 7.27 | 7.16 | 7.19 | 7.12 | 7.19 | 7.65 | 7.86 | 8.02 | 8.12 | 7.95 | 8.03 | 7.43 |
| Total | 16.36 | 16.02 | 16.14 | 16.58 | 17.23 | 17.72 | 17.99 | 18.49 | 18.84 | 18.88 | 19.29 | 18.79 |

*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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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, 1990-2001

| | Methane | Carbon Equivalent |
|--|---------|-------------------|
| Estimated 2001 Emissions (Million Metric Tons) | 28.0 | 175.8 |
| Change Compared to 2000 (Million Metric Tons) | -0.3 | -1.9 |
| Change from 2000 (Percent) | -1.1% | -1.1% |
| Change Compared to 1990 (Million Metric Tons) | -3.7 | -22.9 |
| Change from 1990 (Percent) | -11.5% | -11.5% |

U.S. anthropogenic methane emissions totaled 28.0 million metric tons in 2001, a decrease of 0.3 million metric tons from 2000 levels (Table 13). The decline in total methane emissions is primarily the result of a 0.2 million metric ton decrease in methane emissions from the natural gas system and a 0.2 million metric ton decrease in methane emissions from coal mining. These decreases more than offset a 0.1 million metric ton increase in methane emissions from landfills, the first increase in methane emissions from landfills in more than a decade.

While U.S. natural gas consumption dropped in 2001, gas production rose, reducing the need for gas withdrawals from storage and related methane emissions. At the same time, methane emissions from the ventilation and degasification systems in the Nation's gassiest mines also fell. Growth in methane emissions from landfills in 2001 is attributed to increased landfilling of

wastes between 1998 and 2001 and a leveling off of previously increasing rates of methane recovery at landfills.

Estimated U.S. emissions of methane in 2001 were 3.7 million metric tons below the 1990 level, a decrease equivalent to 22.9 million metric tons of carbon, or 1.2 percent of total U.S. anthropogenic greenhouse gas emissions.⁵² In addition to a 3.2 million metric ton decrease in methane emissions from landfills since 1990, there has also been a 1.4 million metric ton decrease in methane emissions from coal mines during the same period (Table 14). The 34.3-percent decline in emissions from coal mining is the result of a 143.9-percent increase in methane recovery from coal mines and a shift in production away from gassy mines. Overall, methane emissions account for about 9.3 percent of total U.S. greenhouse gas emissions when weighted by methane's global warming potential factor.

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.⁵³ Thus, methane emission estimates must often rely on proxy measurements.

Estimated U.S. anthropogenic methane emissions for 2001 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—represent three-fifths of all U.S. methane emissions. Thus, comparisons between 2000 and 2001 numbers are more likely to be valid in the context of directional change rather than magnitude of change. For example, because 2001 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.

⁵²Based on a revised estimate of the global warming potential factor of 23 for methane. For an expanded discussion of global warming potentials, see Chapter 1.

⁵³Wherever 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 Appendix A, "Estimation Methods." 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 Appendix C, "Uncertainty in Emissions Estimates").

Energy Sources

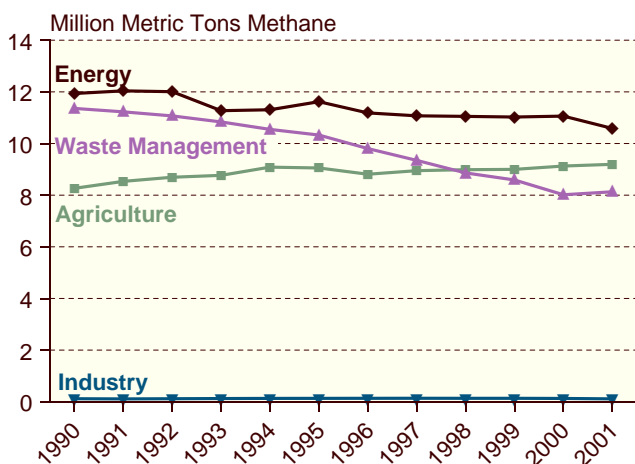
Principal Sources of U.S. Anthropogenic Methane Emissions, 1990-2001

| Source | Million Metric Tons Methane | | Percent Change | |
|----------------------|-----------------------------|-------|----------------|-----------|
| | 1990 | 2001 | 1990-2001 | 2000-2001 |
| Energy | 11.94 | 10.58 | -11.3% | -4.3% |
| Waste Management | 11.36 | 8.14 | -28.4% | 1.4% |
| Agriculture | 8.26 | 9.19 | 11.3% | 0.7% |
| Industrial Processes | 0.12 | 0.11 | -4.1% | -11.7% |

U.S. methane emissions from energy sources were estimated at 10.6 million metric tons in 2001, 0.5 million metric tons lower than 2000 levels and 1.4 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 34.3 percent (1.4 million metric tons) between 1990 and 2001. 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 gassiest underground mines in Central Appalachia.

Figure 3. U.S. Emissions of Methane by Source, 1990-2001



Source: Estimates presented in this chapter.

Between 1990 and 2001, the share of coal production represented by underground mines declined from 41.2 percent to 33.3 percent. Methane emissions from petroleum systems dropped from 1.3 million metric tons in 1990 to 1.0 million metric tons in 2001. A decrease of 0.2 million metric tons in estimated emissions from stationary combustion made a smaller contribution to the overall drop in emissions from energy sources between 1990 and 2001. Together, the declines in emissions from coal mining, petroleum systems, and stationary combustion more than compensated for the increase of 0.5 million metric tons in emissions from the natural gas system, attributed to increasing U.S. consumption of natural gas between 1990 and 2001.

Coal Mining

U.S. Methane Emissions from Coal Mining, 1990-2001

| | |
|--|--------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 2.8 |
| Change Compared to 2000 (Million Metric Tons Methane) | -0.2 |
| Change from 2000 (Percent) | -6.8% |
| Change Compared to 1990 (Million Metric Tons Methane) | -1.4 |
| Change from 1990 (Percent) | -34.3% |

The preliminary estimate of methane emissions from coal mines for 2001 is 2.8 million metric tons (Table 14), a decrease of 6.8 percent from the 2000 level.⁵⁴ This decrease can be traced to declines in emissions from the ventilation and degasification systems of underground coal mines, despite an increase in coal production levels, which rose by 4.4 percent in 2001 after falling for two consecutive years.

U.S. coal production rose from 1.07 billion short tons in 2000 to 1.12 billion short tons in 2001, returning to 1998 levels after two years of decline. Approximately three-fifths of the increased production was added to coal stocks rather than consumed. Between 1990 and 2001, methane emissions from coal mines dropped by 34.3 percent from the 1990 level of 4.22 million metric tons. The decline is attributed to three important trends: (1) methane recovery from active coal mines for use as an energy resource increased from 0.3 million metric tons in 1990 to about 0.7 million metric tons in 2001; (2) methane drainage from degasification in active mines decreased by more than 0.4 million metric tons between 1990 and 2001; and (3) methane emissions from

⁵⁴Further details on emissions from abandoned coal mines are available in Appendix D "Emissions Sources Excluded."

ventilation systems at gassy mines dropped by about 0.6 million metric tons between 1990 and 2001 (Table 14).⁵⁵

Natural Gas Systems

U.S. Methane Emissions from Natural Gas Systems, 1990-2001

| | |
|---|-------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 6.1 |
| Change Compared to 2000 (Million Metric Tons Methane) | -0.2 |
| Change from 2000 (<i>Percent</i>) | -3.9% |
| Change Compared to 1990 (Million Metric Tons Methane) | 0.5 |
| Change from 1990 (<i>Percent</i>) | 9.1% |

At 6.1 million metric tons, 2001 estimated methane emissions from natural gas production, processing, and distribution were down from the revised estimate of 6.4 million metric tons for 2000 (Table 15). The 3.9-percent decline in emissions levels can be traced to a drop in gas withdrawals from storage and a decrease in the number of operating gas processing plants in the United States; however, the 2001 estimate is preliminary, because pipeline data for 2001 had not been finalized as of the publication of this report. The estimated 2001 emissions level is 9.1 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.⁵⁶

Petroleum Systems

Methane emissions from petroleum systems are estimated at 1.03 million metric tons in 2001, nearly unchanged from 2000 levels and down some 20.7 percent from 1.29 million metric tons in 1990. Domestic oil production in 2001 was approximately 80 percent of the 1990 level, accounting for the decline in methane emissions from this source. Approximately 97 percent of all emissions from petroleum systems occur during exploration and production. Of the 1.0 million metric tons of emissions annually from this source, 90 percent can be traced to venting, of which nearly half is attributable to venting from oil tanks (Table 16). A much smaller

U.S. Methane Emissions from Petroleum Systems, 1990-2001

| | |
|---|--------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 1.0 |
| Change Compared to 2000 (Million Metric Tons Methane) | * |
| Change from 2000 (<i>Percent</i>) | -0.2% |
| Change Compared to 1990 (Million Metric Tons Methane) | -0.3 |
| Change from 1990 (<i>Percent</i>) | -20.7% |

*Less than 0.05 million metric tons.

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, 1990-2001

| | |
|---|--------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 0.4 |
| Change Compared to 2000 (Million Metric Tons Methane) | * |
| Change from 2000 (<i>Percent</i>) | -5.7% |
| Change Compared to 1990 (Million Metric Tons Methane) | -0.2 |
| Change from 1990 (<i>Percent</i>) | -26.8% |

*Less than 0.05 million metric tons.

U.S. methane emissions from stationary combustion in 2001 were 0.41 million metric tons, down by 5.7 percent from the 2000 level and 27 percent below 1990 levels (Table 17). Residential wood consumption typically accounts for about 87 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 Appendix C). The

⁵⁵The 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.

⁵⁶The EPA estimates that the companies participating in the Natural Gas STAR program together avoided emissions of more than 711,000 metric tons of methane in 2000 and 805,000 metric tons in 2001. Program participants report annually on emissions reductions achieved through such activities as equipment replacement, enhanced inspection and maintenance, and improved operations management. Participating companies may either use their own techniques to estimate reductions achieved or employ default values developed by the EPA and the Gas Technology Institute (formerly the Gas Research Institute).

Methane Emissions

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 1997 RECS. Residential wood consumption for the years after 1997 is estimated by scaling the 1997 estimates to heating degree-days. Updated data on residential wood consumption for calendar year 2001 will be available from the 2003 RECS.

Mobile Combustion

| U.S. Methane Emissions from Mobile Combustion, 1990-2001 | |
|--|------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 0.2 |
| Change Compared to 2000 (Million Metric Tons Methane) | * |
| Change from 2000 (Percent) | 1.1% |
| Change Compared to 1990 (Million Metric Tons Methane) | * |
| Change from 1990 (Percent) | 2.0% |

*Less than 0.05 million metric tons.

Estimated U.S. methane emissions from mobile combustion in 2000 were 0.2 million metric tons, up by 1.1 percent from 2000 levels and 2.0 percent higher 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. Although the rapid growth in emissions from light-duty trucks ended in 2000 and their emissions have declined over the past 2 years, that small decline has been offset by an increase in emissions from residual and distillate fuel consumed in marine vessels.

Waste Management

Methane emissions from waste management account for 29 percent of U.S. anthropogenic methane emissions (Figure 3), down from 36 percent in 1990. Landfills represent 98 percent of the 8.1 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 estimate emissions from industrial wastewater treatment (for further details, see box on page 41 and Appendix D).

Landfills

U.S. Methane Emissions from Landfills, 1990-2001

| | |
|--|--------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 8.0 |
| Change Compared to 2000 (Million Metric Tons Methane) | 0.1 |
| Change from 2000 (Percent) | 1.4% |
| Change Compared to 1990 (Million Metric Tons Methane) | -3.2 |
| Change from 1990 (Percent) | -29.0% |

Due to record levels of municipal solid waste reaching U.S. landfills since 1998,⁵⁷ estimated methane emissions from landfills rose to 8.0 million metric tons in 2001, 1.4 percent above the 2000 level of 7.8 million metric tons but still 3.2 million metric tons (29 percent) below 1990 levels (Table 19). The dramatic decrease in methane emissions since 1990 is directly attributable to a 3.9 million metric ton increase in methane captured that otherwise would have been emitted to the atmosphere. Of the 4.9 million metric tons of methane believed to be captured from this source, 2.5 million metric tons were recovered for energy use, and 2.4 million metric tons were recovered and flared. While estimates of methane recovered and disposed of in both practices are drawn from data collected by the EPA's Landfill Methane Outreach Program,⁵⁸ 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 resulted from 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 kilowatt-hour for electricity generated from landfill gas. However, this

⁵⁷"Nationwide Survey: The State of Garbage in America, 1999," *Biocycle* (April 2000) for years before 2000. Waste generation for 2000 estimated on the basis of annual economic growth.

⁵⁸See web site www.epa.gov/lmop.

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.

^aU.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, EPA-236-R-02-001 (Washington, DC, April 2002), web site www.epa.gov.

In its report, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*, 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 more than 700,000 metric tons of methane emissions in 2000, an amount that would be four times EIA's current estimate of methane emissions from wastewater treatment and would be equivalent to 2.5 percent of total estimated U.S. methane emissions.

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. Both the Senate and House versions of the comprehensive energy bill that went to conference committee in September 2002 contained new landfill gas-to-energy incentives under Section 29 and Section 45 of the Internal Revenue Code. According to the Solid Waste Association of North America (SWANA), a waste management trade association, the provisions in the existing bills provide insufficient incentives for the development of landfill gas-to-energy projects.⁵⁹ Senator Blanche Lincoln (D-AR) and Congressman Dave Camp (R-MI) have proposed a substitute amendment to the provision. At the time of this writing it is unclear what the ultimate legislative outcome of this issue will be.

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 as an energy resource.

The total volume of waste placed in U.S. landfills increased between 1998 and 2001. Because of the time lag associated with the decomposition of wastes, methane emissions began to grow again in 2001 and are likely to continue to increase later in this decade. Throughout the 1990s, methane recovery for energy and flaring at landfills offset increases in methane generated from decomposition of wastes. Unless methane recovery from landfills continues to increase, the rising level of

waste landfilled since 1998 will result in higher levels of methane emissions levels from this source in the future.

Domestic and Commercial Wastewater Treatment

U.S. Methane Emissions from Domestic and Commercial Wastewater Treatment, 1990-2001

| | |
|---|-------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 0.2 |
| Change Compared to 2000 (Million Metric Tons Methane) | * |
| Change from 2000 (Percent) | 0.9% |
| Change Compared to 1990 (Million Metric Tons Methane) | * |
| Change from 1990 (Percent) | 14.2% |

*Less than 0.05 million metric tons.

With the U.S. population growing slowly, methane emissions from domestic and commercial wastewater treatment are estimated to have grown by 0.9 percent between 2000 and 2001 to 0.17 million metric tons. This is about 14.2 percent above the 1990 level of 0.15 million metric tons (Table 13). Methane emissions from industrial wastewater treatment are discussed in the box above.

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

⁵⁹See web site www.swana.org.

treated aerobically or anaerobically. If it is treated aerobically, methane emissions will be low. Under anaerobic conditions, methane emissions will be high. There is little information available on wastewater treatment methods. Data on flaring or energy recovery from methane generated by wastewater are also sparse. EIA believes that emissions from this source are relatively small, representing on the order of 0.6 percent of all U.S. methane emissions. Thus, emissions are estimated using a default per-capita emissions factor and U.S. population data.

Agricultural Sources

Estimated agricultural methane emissions increased slightly between 2000 and 2001 (from 9.1 to 9.2 million metric tons) due mainly to an increase in emissions from rice cultivation, as well as enteric fermentation and the solid waste of domesticated animals associated with continued growth in average cattle size. At an estimated 9.2 million metric tons, methane emissions from agricultural activities represent 32.8 percent of total U.S. anthropogenic methane emissions (Table 13). Ninety-four percent of methane emissions from agricultural activities result from livestock management. About 64 percent of these emissions can be traced to enteric fermentation in ruminant animals, and the remainder is attributable to the anaerobic decomposition of livestock wastes. A small portion of U.S. methane emissions result from crop residue burning and wetland rice cultivation.

Enteric Fermentation in Domesticated Animals

U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-2001

| | |
|---|------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 5.6 |
| Change Compared to 2000 (Million Metric Tons Methane) | * |
| Change from 2000 (Percent) | 0.5% |
| Change Compared to 1990 (Million Metric Tons Methane) | 0.5 |
| Change from 1990 (Percent) | 9.0% |

*Less than 0.05 million metric tons.

In 2001, estimated methane emissions from enteric fermentation in domesticated animals rose by 0.5 percent to 5.6 million metric tons (Table 20). Because cattle

account for about 96 percent of all emissions from enteric fermentation, trends in emissions correlate with trends in cattle populations. While cattle populations were flat or somewhat declining in 2001 (with the exception of cattle on feedlots), average cattle size (excluding calves) reached a 22-year high in 2001. Animal size is a principal determinant of energy intake requirements, which relate directly to methane emissions. Emissions remain 9.0 percent above 1990 levels, principally due to 7.5-percent growth in average cattle size between 1990 and 2001.⁶⁰ Meanwhile, cattle populations have fluctuated in a cyclical pattern, settling in 2001 at levels very similar to those seen in 1990.

Solid Waste of Domesticated Animals

U.S. Methane Emissions from Solid Waste of Domesticated Animals, 1990-2001

| | |
|---|-------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 3.1 |
| Change Compared to 2000 (Million Metric Tons Methane) | * |
| Change from 2000 (Percent) | 0.3% |
| Change Compared to 1990 (Million Metric Tons Methane) | 0.4 |
| Change from 1990 (Percent) | 14.6% |

*Less than 0.05 million metric tons.

Estimated methane emissions from the solid waste of domesticated animals increased from 3.07 million metric tons in 2000 to 3.08 million metric tons in 2001 (Table 21). This small increase was the result of an increase in cattle sizes, which more than offset a slight decrease in cattle and swine populations. There has also been 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.⁶¹ EIA does not have sufficient data to substantiate that belief at this time. If true, however, it would likely change the trend in emissions from this source from flat to slightly positive (see box on page 43). Estimated 2001 emission levels were approximately 0.39 million metric tons above 1990 levels due to a general increase in the size of cattle over the past decade and an 11-percent increase in the population of market swine.

Rice Cultivation

Estimated methane emissions from U.S. rice cultivation rose to 0.48 million metric tons in 2001 from 0.45 million

⁶⁰U.S. Department of Agriculture, National Agricultural and Statistics Service, Livestock, web site www.nass.usda.gov:81/ipedb.

⁶¹U.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 www.epa.gov.

Potential Effects of a Shift in Swine Farm Size

The U.S. Department of Agriculture's Census of Agriculture showed a shift in farm size distribution for the management of swine from smaller to larger farms between the 1992 and 1997 census. It is possible that the shift to larger farm sizes has resulted in the increased use of liquid systems to manage swine waste. Generally, liquid management of animal waste leads to increased methane emissions; however, methane emissions from liquid systems are subject to a great deal of variability due to specific conditions. In fact, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, published by the Intergovernmental Panel on Climate Change,^a provides a default range of methane conversion factors for anaerobic lagoon systems of 0 percent to 100 percent. Given that range of uncertainty, and because it has not been possible to document a continued shift to larger farms since 1997, EIA has not tried to capture the effects of the apparent shift toward larger farms for swine management in its estimate of methane emissions from agricultural sources.

^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).

metric tons in 2000. The increase was the result of a 9-percent rise in the number of acres harvested. Arkansas, Mississippi, Louisiana, and Texas all saw substantial increases in acres harvested. Methane emissions from rice cultivation in 2001 were 18 percent higher than in 1990 (Table 13).

Burning of Crop Residues

Crop residue burning, being the smallest contributor to agricultural greenhouse gas emissions, represents less than 0.2 percent of total U.S. methane emissions.

Estimated 2001 methane emissions from the burning of crop residues were 0.04 million metric tons, down by 2.3 percent from 2000 levels but still 8.6 percent above 1990 levels (Table 13). The small decrease is attributable mainly to declines in corn, wheat, sugar beet, and potato production.

Industrial Sources

U.S. Methane Emissions from Industrial Sources, 1990-2001

| | |
|---|--------|
| Estimated 2001 Emissions (Million Metric Tons Methane) | 0.1 |
| Change Compared to 2000 (Million Metric Tons Methane) | * |
| Change from 2000 (Percent) | -11.7% |
| Change Compared to 1990 (Million Metric Tons Methane) | * |
| Change from 1990 (Percent) | -4.1% |

*Less than 0.05 million metric tons.

Chemical Production

The preliminary estimate of methane emissions from U.S. chemical production in 2001 is 0.064 million metric tons, 10.8 percent less than in 2000 and the lowest level since 1993. The decrease was attributable to drops in ethylene and styrene production. Methane emissions from chemical production, however, are still 15.8 percent above their level in 1990 (Table 22).

Iron and Steel Production

With production of pig iron and coke dropping, methane emissions from iron and steel production fell by 12.8 percent between 2000 and 2001, to the lowest levels in more than 20 years. Emissions in 2001, at 0.048 million metric tons, were 21.9 percent below the 1990 level of 0.062 million metric tons (Table 22).

Methane Emissions

Table 13. U.S. Methane Emissions from Anthropogenic Sources, 1990-2001
(Million Metric Tons Methane)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Energy Sources | | | | | | | | | | | | |
| Coal Mining | 4.22 | 4.08 | 3.99 | 3.41 | 3.47 | 3.63 | 3.21 | 3.24 | 3.29 | 3.12 | 2.98 | 2.78 |
| Natural Gas Systems | 5.60 | 5.83 | 5.89 | 5.88 | 5.89 | 5.98 | 6.00 | 6.01 | 6.02 | 6.19 | 6.36 | 6.11 |
| Petroleum Systems | 1.30 | 1.31 | 1.27 | 1.21 | 1.18 | 1.17 | 1.15 | 1.14 | 1.11 | 1.04 | 1.03 | 1.03 |
| 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 |
| Mobile Sources | 0.25 | 0.23 | 0.24 | 0.24 | 0.24 | 0.25 | 0.24 | 0.24 | 0.24 | 0.26 | 0.25 | 0.25 |
| Total Energy Sources | 11.94 | 12.04 | 12.01 | 11.27 | 11.31 | 11.62 | 11.18 | 11.07 | 11.05 | 11.02 | 11.06 | 10.58 |
| Waste Management | | | | | | | | | | | | |
| Landfills | 11.21 | 11.07 | 10.91 | 10.68 | 10.39 | 10.17 | 9.65 | 9.19 | 8.70 | 8.42 | 7.85 | 7.96 |
| Wastewater Treatment | 0.15 | 0.15 | 0.15 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.17 | 0.17 |
| Total Waste Management | 11.36 | 11.23 | 11.07 | 10.84 | 10.55 | 10.33 | 9.80 | 9.35 | 8.86 | 8.59 | 8.02 | 8.13 |
| Agricultural Sources | | | | | | | | | | | | |
| Enteric Fermentation | 5.13 | 5.31 | 5.39 | 5.46 | 5.59 | 5.60 | 5.41 | 5.36 | 5.36 | 5.41 | 5.57 | 5.59 |
| Animal Waste | 2.69 | 2.79 | 2.81 | 2.87 | 2.97 | 2.97 | 2.95 | 3.10 | 3.11 | 3.05 | 3.07 | 3.08 |
| Rice Cultivation | 0.40 | 0.40 | 0.45 | 0.41 | 0.48 | 0.44 | 0.41 | 0.45 | 0.47 | 0.50 | 0.45 | 0.48 |
| Crop Residue Burning | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.04 |
| Total Agricultural Sources | 8.26 | 8.53 | 8.69 | 8.77 | 9.09 | 9.05 | 8.81 | 8.95 | 8.99 | 9.00 | 9.13 | 9.19 |
| 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 |
| Total | 31.68 | 31.91 | 31.88 | 31.00 | 31.07 | 31.13 | 29.93 | 29.50 | 29.03 | 28.74 | 28.33 | 28.02 |

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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 www.epa.gov.

Table 14. U.S. Methane Emissions from Coal Mining and Post-Mining Activities, 1990-2001
(Million Metric Tons Methane)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 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 |
| Post-Mining | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 |
| 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 | 1.49 |
| 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 | 0.03 |
| Degasification Systems | 1.26 | 1.23 | 1.17 | 1.05 | 1.06 | 1.21 | 1.02 | 1.06 | 0.95 | 0.79 | 0.87 | 0.82 |
| Post-Mining | 0.64 | 0.61 | 0.61 | 0.53 | 0.60 | 0.60 | 0.62 | 0.63 | 0.63 | 0.59 | 0.56 | 0.56 |
| Methane Recovery for Energy (-) | 0.29 | 0.29 | 0.37 | 0.47 | 0.56 | 0.60 | 0.67 | 0.80 | 0.67 | 0.61 | 0.70 | 0.70 |
| Net Emissions. | 4.22 | 4.08 | 3.99 | 3.41 | 3.47 | 3.63 | 3.21 | 3.24 | 3.29 | 3.12 | 2.98 | 2.78 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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, 1995-2000). 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.

Methane Emissions

Table 15. U.S. Methane Emissions from Natural Gas Systems, 1990-2001
(Million Metric Tons Methane)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|------------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Production | 1.47 | 1.49 | 1.49 | 1.51 | 1.55 | 1.57 | 1.58 | 1.65 | 1.67 | 1.62 | 1.64 | 1.66 |
| Gas Processing | 0.65 | 0.71 | 0.70 | 0.71 | 0.71 | 0.72 | 0.73 | 0.71 | 0.69 | 0.70 | 0.71 | 0.68 |
| Transmission and Storage | 2.10 | 2.21 | 2.23 | 2.15 | 2.11 | 2.14 | 2.11 | 2.05 | 2.00 | 2.06 | 2.18 | 1.94 |
| Distribution | 1.39 | 1.42 | 1.47 | 1.51 | 1.53 | 1.55 | 1.58 | 1.59 | 1.66 | 1.80 | 1.83 | 1.83 |
| Total | 5.60 | 5.83 | 5.89 | 5.88 | 5.89 | 5.98 | 6.00 | 6.01 | 6.02 | 6.19 | 6.36 | 6.11 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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(2002/07) (Washington, DC, July 2002); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Table 16. U.S. Methane Emissions from Petroleum Systems, 1990-2001
(Million Metric Tons Methane)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--------------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 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 |
| 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 | 1.00 |
| 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 |
| Total | 1.30 | 1.31 | 1.27 | 1.21 | 1.18 | 1.17 | 1.15 | 1.14 | 1.11 | 1.04 | 1.03 | 1.03 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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, 1990-2001
(Thousand Metric Tons Methane)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Residential | | | | | | | | | | | | |
| Coal | * | * | * | * | * | * | * | * | * | * | * | * |
| Fuel Oil ^a | 4 | 4 | 4 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 |
| Natural Gas | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 5 | 5 |
| LPG | * | * | * | * | * | * | 1 | 1 | 1 | 1 | 1 | 1 |
| Wood | 512 | 541 | 569 | 483 | 474 | 526 | 525 | 382 | 341 | 365 | 382 | 359 |
| Total | 521 | 550 | 578 | 493 | 483 | 535 | 535 | 392 | 350 | 374 | 392 | 369 |
| Commercial | | | | | | | | | | | | |
| Coal | 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 |
| LPG | * | * | * | * | * | * | * | * | * | * | * | * |
| Wood | * | * | * | * | * | * | * | * | * | * | * | * |
| Total | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 5 | 5 | 5 | 5 |
| Industrial | | | | | | | | | | | | |
| Coal | 7 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 |
| Fuel Oil ^a | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Natural Gas | 11 | 12 | 12 | 13 | 13 | 14 | 14 | 14 | 13 | 12 | 13 | 12 |
| LPG | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Wood | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 |
| Total | 26 | 25 | 26 | 27 | 27 | 28 | 28 | 28 | 27 | 26 | 27 | 25 |
| Electric Power | | | | | | | | | | | | |
| Coal | 10 | 10 | 10 | 10 | 10 | 10 | 11 | 11 | 12 | 12 | 12 | 12 |
| Fuel Oil ^a | 1 | 1 | 1 | 1 | 1 | * | * | 1 | 1 | 1 | 1 | 1 |
| Natural Gas | * | * | * | * | * | * | * | * | * | * | * | * |
| Wood | * | * | * | * | * | * | * | * | * | * | * | * |
| Total | 11 | 11 | 11 | 11 | 11 | 11 | 12 | 12 | 13 | 13 | 13 | 13 |
| Total All Fuels | | | | | | | | | | | | |
| Coal | 17 | 17 | 17 | 17 | 17 | 17 | 18 | 18 | 18 | 18 | 18 | 18 |
| Fuel Oil ^a | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 6 | 6 | 6 | 6 | 6 |
| Natural Gas | 19 | 20 | 20 | 21 | 21 | 22 | 23 | 23 | 22 | 21 | 22 | 21 |
| LPG | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 3 | 4 | 4 | 4 |
| Wood | 516 | 544 | 573 | 487 | 478 | 530 | 529 | 387 | 346 | 370 | 386 | 363 |
| Total | 563 | 591 | 620 | 536 | 527 | 580 | 581 | 438 | 395 | 418 | 437 | 412 |

*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.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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/chieff; 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 1998*, DOE/EIA-0214(98) (Washington, DC, September 2000), *Monthly Energy Review*, DOE/EIA-0035(2002/07) (Washington, DC, July 2002), and *Annual Energy Review 2001*, DOE/EIA-0384(2001) (Washington, DC, November 2002).

Methane Emissions

Table 18. U.S. Methane Emissions from Mobile Sources, 1990-2001
(Thousand Metric Tons Methane)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|----------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Motor Vehicles | | | | | | | | | | | | |
| Passenger Cars | 142 | 132 | 131 | 126 | 117 | 109 | 107 | 105 | 105 | 106 | 101 | 101 |
| Buses | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Motorcycles | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| Light-Duty Trucks | 63 | 63 | 63 | 75 | 85 | 99 | 92 | 91 | 91 | 108 | 100 | 99 |
| Other Trucks | 12 | 12 | 12 | 13 | 14 | 14 | 15 | 15 | 16 | 17 | 16 | 17 |
| Total | 222 | 212 | 212 | 219 | 221 | 228 | 219 | 217 | 217 | 236 | 223 | 223 |
| Other Transport. | 23 | 23 | 24 | 22 | 22 | 23 | 23 | 21 | 21 | 21 | 24 | 27 |
| Total Transport | 245 | 235 | 235 | 241 | 243 | 250 | 242 | 238 | 238 | 257 | 247 | 250 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001).

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.

Table 19. U.S. Methane Emissions from Landfills, 1990-2001
(Million Metric Tons Methane)

| Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--|-------------|-------------|-------------|-------------|-------------|-------------|------------|------------|------------|------------|------------|------------|
| Gross Emissions from Landfills | 12.2 | 12.3 | 12.4 | 12.5 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.7 | 12.8 |
| Methane Recovered for Energy (-) . . . | 0.8 | 0.8 | 0.9 | 0.9 | 1.1 | 1.1 | 1.3 | 1.6 | 1.9 | 2.2 | 2.5 | 2.5 |
| Methane Assumed Flared (-) | 0.2 | 0.4 | 0.7 | 0.9 | 1.1 | 1.3 | 1.7 | 1.8 | 2.0 | 2.0 | 2.4 | 2.4 |
| Net Emissions. | 11.2 | 11.1 | 10.9 | 10.7 | 10.4 | 10.2 | 9.6 | 9.2 | 8.7 | 8.4 | 7.8 | 8.0 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001).

Sources: Municipal solid waste landfilled from "Nationwide Survey: The State of Garbage in America," *Bicycle* (various years) for years before 2001. Waste generation for 2001 estimated on the basis of annual economic growth. Emissions calculations based on S.A. Thorneloe et al., "Estimate of Methane Emissions from U.S. Landfills," Prepared for the U.S. Environmental Protection Agency, Office of Research and Development (April 1994), and D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global 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, 1990-2000
(Million Metric Tons Methane)

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Cattle | 4.84 | 5.02 | 5.10 | 5.18 | 5.31 | 5.33 | 5.16 | 5.10 | 5.11 | 5.16 | 5.33 | 5.35 |
| 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 |
| Pigs | 0.15 | 0.15 | 0.14 | 0.13 | 0.13 | 0.12 | 0.11 | 0.10 | 0.10 | 0.09 | 0.09 | 0.09 |
| Goats | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 |
| Horses | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 |
| Total | 5.13 | 5.31 | 5.39 | 5.46 | 5.59 | 5.60 | 5.41 | 5.36 | 5.36 | 5.41 | 5.57 | 5.59 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), web site www.epa.gov; 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, 1990-2001
(Thousand Metric Tons Methane)

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Cattle | | | | | | | | | | | | |
| Beef Cattle | 249 | 264 | 271 | 278 | 284 | 286 | 275 | 275 | 273 | 275 | 280 | 281 |
| Dairy Cattle | 917 | 923 | 927 | 964 | 1,011 | 1,045 | 1,073 | 1,105 | 1,112 | 1,119 | 1,137 | 1,150 |
| Swine | | | | | | | | | | | | |
| Market Swine | 861 | 912 | 924 | 919 | 975 | 951 | 916 | 1,002 | 1,026 | 982 | 981 | 977 |
| Breeding Swine | 487 | 515 | 506 | 510 | 501 | 485 | 471 | 498 | 478 | 447 | 449 | 444 |
| Poultry | | | | | | | | | | | | |
| Layers | 83 | 84 | 86 | 88 | 90 | 91 | 92 | 94 | 97 | 100 | 102 | 104 |
| Broilers | 73 | 77 | 81 | 91 | 95 | 100 | 102 | 105 | 106 | 110 | 104 | 105 |
| Other Animals | | | | | | | | | | | | |
| Sheep | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 |
| Goats | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Horses | 12 | 11 | 11 | 11 | 12 | 12 | 13 | 13 | 13 | 14 | 14 | 14 |
| Total | 2,688 | 2,792 | 2,812 | 2,867 | 2,973 | 2,974 | 2,946 | 3,095 | 3,111 | 3,049 | 3,071 | 3,080 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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. 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, and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-230-00-001 (Washington, DC, April 2000). 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), web site www.epa.gov.

Methane Emissions

Table 22. U.S. Methane Emissions from Industrial Processes, 1990-2001
(Thousand Metric Tons Methane)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Chemical Production | | | | | | | | | | | | |
| Ethylene | 17 | 18 | 19 | 19 | 20 | 21 | 22 | 23 | 23 | 25 | 23 | 20 |
| Ethylene Dichloride | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 |
| Styrene | 15 | 15 | 16 | 18 | 20 | 21 | 22 | 21 | 21 | 22 | 20 | 16 |
| Methanol | 8 | 8 | 7 | 10 | 10 | 10 | 11 | 12 | 11 | 11 | 9 | 9 |
| Carbon Black | 14 | 13 | 15 | 16 | 16 | 17 | 17 | 17 | 18 | 18 | 17 | 16 |
| Total | 56 | 57 | 60 | 66 | 70 | 72 | 75 | 77 | 77 | 80 | 72 | 64 |
| Iron and Steel Production | | | | | | | | | | | | |
| Coke ^a | 11 | 9 | 9 | 9 | 8 | 9 | 8 | 7 | 7 | 6 | 7 | 6 |
| Sinter | 6 | 5 | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 6 | 5 | 5 |
| Pig Iron | 45 | 40 | 43 | 43 | 44 | 46 | 44 | 45 | 43 | 42 | 43 | 38 |
| Total | 62 | 54 | 57 | 58 | 59 | 61 | 59 | 58 | 56 | 54 | 55 | 48 |
| Total Industrial Processes | 117 | 111 | 117 | 124 | 129 | 132 | 134 | 134 | 133 | 133 | 127 | 112 |

^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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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, 1990-2001

| | Nitrous Oxide | Carbon Equivalent |
|---|---------------|-------------------|
| Estimated 2001 Emissions (Thousand Metric Tons) | 1,207 | 97,462 |
| Change Compared to 2000 (Thousand Metric Tons) | -12 | -954 |
| Change from 2000 (Percent) | -1.0% | -1.0% |
| Change Compared to 1990 (Thousand Metric Tons) | 37 | 3,004 |
| Change from 1990 (Percent) | 3.2% | 3.2% |

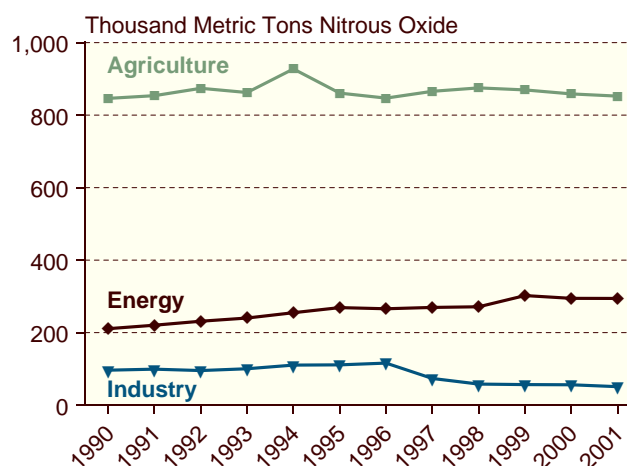
Estimated U.S. anthropogenic nitrous oxide emissions totaled 1,207 thousand metric tons in 2001, 1.0 percent less than in 2000 but still 3.2 percent above 1990 levels (Table 23). Nearly all of the increase from 1990 can be attributed to emissions from mobile combustion, which grew by 69 thousand metric tons between 1990 and 2001, more than offsetting the 45 thousand metric ton decrease in emissions from industrial sources (adipic acid and nitric acid production) since 1990. Weighted by global warming potential, total nitrous oxide emissions in 2001 were equivalent to 97.5 million metric tons carbon equivalent, or 5.2 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 70.6 percent of the total. Nitrogen fertilization of agricultural soils represents 72.8 percent of emissions from agricultural activities. Most of the remainder is from the handling of animal waste in managed systems. Small quantities of nitrous oxide are also released from the burning of crop residues. Estimated emissions of nitrous oxide from agricultural sources

were 852 thousand metric tons in 2001, 0.7 percent below 2000 levels but 0.7 percent above 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.⁶² 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.

Figure 4. U.S. Emissions of Nitrous Oxide by Source, 1990-2001



Source: Estimates presented in this chapter.

Principal Sources of U.S. Anthropogenic Nitrous Oxide Emissions, 1990-2001

| Source | Thousand Metric Tons Nitrous Oxide | | Percent Change | |
|-------------|------------------------------------|------|----------------|-----------|
| | 1990 | 2001 | 1990-2001 | 2000-2001 |
| Energy | 211 | 284 | 34.7% | -0.2% |
| Agriculture | 846 | 852 | 0.7% | -0.7% |
| Industrial | 96 | 51 | -47.1% | -9.2% |

⁶²Intergovernmental 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.

The second-largest source of anthropogenic nitrous oxide emissions is energy consumption, which includes mobile source combustion from passenger cars, buses, motorcycles, and trucks and stationary source combustion from commercial, residential, industrial, and electric power sector energy use. Energy use was responsible for the release of 284 thousand metric tons of nitrous oxide in 2001 (23.5 percent of total U.S. nitrous oxide emissions), 0.2 percent lower than in 2000 but 34.7 percent higher than in 1990.

Industrial production of adipic and nitric acid, which releases nitrous oxide as a byproduct, accounted for emissions of 51 thousand metric tons of nitrous oxide in 2001 (4.2 percent of total U.S. nitrous oxide emissions), a 47.1-percent decrease from 1990 levels and a 9.2-percent decline from 2000 levels. The large decline in emissions from this source 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, 1990-2001

| | |
|--|-------|
| Estimated 2001 Emissions (Thousand Metric Tons Nitrous Oxide) | 284 |
| Change Compared to 2000 (Thousand Metric Tons Nitrous Oxide) | -1 |
| Change from 2000 (Percent) | -0.2% |
| Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide) | 73 |
| Change from 1990 (Percent) | 34.7% |

The energy use category includes nitrous oxide emissions from both mobile and stationary sources as byproducts of fuel combustion. Estimated 2001 energy-related emissions were 284 thousand metric tons, or 23.5 percent of total U.S. anthropogenic nitrous oxide emissions (Table 23). Emissions from energy use are dominated by mobile combustion (82.7 percent of nitrous oxide emissions from energy use in 2001).

Mobile Combustion

Nitrous oxide emissions from mobile source combustion in 2001 were 235 thousand metric tons, nearly unchanged from 2000 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 93.8 percent of nitrous oxide emissions from mobile combustion (Table 24). Emissions 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. The shift to advanced three-way catalytic converters (so-called because they reduce three pollutants: carbon monoxide, volatile organic compounds, and oxides of nitrogen) in 1996 through 2001 model year cars has slowed but not abated emissions growth from this source.

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

Stationary Combustion

In 2001, estimated nitrous oxide emissions from stationary combustion sources were 49 thousand metric tons, 2.0 percent lower than in 2000 but 10.4 percent higher than in 1990 (Table 25). The emissions increase from this source between 1990 and 2001 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 62.7 percent of the 2001 emissions of nitrous oxide from stationary combustion, and the electric power sector accounted for 70.3 percent of all nitrous oxide emissions from stationary combustion sources. During combustion, nitrous oxide is produced as a result of chemical interactions between nitrogen oxides (mostly NO_2) and other combustion products. With most conventional stationary combustion systems, high temperatures destroy almost all nitrous oxide, limiting the quantity that escapes; therefore, emissions from these systems typically are low.

Agriculture

U.S. Nitrous Oxide Emissions from Agriculture, 1990-2001

| | |
|--|-------|
| Estimated 2001 Emissions (Thousand Metric Tons Nitrous Oxide) | 852 |
| Change Compared to 2000 (Thousand Metric Tons Nitrous Oxide) | -6 |
| Change from 2000 (Percent) | -0.7% |
| Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide) | 6 |
| Change from 1990 (Percent) | 0.7% |

Nitrous oxide emissions from agricultural activities grew by 0.7 percent between 1990 and 2001. Agricultural activities were responsible for 70.6 percent of U.S. nitrous oxide emissions in 2001, roughly the same percentage that agricultural practices contribute to nitrous oxide emissions globally.⁶³ Nitrogen fertilization of agricultural soils accounted for 72.8 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 2001.

Nitrogen Fertilization of Agricultural Soils

EIA estimates that a total of 621 thousand metric tons of nitrous oxide was released into the atmosphere as a result of direct and indirect emissions associated with fertilization practices in 2001 (Table 26). Estimated emissions decreased by 0.8 percent compared with 2000 levels but were still 0.8 percent higher than in 1990. Nitrous oxide emissions from the application of nitrogen-based fertilizers and biological fixation in crops accounted for 61.6 percent of total nitrous oxide emissions from this source during 2001.

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.⁶⁴ 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 2001, estimated emissions of nitrous oxide from crop residue burning were 2 thousand metric tons, up by less than 0.5 thousand metric tons (less than 0.1 percent) from 2000 levels (Table 23). The small increase is mainly attributable to increased 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 2001 nitrous oxide emissions from animal waste management were 230 thousand metric tons, down by 0.4 percent from 2000 levels but 0.5 percent higher than 1990 levels (Table 27), making animal waste the second-largest U.S. agricultural source of nitrous oxide emissions, after nitrogen fertilization of soils. Nitrous oxide emissions from animal waste are dominated by emissions from cattle waste, which account for 93.9 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,

⁶³A.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.

⁶⁴A.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).

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, 1990-2001

| | |
|--|-------|
| Estimated 2001 Emissions (Thousand Metric Tons Nitrous Oxide) | 20 |
| Change Compared to 2000 (Thousand Metric Tons Nitrous Oxide) | * |
| Change from 2000 (Percent) | 0.9% |
| Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide) | 3 |
| Change from 1990 (Percent) | 19.9% |

*Less than 0.5 thousand metric tons.

Nitrous oxide emissions from waste management are estimated at 20 thousand metric tons for 2001, 1.6 percent of all U.S. anthropogenic nitrous oxide emissions (Table 23). During 2001, emissions from human sewage in wastewater were responsible for 95.8 percent of the estimated emissions from this source, and the remainder was associated with waste combustion. Estimated emissions from waste management increased by 0.9 percent between 2000 and 2001 and by 19.9 percent between 1990 and 2001. 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 2001, estimated nitrous oxide emissions from waste combustion were 1 thousand metric tons, down 8.9 percent from 2000 levels and 0.3 percent above 1990 levels. Data on the amount of waste generated in the United States in 2001 were not available in time for this report; therefore, EIA scaled the 2001 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 2000 to 2001, 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 2001; however, the share of waste burned in 2001 was just 7.5 percent, compared with 11.5 percent in 1990.⁶⁵

Human Sewage in Wastewater

In 2001, nitrous oxide emissions from wastewater were 19 thousand metric tons, a 0.9-percent increase from 2000 levels and a 21.6-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 and 2001. 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).⁶⁶

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),⁶⁷ and nitrogen concentration.

Industrial Processes

U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-2001

| | |
|--|--------|
| Estimated 2001 Emissions (Thousand Metric Tons Nitrous Oxide) | 51 |
| Change Compared to 2000 (Thousand Metric Tons Nitrous Oxide) | -5 |
| Change from 2000 (Percent) | -9.2% |
| Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide) | -45 |
| Change from 1990 (Percent) | -47.1% |

Emissions from industrial processes were 51 thousand metric tons in 2001, a decrease of 45 thousand metric tons (47.1 percent) since 1990 and a decrease of 5 thousand metric tons (9.2 percent) from 2000. Nitrous oxide is emitted as a byproduct of certain chemical production

⁶⁵“Nationwide Survey: The State of Garbage in America 1999,” *Bicycle* (April 2000). Waste streams were estimated for 2001 by scaling to economic growth, and the share of waste combusted was held constant at the 2000 level.

⁶⁶Food and Agriculture Organization of the United Nations, statistical databases, web site <http://apps.fao.org>.

⁶⁷Biochemical oxygen demand is a measure of the organic content within the wastewater that is subject to decomposition.

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 fell from 14 thousand metric tons of nitrous oxide in 2000 to 12 thousand metric tons in 2001—a decrease of 13.7 percent. As discussed below, emissions from this source have been in the range of 12 to 14 thousand metric tons 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.⁶⁸ Between 1990 and 1996, emissions from adipic acid manufacture grew by 23.2 percent, reaching 70 thousand metric tons before dropping sharply to 27 thousand metric tons 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.⁶⁹ 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.⁷⁰ Estimated emissions of nitrous oxide from uncontrolled adipic acid production decreased from 22 thousand metric tons in 1997 to 7 thousand metric tons in 2001, and 2001 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 7.1 million metric tons of nitric acid manufactured in 2001 resulted in estimated emissions of 39 thousand metric tons of nitrous oxide (Table 28). This estimate was 7.7 percent lower than 2000 levels and 1.4 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.⁷¹ 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.

⁶⁸M.H. Thiemens and W.C. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 1991).

⁶⁹Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

⁷⁰R.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).

⁷¹Intergovernmental 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.

Nitrous Oxide Emissions

Table 23. Estimated U.S. Emissions of Nitrous Oxide, 1990-2001
(Thousand Metric Tons Nitrous Oxide)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Energy | | | | | | | | | | | | |
| Mobile Combustion | 166 | 176 | 186 | 195 | 209 | 222 | 217 | 221 | 222 | 244 | 234 | 235 |
| Stationary Combustion | 45 | 44 | 45 | 46 | 46 | 47 | 49 | 49 | 49 | 49 | 50 | 49 |
| Total | 211 | 220 | 232 | 240 | 255 | 269 | 266 | 270 | 271 | 293 | 285 | 284 |
| Agriculture | | | | | | | | | | | | |
| Nitrogen Fertilization of Soils | 616 | 621 | 639 | 624 | 686 | 617 | 607 | 628 | 640 | 636 | 626 | 621 |
| Crop Residue Burning | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Solid Waste of Domesticated Animals | 229 | 231 | 234 | 237 | 239 | 242 | 238 | 236 | 233 | 232 | 231 | 230 |
| Total | 846 | 854 | 874 | 862 | 927 | 861 | 847 | 866 | 875 | 870 | 859 | 852 |
| Waste Management | | | | | | | | | | | | |
| Waste Combustion | 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 |
| Total | 17 | 17 | 17 | 17 | 18 | 18 | 18 | 18 | 18 | 19 | 20 | 20 |
| Industrial Processes | 96 | 99 | 95 | 100 | 110 | 111 | 116 | 74 | 58 | 57 | 56 | 51 |
| Total | 1,170 | 1,190 | 1,218 | 1,220 | 1,311 | 1,259 | 1,247 | 1,227 | 1,223 | 1,238 | 1,219 | 1,207 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov.

Table 24. U.S. Nitrous Oxide Emissions from Mobile Combustion, 1990-2001
(Thousand Metric Tons Nitrous Oxide)

| Item | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---------------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Motor Vehicles | | | | | | | | | | | | |
| Passenger Cars | 99 | 107 | 115 | 112 | 111 | 108 | 109 | 109 | 110 | 112 | 108 | 107 |
| Buses | * | * | * | * | * | * | * | * | * | * | * | * |
| Motorcycles | * | * | * | * | * | * | * | * | * | * | * | * |
| Light-Duty Trucks | 49 | 51 | 53 | 64 | 78 | 94 | 88 | 91 | 92 | 111 | 104 | 104 |
| Other Trucks | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 8 | 8 | 8 | 8 | 8 |
| Total | 154 | 164 | 174 | 183 | 196 | 210 | 205 | 208 | 210 | 231 | 221 | 220 |
| Other Mobile Sources | 12 | 12 | 12 | 12 | 12 | 12 | 13 | 12 | 12 | 13 | 14 | 14 |
| Total | 166 | 176 | 186 | 195 | 209 | 222 | 217 | 221 | 222 | 244 | 234 | 235 |

*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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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. 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, 1990-2001
(Thousand Metric Tons Nitrous Oxide)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Residential | | | | | | | | | | | | |
| Coal | * | * | * | * | * | * | * | * | * | * | * | * |
| Fuel Oil ^a | 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 |
| Total | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| Commercial | | | | | | | | | | | | |
| Coal | * | * | * | * | * | * | * | * | * | * | * | * |
| Fuel Oil ^a | 1 | 1 | * | * | * | * | * | * | * | * | * | * |
| Natural Gas | * | * | * | * | * | * | * | * | * | * | * | * |
| Wood | * | * | * | * | * | * | * | * | * | * | * | * |
| Total | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Industrial | | | | | | | | | | | | |
| Coal | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| Fuel Oil ^a | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 5 | 6 | 6 | 6 |
| Natural Gas | 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 |
| Total | 10 | 9 | 10 | 9 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 9 |
| Electric Power | | | | | | | | | | | | |
| Coal | 23 | 23 | 23 | 24 | 24 | 25 | 26 | 27 | 27 | 27 | 28 | 28 |
| Fuel Oil ^a | 1 | 1 | 1 | 1 | 1 | * | * | 1 | 1 | 1 | 1 | 1 |
| Natural Gas | * | * | * | * | * | * | * | * | * | * | * | * |
| Wood | * | * | 1 | 1 | 1 | * | 1 | 1 | 1 | 1 | 1 | 1 |
| Total | 25 | 24 | 25 | 26 | 26 | 26 | 27 | 28 | 29 | 29 | 30 | 30 |
| Fuel Totals | | | | | | | | | | | | |
| Coal | 27 | 27 | 27 | 28 | 28 | 28 | 30 | 30 | 30 | 30 | 32 | 31 |
| Fuel Oil ^a | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 8 | 8 | 8 |
| Natural Gas | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Wood | 9 | 9 | 9 | 9 | 9 | 10 | 10 | 9 | 9 | 9 | 9 | 9 |
| Total | 45 | 44 | 45 | 46 | 46 | 47 | 49 | 49 | 49 | 49 | 50 | 49 |

*Less than 500 metric tons of 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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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 2001); and *Monthly Energy Review*, DOE/EIA-0035(2002/08) (Washington, DC, August 2002).

Table 26. U.S. Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils, 1990-2001
(Thousand Metric Tons Nitrous Oxide)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Direct Emissions | | | | | | | | | | | | |
| Nitrogen Fertilizers | 179 | 182 | 183 | 193 | 195 | 173 | 159 | 159 | 161 | 161 | 154 | 148 |
| Animal Manure | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| Crop Residues | 94 | 91 | 104 | 86 | 112 | 94 | 106 | 114 | 116 | 113 | 116 | 116 |
| Soil Mineralization | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Biological Fixation in Crops | 198 | 201 | 203 | 190 | 222 | 210 | 212 | 224 | 232 | 230 | 229 | 235 |
| Total | 484 | 487 | 504 | 482 | 543 | 490 | 489 | 511 | 522 | 517 | 512 | 511 |
| Indirect Emissions | | | | | | | | | | | | |
| Soil Leaching | 112 | 114 | 115 | 121 | 122 | 109 | 100 | 101 | 101 | 102 | 97 | 93 |
| Atmospheric Deposition | 19 | 20 | 20 | 21 | 21 | 19 | 17 | 17 | 17 | 17 | 17 | 16 |
| Total | 132 | 134 | 135 | 142 | 143 | 128 | 118 | 118 | 119 | 119 | 114 | 109 |
| Total | 616 | 621 | 639 | 624 | 686 | 617 | 607 | 628 | 640 | 636 | 626 | 621 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). 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; 1995-2001, 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 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov.

Table 27. U.S. Nitrous Oxide Emissions from Solid Waste of Domesticated Animals, 1990-2001
(Thousand Metric Tons Nitrous Oxide)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Cattle | 215 | 217 | 219 | 223 | 225 | 228 | 224 | 221 | 218 | 218 | 217 | 216 |
| Swine | 5 | 5 | 5 | 5 | 6 | 5 | 5 | 6 | 6 | 6 | 6 | 5 |
| Poultry | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Sheep | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 |
| Goats | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Horses | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Total | 229 | 231 | 234 | 237 | 239 | 242 | 238 | 236 | 233 | 232 | 231 | 230 |

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 Processes, 1990-2001
(Thousand Metric Tons Nitrous Oxide)

| Source | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|----------------------------|-----------|-----------|-----------|------------|------------|------------|------------|-----------|-----------|-----------|-----------|-----------|
| Adipic Acid | | | | | | | | | | | | |
| Controlled Sources | 3 | 4 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 |
| Uncontrolled Sources | 54 | 56 | 52 | 56 | 63 | 63 | 66 | 22 | 7 | 7 | 9 | 7 |
| Total | 57 | 60 | 55 | 59 | 67 | 67 | 70 | 27 | 12 | 12 | 14 | 12 |
| Nitric Acid..... | 40 | 40 | 41 | 41 | 43 | 44 | 46 | 47 | 46 | 45 | 42 | 39 |
| Total | 96 | 99 | 95 | 100 | 110 | 111 | 116 | 74 | 58 | 57 | 56 | 51 |

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 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001). Totals may not equal sum of components due to independent rounding.

Sources: Data sources and methods documented in Appendix A, "Estimation Methods."

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

Overview

Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2001

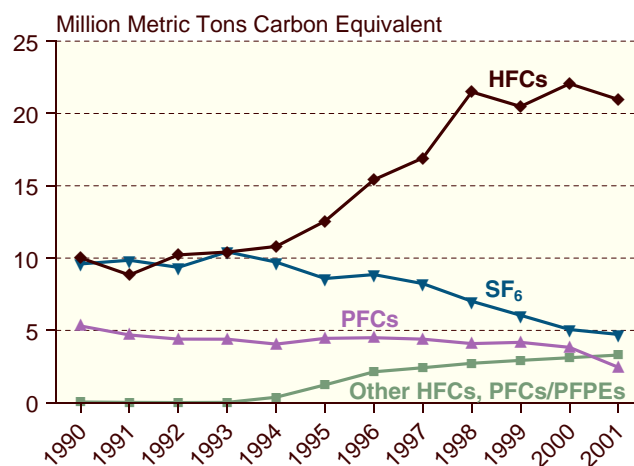
| | |
|---|-------|
| Estimated 2001 Emissions (Million Metric Tons Carbon Equivalent) | 31.4 |
| Change Compared to 2000 (Million Metric Tons Carbon Equivalent) | -2.6 |
| Change from 2000 (Percent) | -7.7% |
| Change Compared to 1990 (Million Metric Tons Carbon Equivalent) | 6.5 |
| Change from 1990 (Percent) | 25.9% |

In addition to the three principal greenhouse gases (carbon dioxide, methane, and nitrous oxide), there are other gases that account for 1.7 percent of U.S. greenhouse gas emissions when weighted by 100-year global warming potential (GWP).⁷² The U.S. Environmental Protection Agency (EPA) estimates total emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) in 2001 at 31.4 million metric tons carbon equivalent—a 7.7-percent decrease over 2000 emissions and a 25.9-percent increase over 1990 emissions. Table 29 summarizes U.S. emissions of HFCs, PFCs, and SF₆ from 1990 to 2001, and Table 30 shows the corresponding emissions in metric tons carbon equivalent.

In summary, revised EPA data for 1990-2000 and new estimates for 2001 show that emissions of HFCs have risen overall except for a decline in 2001; annual emissions of PFCs were nearly unchanged from 1990 through 1999 and declined in 2000 and 2001; and SF₆ emissions have dropped by more than half (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 chemicals that are being phased out under the Montreal Protocol because they damage the Earth's stratospheric ozone layer (see box on page 62).⁷³ CFCs had been widely used as refrigerants, aerosol propellants, and foam blowing agents for many years, but with U.S. CFC production virtually ceasing by 1996, HFCs have been introduced into the market to fill the void in many key applications. 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. Emissions of perfluoropolyethers (PFPEs) have been rising since 1990 because of the recent commercial introduction of new PFPEs for use in various applications in the solvent cleaning industry. PFC

Figure 5. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2001



Source: Estimates presented in this chapter.

⁷²Preliminary data estimates received by EIA from the U.S. Environmental Protection Agency (EPA), Office of Air and Radiation, September 2002. Note that EIA calculates emissions in carbon-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.

⁷³In 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 Appendix D, "Emissions Sources Excluded."

Alternatives to Chlorofluorocarbons: Lowering Ozone Depletion Potentials vs. Raising Global Warming Potentials

The first international agreement of global cooperation to protect the stratospheric ozone layer was the Montreal Protocol on Substances that Deplete the Ozone Layer, signed in September 1987. In 1990, the Parties to the Protocol agreed to a phaseout of controlled substances—including chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—between 1994 and 2040, depending in each case on the substance and the country. The U.S. Environmental Protection Agency (EPA), through its authority under the Clean Air Act, accelerated the phaseout schedule of some of the gases.

The phaseout of ozone-depleting substances fostered the development of alternative fluorocarbons, such as hydrofluorocarbons (HFCs) and HCFCs. Both HCFCs and HFCs are considered environmentally superior because they are largely destroyed in the lowest region of the atmosphere and do not increase the atmospheric loading of chlorine that leads to ozone depletion.^a Although HCFCs do contain chlorine, they are mostly destroyed before reaching the stratospheric ozone layer. Also, HCFC compounds are only partially halogenated. Their hydrogen-carbon bonds are more vulnerable to oxidation in the troposphere, and therefore they pose only one-tenth to one-hundredth the threat that CFCs pose to the stratospheric ozone layer.^b

The Ozone Depletion Potential (ODP) index was created to evaluate the relative effects of comparable emissions of these compounds and assist in setting regulatory policy. The ODP of a compound is a fixed value calculated as 1 kilogram of the compound divided by the ODP of 1 kilogram of CFC-11.^c

Concern over global environmental issues began to push climate change onto the international agenda in the mid-1980s and led to the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC created the global warming potential (GWP) index to compare the relative radiative forcing effects of greenhouse gases on the atmosphere. The GWP of a compound approximates the time-integrated warming effect of an emission of a gas relative to that of an emission of an equivalent mass of carbon dioxide (e.g., 100 years). The ODPs and GWPs for various

CFCs, HCFCs, and HFCs are shown in the figures on the opposite page.

While the Montreal Protocol and related regulations cause an industry transition that lowers emissions of high-ODP gases, it increases the emissions of high-GWP gases, particularly in the case of many HCFCs replaced by HFCs. On the other hand, international negotiations by the United Nations Framework Convention on Climate Change (UNFCCC) aim to stabilize atmospheric concentrations of greenhouse gases. Stabilization of concentrations would require lowering of global emissions of greenhouse gases that could be rising as a result of other international agreements. This illustrates the difficulty of balancing conflicting environmental goals.

Although the Montreal Protocol has had success in reversing stratospheric chlorine levels and ozone depletion, it may be increasing the atmospheric concentrations of replacement gases with high GWPs, which would disproportionately raise greenhouse gas emissions—in opposition to the goals of the UNFCCC. The two indexes, ODP and GWP, compare different chemical reactions in the atmosphere and different atmospheric impacts and therefore cannot be combined into a system to prioritize atmospheric pollutants by contrasting disparate qualitative environmental impacts.^d Neither index can be viewed in isolation, however, as progress in one area can affect the other.

The importance of this issue has been recognized internationally by the UNFCCC, the IPCC, and the Technology and Assessment Panel (TEAP) of the Montreal Protocol. In November 1998, at UNFCCC negotiations, the relationship between efforts to protect the stratospheric ozone layer and mitigate climate change was placed on the agenda. At the November 2002 COP-8 meetings in New Delhi, the Parties reached a decision to address “efforts to protect the stratospheric ozone layer and efforts to safeguard the global climate system, issues relating to hydrofluorocarbons and perfluorocarbons” that requests the IPCC and TEAP “to develop a balanced scientific, technical, and policy-relevant special report . . . by early 2005.”^e

(continued on page 63)

^aA.R. Ravishankara, A.A. Turnipseed, N.R. Jensen, S. Barone, M. Mills, C.J. Howard, and S. Solomon, “Do Hydrocarbons Destroy Stratospheric Ozone?” *Science*, Vol. 263 (1994), pp. 71-75.

^bU.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.

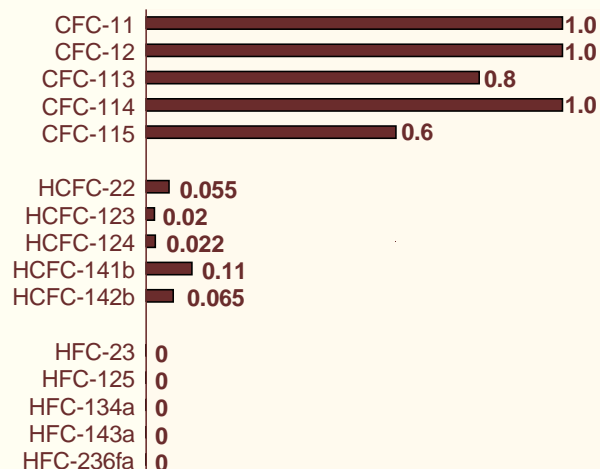
^cAlternative Fluorocarbons Environmental Acceptability Study, “Atmospheric Chlorine: CFCs and Alternative Fluorocarbons,” web site www.afeas.org/atmospheric_chlorine.html.

^dT.P. Seager and T.L. Theis, “A Thermodynamic Basis for Evaluating Environmental Policy Trade-offs,” *Clean Technology and Environmental Policy*, Vol. 4, No. 3 (2002).

^eUnited Nations Framework Convention on Climate Change, 8th Session of the Conference of the Parties, Decision_CP.8, web site http://unfccc.int/cop8/latest/15_sbsta19add1.pdf.

Alternatives to Chlorofluorocarbons: Lowering Ozone Depletion Potentials vs. Raising Global Warming Potentials (Continued)

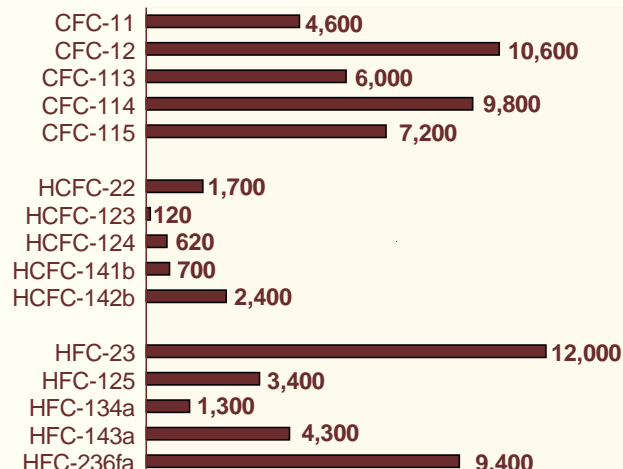
Ozone Depletion Potentials for CFCs and Alternatives (HCFCs and HFCs)



Note: The HCFCs and HFCs listed above are the substances studied by the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS). All HFCs have ODPs equal to zero.

Source: Alternative Fluorocarbons Environmental Acceptability Study, "Atmospheric Chlorine: CFCs and Alternative Fluorocarbons" (2002), web site www.afeas.org/atmospheric_chlorine.html.

Global Warming Potentials for CFCs and Alternatives (HCFCs and HFCs)



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

emissions from the aluminum industry have been falling, and the decrease is only partially offset by increases in PFC emissions from the semiconductor industry. Emissions of SF₆ have declined overall as a result of industry efforts to reduce emissions, mostly from utilities and magnesium processors, and because of the rising cost of the gas.⁷⁴

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.⁷⁵ 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 absorption in the atmosphere, and long atmospheric lifetimes.⁷⁶ 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 of the HFCs, with a GWP of 12,000, while other HFCs have GWPs in the range of 100 to 10,000.⁷⁷

The emissions estimates in Table 29 are taken from data supplied by the EPA's Office of Air and Radiation.⁷⁸ 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-equivalent units by EIA, using GWP values from

⁷⁴U.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.

⁷⁵See Chapter 1, Table 1. Naturally occurring (pre-industrial) emissions of perfluoromethane (CF₄) were 40 parts per trillion. Their concentration had doubled by 1998.

⁷⁶See discussion of relative forcing effects of gases in Chapter 1.

⁷⁷Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

⁷⁸Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2002.

the IPCC's 2001 Third Assessment Report. The 2001 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 and new data for SF₆ (see boxes on pages 65 and 66). The revisions are reflected in the emissions estimates presented in this chapter.

Hydrofluorocarbons (HFCs)

U.S. Emissions of Hydrofluorocarbons, 1990-2000

| | |
|---|--------|
| Estimated 2001 Emissions (Million Metric Tons Carbon Equivalent) | 21.0 |
| Change Compared to 2000 (Million Metric Tons Carbon Equivalent) | -1.1 |
| Change from 2000 (Percent) | -5.0% |
| Change Compared to 1990 (Million Metric Tons Carbon Equivalent) | 11.0 |
| Change from 1990 (Percent) | 109.4% |

Since 1990, HFC emissions have accounted for a growing share (66.7 percent in 2001) of total carbon-equivalent emissions of HFCs, PFCs, and SF₆ combined. The EPA estimates U.S. emissions of all HFCs in 2001 at 21.0 million metric tons carbon equivalent, a 5.0-percent decrease from 2000 emissions and a 109.4-percent increase from 1990.⁷⁹ The decrease in 2001 is attributable solely to a drop in HFC-23 emissions from HCFC-22 production. Emissions of all other HFCs, most notably HFC-134a, have risen steadily 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 as solvents, domestic and commercial refrigerants, firefighting agents, propellants for pharmaceutical and industrial aerosols, foam blowing agents, and in blends for air conditioning refrigerants.

⁷⁹Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2002. Note that EIA calculates emissions in carbon-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.

⁸⁰European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/others/firefighting/main_appli/main.htm.

⁸¹European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/insulation/main_appli/main.htm.

⁸²Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2002.

⁸³Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

⁸⁴U.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.

⁸⁵C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

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. 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.⁸⁰ 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.⁸¹

Trifluoromethane (HFC-23)

The EPA estimates 2001 emissions of HFC-23 at 1,760 metric tons of gas.⁸² Annual emissions have fluctuated since 1990, before dropping by 32.6 percent in 2001. Although emissions of HFC-23 are relatively small, its high GWP (12,000)⁸³ gives it a substantial potential climatic effect. HFC-23 is created as a byproduct in the production of chlorodifluoromethane (HCFC-22) and is generally vented to the atmosphere. In some cases it is captured for use in a limited number of applications. While production of HCFC-22 continues to grow (by 35 percent from 1990 to 2000), emissions of HFC-23 from this source have declined (by 15 percent from 1990 to 2000), and the intensity of HFC-23 emissions (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined by 37 percent from 1990 to 2000.⁸⁴

HCFC-22 continues to dominate the refrigerant market for stationary refrigeration and air conditioning (including chillers, room and household (central) air conditioners, and dehumidifiers).⁸⁵ HCFC-22 is also used as a blowing agent component for polyurethane foams and extruded polystyrene foams. 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, although its production for use as a feedstock in the production of other

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.

^aU.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, EPA-430-R-02-003 (Washington, DC, April 2002), Annex J, web site www.epa.gov.

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.

chemicals (fluorinated polymers) will be allowed to continue indefinitely.⁸⁶

Tetrafluoroethane (HFC-134a)

According to EPA estimates, emissions of HFC-134a, which has a GWP of 1,300,⁸⁷ have grown from 564 metric tons in 1990 to 31,552 metric tons in 2001.⁸⁸ The 2001 estimate is 9.2 percent higher than that for 2000. Since 1994, HFC-134a has been the automobile 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.

Automobile air conditioners are subject to leakage, with sufficient refrigerant leaking (15 to 30 percent of the charge) over a 5-year period to require servicing. On its Form EIA-1605, General Motors (GM) reported total HFC-134a emissions of about 2,566 metric tons of gas in 1999.⁸⁹ GM based its estimate on an assumed annual leakage rate from mobile sources of 10 percent per year. With GM vehicles accounting for about one-third of the

U.S. light-duty fleet,⁹⁰ the GM emissions estimate implies that total U.S. HFC-134a emissions from mobile air conditioners were equal to about 7,700 metric tons in 1999. Emissions from this source are expected to continue to increase in the near future, as the replacement of vehicles using CFCs proceeds at a rapid pace.

In addition to its use in all new automobiles, an automotive aftermarket for HFC-134a has also developed. Spurred by rising prices for CFC-12, 5 million cars were retrofitted for HFC-134a use in 1997.⁹¹ This trend toward retrofitting is expected to continue, given that CFC-12 is no longer produced, remaining inventories are being depleted, and CFC-12 prices are expected to rise.⁹² Furthermore, many of the air conditioners in mid-1990s vehicle models (which were among the first automobiles to use HFC-134a) are now due to be serviced. In 1999, a spokesperson for Elf Atochem North America estimated the U.S. aftermarket for HFC-134a at 45 to 50 million pounds, or roughly 35 percent of total annual demand. He believed that, as the market for HFC-134a matures, the aftermarket eventually would be about twice the size of the original equipment market.⁹³ The automotive aftermarket is already responsible for much of the growth in current HFC-134a demand.⁹⁴

⁸⁶U.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.

⁸⁷Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

⁸⁸Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2002.

⁸⁹Form EIA-1605 is a greenhouse gas emissions and emissions reductions reporting form, which is submitted to EIA on a voluntary basis by entities interested in creating a public record of their emissions reduction activities.

⁹⁰American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures 96* (Detroit, MI, 1999).

⁹¹"Fluorocarbon Outlook Turns Bullish," *Chemical Market Reporter* (May 25, 1998).

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

⁹³"HFC-134a Prices Rise as Market Tightens," *Chemical Market Reporter* (March 15, 1999).

⁹⁴J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

HFC-134a is also used in refrigerant blends (e.g. R-404A) in most new refrigerators 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 non-flammability, thermal and chemical stability, excellent

dielectric properties, high material compatibility, low surface tension and viscosity, and high liquid density. HFC-134a, in particular, is used in special extraction processes to produce important natural active pharmaceuticals, such as taxol for breast cancer treatment, nutraceuticals, flavors, and fragrances.⁹⁵

According to the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), worldwide sales of HFC-134a for short-term applications jumped almost fourfold between 1994 and 1995. Sales for short-term uses leveled off at 10,500 metric tons in 1996 and then dropped to 6,500 metric tons in 1998; however, new developments in the U.S. market have reversed the

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 for 2002, which includes emissions estimates through 2001, incorporates a number of revisions to the estimates of HFC, PFC, and SF₆ emissions before 2000. 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:

- The EPA Voluntary SF₆ Emissions Reduction Partnership to reduce emissions of SF₆ from equipment used to transmit and distribute electricity has new information from its 1999 and 2000 reporters. This, in addition to new information on world sales of SF₆ to electric power systems from 1990 to 1999, has reduced the uncertainty in estimates of SF₆ emissions from electric power systems, resulting in changes from the previously estimated trends in both magnitude and direction. According to the revised estimates, those emissions were nearly unchanged from 1990 to 1994 and decreased from 1995 to 2001.
- The Voluntary Aluminum Industrial Partnership Program and EPA's Climate Protection Partnerships Division continually revise the estimation methods for emissions from aluminum production and the models used to calculate emissions. New

information on aluminum production (smelters) and anode effects led to revisions of the estimates for PFC emissions from 1990 to 1999. The revisions show an average 2.8-percent annual decrease in CF₄ and C₂F₆ emissions.

- The methodology for estimating emissions from semiconductor manufacturing has been changed to one based on total annual emissions reported by participants in the PFC Emission Reduction Partnership for the Semiconductor Industry program. The revisions resulted in an average 1.5-percent decrease in annual HFC, PFC, and SF₆ emissions from semiconductor manufacturing for 1990 to 1999.
- For ozone-depleting substance (ODS) substitutes, revisions to chemical substitution trends and new information from industry representatives have led to revised assumptions for the EPA's Vintaging Model, particularly in the areas of cleaning solvents, stationary refrigeration, and fire extinguishing equipment. The revisions resulted in an average 10.6-percent decrease in annual emissions of HFCs, PFCs, and SF₆ from their use as ODS substitutes for 1994 to 1999.
- EPA's correction of an error in the conversion of gigagrams (Gg) of HFC-23 to teragrams (Tg) of carbon dioxide equivalent affected the EPA estimates of HFC-23 emissions from HCFC-22 production for 1990 to 1998. The revision resulted in an average decrease of less than 0.1 percent in annual HFC-23 emissions from the production of HCFC-22.

^aU.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.

⁹⁵European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/solvents/main_appli/main.htm.

downward trend, as sales of HFC-134a totaled 14,300 metric tons in 1999.⁹⁶

In January 1999, the major marketers of tire inflators began requiring the use of nonflammable material, creating additional demand for HFC-134a. Pennzoil was the first company to enter this new market, after removing its hydrocarbon-based canisters and reconfiguring them to use HFC-134a.⁹⁷

For many years, the HFC-134a market was characterized by excess capacity and low prices, because the transition away from CFC-12 occurred more slowly than producers had expected.⁹⁸ In 1998 and 1999, however, the market tightened considerably, as evidenced by a series of price increases. Driven in part by a demand surge triggered by an unusually hot summer in 1999, prices nearly doubled, rising from a low of \$1.50 per pound to \$2.50 per pound by September 1999. For the rest of 1999 and the first half of 2000, the market stabilized, with only one minor price increase in early 2000.

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. According to a representative of Elf Atochem, the market will face significant supply shortages unless more investment in new capacity is undertaken over the next several years.⁹⁹ The required capacity will presumably be built, but it is possible that the expansion in supply will lag behind the growth in demand. Anticipating and planning for this growth has proven to be a difficult challenge for producers, who must manage as best as possible an unprecedented transition from an established product (CFC-12) which is being phased out under a global treaty, to a new product (HFC-134a). In the long term, consumption and emissions of HFC-134a will continue to rise rapidly, although it is possible that capacity constraints may act as a brake on consumption in the near term.

Difluoroethane (HFC-152a)

Estimates of HFC-152a emissions are not provided by the EPA because the data are considered confidential and could affect business practices. As a non-ozone-depleting substance with a GWP of 120,¹⁰⁰ HFC-152a is an attractive potential replacement for CFCs. It can be used as an aerosol propellant, a blowing agent, an ingredient in refrigerant blends (e.g., in R-500), and in fluoropolymer manufacturing applications. There are no HFC-152a emissions associated with the latter application, because the HFC-152a is consumed in the manufacturing process. In 1996, 5 million pounds of HFC-152a was consumed in fluoropolymer manufacturing.¹⁰¹ HFC-152a is also compatible with the components used in aerosol products. Unlike CFCs, however, HFC-152a is flammable.

Only one U.S. company (DuPont) produces HFC-152a, using the trade name Dymel-152a. DuPont probably was producing HFC-152a at nearly full capacity in 1994, corresponding to production of about 8,000 metric tons. In 1995, the company reported having doubled its production capacity from 1992 levels to 15,875 metric tons.¹⁰² The company reported to EIA's Voluntary Reporting of Greenhouse Gases Program that HFC-152a emissions peaked in 1994 at 181.4 metric tons and dropped to 45.4 metric tons in 2001.

Other HFCs

Other hydrofluorocarbons with considerable radiative forcing potential include HFC-125, HFC-143a, HFC-227ea, HFC-236fa, and HFC-4310mee, with 100-year GWPs of 3,400, 4,300, 3,500, 9,400, and 1,500, respectively.¹⁰³ The EPA estimates total emissions of this group of "other HFCs" (including HFC-152a, HFC-227ea, and HFC-4310mee but not HFC-32, HFC-125, HFC-134a, or HFC-236fa) at 3.3 million metric tons carbon equivalent in 2001, representing 10.5 percent of all emissions of HFCs, PFCs, and SF₆ reported.¹⁰⁴ Emissions of these HFCs are small but growing rapidly, as they continue to find applications as substitutes for

⁹⁶Alternative Fluorocarbons Environmental Acceptability Study, Production, Sales and Atmospheric Release, web site www.afeas.org/prodsales_download.html.

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

⁹⁸C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

⁹⁹J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

¹⁰⁰Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

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

¹⁰²"DuPont Set To Expand Markets for Ozone-Safe HFC-152a Product," *Ozone Depletion Online Today* (Alexandria, VA, June 9, 1995).

¹⁰³Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 388.

¹⁰⁴Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2002. Note that EIA calculates emissions in carbon-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.

Other Gases

CFCs and HCFCs. Emissions of “other HFCs” have increased by 6.0 percent since 2000.

The EPA estimates emissions of HFC-125 (pentafluoroethane) at 236 metric tons of gas in 1992, increasing to 1,869 metric tons in 2001.¹⁰⁵ The estimate for 2001 is 19.9 percent higher than the estimate for 2000.¹⁰⁶ 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 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, Honeywell expects a rapid increase in the demand for R-410A.¹⁰⁷ HFC-125 can also be used as a firefighting agent.

The EPA estimates 1993 emissions of for HFC-143a (trifluoroethane) at 12 metric tons of gas, increasing to 1,142 metric tons in 2001. The 2001 estimate is 26.5 percent higher than the estimate for 2000.¹⁰⁸ HFC-143a is a halocarbon used in blends for commercial refrigeration and air conditioning, such as R-404A, R-406A, R-408A, and R-507A. HFC-143a 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, its GWP is lower than those of the gases it replaces, such as CFC-11.

The EPA estimates 1997 emissions of HFC-236fa (hexafluoropropane) at 15 metric tons of gas, increasing to 370 metric tons in 2001. The estimate for 2001 is 24.8 percent higher than the estimate for 2000.¹⁰⁹ HFC-236fa is also used as a refrigerant, in particular by the U.S. Navy for shipboard applications.¹¹⁰ In another application, HFC-236fa is used as a firefighting agent.

Other HFCs and HFC blends are also likely to gain market share as a result of the phaseout of CFCs and HCFCs, because no single product is suited for all applications. For example, each potential replacement product has an optimal operating temperature range; hence,

the refrigerant best suited for use in ice cream freezers will differ from the best choice for milk coolers.¹¹¹

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.¹¹² 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, to become fully operational in 2002.¹¹³ Honeywell is also developing blends that combine HFC-245fa with other materials to enhance its cost/performance ratio. To date, however, the foam blowing industry has failed to signal a clear preference for HFC-245fa or other alternatives. Instead, it continues to rely primarily on HCFC-141b while waiting to see which of the possible replacement candidates emerges as the preferred alternative.¹¹⁴ For some applications, non-fluorochemical alternatives (e.g., hydrocarbons) have been identified.¹¹⁵

Perfluorocarbons (PFCs)

U.S. Emissions of Perfluorocarbons, 1990-2001

| | |
|---|--------|
| Estimated 2001 Emissions (Million Metric Tons Carbon Equivalent) | 2.4 |
| Change Compared to 2000 (Million Metric Tons Carbon Equivalent) | -1.4 |
| Change from 2000 (Percent) | -36.1% |
| Change Compared to 1990 (Million Metric Tons Carbon Equivalent) | -2.9 |
| Change from 1990 (Percent) | -53.9% |

The EPA estimates 2001 emissions of PFCs at 2.4 million metric tons carbon equivalent, 53.9 percent lower than

¹⁰⁵Preliminary data estimates received by EIA from the EPA’s Office of Air and Radiation, September 2002.

¹⁰⁶Preliminary data estimates received by EIA from the EPA’s Office of Air and Radiation, September 2002.

¹⁰⁷J. Ouellette, “Fluorocarbon Market Is Poised To Grow,” *Chemical Market Reporter* (June 19, 2000).

¹⁰⁸Preliminary data estimates received by EIA from the EPA’s Office of Air and Radiation, September 2002.

¹⁰⁹Preliminary data estimates received by EIA from the EPA’s Office of Air and Radiation, September 2002.

¹¹⁰E-mail correspondence with the Office of Policy, U.S. Department of Energy, October 18, 2000.

¹¹¹C. Boswell, “Hydrofluorocarbons Build with Transition Away from CFCs,” *Chemical Market Reporter* (September 13, 1999).

¹¹²C. Boswell, “Hydrofluorocarbons Build with Transition Away from CFCs,” *Chemical Market Reporter* (September 13, 1999).

¹¹³Honeywell International Inc., *Focused on Performance: Annual Report 2001*, web site www.honeywell.com/investor/otherpdfs/hon2001annualfnl.pdf (Morristown, NJ, March 2002), p. 9.

¹¹⁴C. Boswell, “Hydrofluorocarbons Build with Transition Away from CFCs,” *Chemical Market Reporter* (September 13, 1999).

¹¹⁵J. Ouellette, “Fluorocarbon Market Is Poised To Grow,” *Chemical Market Reporter* (June 19, 2000).

1990 emissions (Table 30).¹¹⁶ The decrease is the result of improvements in the aluminum industry, which creates PFCs as byproducts; all increases in PFC emissions are from industrial applications, such as 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])¹¹⁷ have drawn attention. PFCs are also characterized by long atmospheric lifetimes (up to 50,000 years); hence, unlike HFCs, they are essentially permanent additions to the atmosphere. PFCs are used in semiconductor manufacturing and as heat transfer fluids (dielectric liquids) for indirect contact cooling of electronics.¹¹⁸

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 551 metric tons of perfluoromethane and 60 metric tons of perfluoroethane in 2001.¹¹⁹ Reductions in primary aluminum production and efficiency improvements to reduce anode effects leading to process inefficiency have reduced emissions of perfluoromethane and perfluoroethane from this source by 77.4 percent and 75.9 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 2001 as a result of cutbacks in smelter production, which in turn were caused by increased energy costs and reduced energy supply in the Pacific Northwest.¹²⁰

Another source of PFC emissions is semiconductor manufacturing. For 2001, the EPA estimates emissions of perfluoromethane and perfluoroethane from

semiconductor manufacturing at 217 metric tons and 326 metric tons of gas, respectively.¹²¹ Both estimates reflect the rapid growth of the semiconductor industry in the 1990s, which resulted in increases of 95.5 percent and 94.9 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 captured, 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, manufactured by Air Products).¹²²

It is difficult to assess trends in PFC emissions from the semiconductor industry. On the one hand, the continued expansion of the worldwide semiconductor market may lead to increased PFC use and emissions. On the other hand, voluntary industry efforts to curb emissions are helping to offset production increases to some extent. The semiconductor industry has introduced new methods to slow or even reverse the increase in PFC emissions.

The global semiconductor industry has also committed to further reductions in PFC emissions. In 1999, the World Semiconductor Council, consisting of manufacturers from Europe, the United States, Japan, and Korea, voluntarily committed to reduce emissions of PFCs by 10 percent from 1995 levels by 2010.¹²³ A number of semiconductor manufacturing firms also participate in the EPA's PFC Emission Reduction Partnership for the Semiconductor Industry with the goal of voluntarily reducing PFC emissions and reporting to the EPA.¹²⁴

Sulfur Hexafluoride (SF₆)

The most recent EPA estimates show a steady decrease in U.S. emissions of sulfur hexafluoride (SF₆), from a

¹¹⁶Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2002. Note that EIA calculates emissions in carbon-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.

¹¹⁷Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

¹¹⁸European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?chfamilies/PFCs/prod_main/prod.htm.

¹¹⁹Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2002.

¹²⁰U.S. Geological Survey, Mineral Commodity Summaries (January 2001), web site <http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/050301.pdf>.

¹²¹Preliminary data estimates received by EIA from the EPA's Office of Air and Radiation, September 2002.

¹²²Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

¹²³World Semiconductor Council, "Position Paper Regarding PFC Emissions Reduction Goal," April 26, 1999, web site www.semiconductorcouncil.org/news/pfc.html.

¹²⁴U.S. Environmental Protection Agency, "Voluntary Aluminum Industrial Partnership," web site www.epa.gov/highgwp1/vaip/.

U.S. Emissions of Sulfur Hexafluoride, 1990-2001

| | |
|---|--------|
| Estimated 2001 Emissions (Million Metric Tons Carbon Equivalent) | 4.7 |
| Change Compared to 2000 (Million Metric Tons Carbon Equivalent) | -0.3 |
| Change from 2000 (Percent) | -6.7% |
| Change Compared to 1990 (Million Metric Tons Carbon Equivalent) | -4.9 |
| Change from 1990 (Percent) | -50.8% |

peak of 1,772 metric tons of gas in 1993 to 780 metric tons in 2001, representing an overall decrease of 50.8 percent since 1990.¹²⁵ 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. Emissions of SF₆ from uses in the semiconductor manufacturing industry have increased. Although it is not emitted in large quantities, SF₆ has a very high GWP of 22,200.¹²⁶

SF₆ is used primarily in electrical applications and 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.¹²⁷ In electrical transmission and distribution systems, SF₆ acts as an insulator 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.¹²⁸ Between 70 and

80 percent of global SF₆ production is used in electricity transmission and distribution.¹²⁹

Other applications that produce SF₆ emissions include magnesium and aluminum 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.¹³⁰ 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.¹³¹

In compiling its estimates, the EPA receives data from participants in the SF₆ Emissions 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.¹³²

¹²⁵Preliminary data estimates received by EIA from the EPA’s Office of Air and Radiation, September 2002.

¹²⁶Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), p. 389.

¹²⁷European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?chfamilies/SF6/prod_main/prod.htm.

¹²⁸U.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.

¹²⁹European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/electri_appli/main_appli/main.htm.

¹³⁰European Fluorocarbon Technical Committee, web site www.fluorocarbons.org/frame.htm?applications/electri_appli/main_appli/main.htm.

¹³¹Historically, 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.

¹³²U.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.

Table 29. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2001
(Thousand Metric Tons of Gas)

| Gas | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| 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 | 1.8 |
| HFC-125 | * | * | 0.2 | 0.5 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.6 | 1.9 |
| 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 |
| HFC-143a | * | * | * | * | 0.1 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 |
| HFC-236fa | * | * | * | * | * | * | * | * | 0.1 | 0.2 | 0.3 | 0.4 |
| Other HFCs | | | | | | | | | | | | |
| HFC-152a | W | W | W | W | W | W | W | W | W | W | W | W |
| HFC-227ea | W | W | W | W | W | W | W | W | W | W | W | W |
| HFC-4310mee | W | W | W | W | W | W | W | W | W | W | W | W |
| Perfluorocarbons | | | | | | | | | | | | |
| CF ₄ | 2.5 | 2.2 | 2.1 | 2.0 | 1.8 | 1.8 | 1.9 | 1.8 | 1.5 | 1.5 | 1.4 | 0.8 |
| C ₂ F ₆ | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 | 0.5 | 0.4 |
| C ₄ F ₁₀ | * | * | * | * | * | * | * | * | * | * | * | * |
| PFCs/PFPEs | W | W | W | W | W | W | W | W | W | W | W | W |
| Sulfur Hexafluoride | 1.6 | 1.6 | 1.5 | 1.7 | 1.6 | 1.4 | 1.5 | 1.4 | 1.2 | 1.0 | 0.8 | 0.8 |

*Less than 50 metric tons of gas.

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

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

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, September 2002).

Table 30. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2001
(Million Metric Tons Carbon Equivalent)

| Gas | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | P2001 |
|--------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Hydrofluorocarbons | | | | | | | | | | | | |
| HFC-23 | 9.8 | 8.6 | 9.8 | 8.9 | 8.9 | 7.6 | 8.8 | 8.5 | 11.4 | 8.7 | 8.5 | 5.8 |
| HFC-125 | * | * | 0.2 | 0.4 | 0.3 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.7 |
| HFC-134a | 0.2 | 0.2 | 0.2 | 1.0 | 1.6 | 4.3 | 5.7 | 7.1 | 8.2 | 9.3 | 10.2 | 11.2 |
| HFC-143a | * | * | * | * | 0.1 | 0.1 | 0.2 | 0.4 | 0.6 | 0.8 | 1.1 | 1.3 |
| HFC-236fa | * | * | * | * | * | * | * | * | 0.3 | 0.5 | 0.8 | 0.9 |
| Total | 10.0 | 8.8 | 10.2 | 10.4 | 10.8 | 12.6 | 15.4 | 16.9 | 21.5 | 20.5 | 22.1 | 21.0 |
| Perfluorocarbons | | | | | | | | | | | | |
| CF ₄ | 4.0 | 3.5 | 3.2 | 3.1 | 2.8 | 2.9 | 3.0 | 2.7 | 2.4 | 2.4 | 2.1 | 1.2 |
| C ₂ F ₆ | 1.4 | 1.2 | 1.2 | 1.2 | 1.2 | 1.6 | 1.5 | 1.7 | 1.7 | 1.8 | 1.7 | 1.3 |
| C ₄ F ₁₀ | * | * | * | * | * | * | * | * | * | * | * | * |
| Total | 5.3 | 4.7 | 4.4 | 4.4 | 4.1 | 4.5 | 4.5 | 4.4 | 4.1 | 4.2 | 3.8 | 2.4 |
| Other HFCs, PFCs/PFPEs | * | * | * | * | 0.4 | 1.2 | 1.0 | 2.4 | 2.7 | 2.9 | 3.1 | 3.3 |
| Sulfur Hexafluoride | 9.6 | 9.9 | 9.4 | 10.4 | 9.7 | 8.6 | 8.9 | 8.2 | 7.0 | 6.0 | 5.1 | 4.7 |
| Total Emissions | 25.0 | 23.4 | 24.0 | 25.3 | 25.0 | 26.8 | 30.9 | 32.0 | 35.3 | 33.6 | 34.1 | 31.4 |

*Less than 50,000 metric tons carbon equivalent.

P = preliminary data.

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

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, September 2002).

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.¹³³ The U.S. Environmental Protection Agency (EPA) estimates annual U.S. carbon sequestration for the year 2000 at 246 million metric tons carbon equivalent, a decline of approximately 17.7 percent from the 299 million metric tons carbon equivalent sequestered in 1990 (Table 31). Between 1990 and 2000, land use change and forestry practices represented an offset of approximately 15.4 percent of total U.S. anthropogenic carbon dioxide emissions.

Land Use Change and Forestry Carbon Sequestration

The EPA’s estimates for carbon sequestration from land use change and forestry in 2000 include four main components: (1) changes in forest carbon stocks (210 million metric tons carbon equivalent or 85.4 percent of the total), (2) changes in agricultural soil carbon stocks (18 million metric tons carbon equivalent or 7.3 percent of the total), (3) changes in carbon stocks in urban trees (16 million metric tons carbon equivalent or 6.5 percent of

Table 31. Net Carbon Dioxide Sequestration from U.S. Land Use Change and Forestry, 1990 and 1995-2000
(Million Metric Tons Carbon Equivalent)

| Component | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|-------------------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Forests | 268 ^a | 267 ^a | 267 ^b | 207 ^b | 205 ^b | 208 ^b | 210 ^b |
| Urban Trees | 16 ^a | 16 ^a | 16 ^a | 16 ^a | 16 ^a | 16 ^a | 16 ^a |
| Agricultural Soils | 10 ^a | 16 ^a | 16 ^a | 17 ^b | 18 ^b | 19 ^b | 18 ^b |
| Landfilled Yard Trimmings | 5 ^a | 3 ^a | 3 ^a | 3 ^b | 2 ^b | 2 ^b | 2 ^b |
| Total | 299^a | 303^a | 302^b | 242^b | 242^b | 245^b | 246^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 1990-2000*, EPA-430-R-02-003 (Washington, DC, April 2002), web site www.epa.gov.

¹³³Intergovernmental 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.

Global Estimates of Carbon Sequestration Through Land Use and Forestry Activities

Two recent studies have attempted to estimate global levels of carbon sequestration. A 2000 report by the Intergovernmental Panel on Climate Change (IPCC) on land use, land use change and forestry (LULUCF) activities provides a range of values for global carbon sequestration attributable to land use and forestry practices. The IPCC maintains that accounting for the amount of carbon being sequestered annually involves a high degree of uncertainty due to lack of data and to difficulties in measuring sequestration. Further, the report states that there are policy and accounting uncertainties regarding which aspects of the biological carbon cycle should be included in national inventories as anthropogenic emissions and removals. Nevertheless, the IPCC does provide values for carbon sequestration attributable to LULUCF activities.^a

The report provides estimates for carbon stock changes resulting from LULUCF activities under IPCC guidelines and, alternatively, under three United Nations Food and Agriculture Organization (FAO) "definitional scenarios." The FAO definitional scenarios are based on different accounting methods, which assume that area conversion rates remain constant and exclude carbon in soils and wood products. All the accounting scenarios provide estimates for sequestration within UNFCCC Annex I countries^b during the first commitment period (2008-2012) of the Kyoto Protocol. The FAO scenarios include the harvest/regeneration cycle, because regeneration is defined as reforestation. Three FAO accounting approaches are distinguished:

- In the FAO *Land-Based I Accounting Scenario*, the stock change over the full commitment period is measured, including stock losses during harvest, as well as delayed emissions from dead organic matter for reforestation. This approach results in estimated Annex I emissions of 333 to 849 million metric tons carbon equivalent per year from land use and forestry activities.
- In the FAO *Land-Based II Accounting Scenario*, the carbon stock change between the beginning of the activity and the end of the commitment period is

measured, including decay from harvest. This approach results in estimates for the Annex I countries that range from net sequestration of 205 million metric tons carbon equivalent per year to net emissions of 280 million metric tons carbon equivalent per year from land use and forestry activities.

- In the FAO *Activity-Based Accounting Scenario*, only the accumulation of carbon in new forest stands and new dead organic matter is counted under reforestation. This approach results in estimates for the Annex I countries that range from net sequestration of 483 million metric tons carbon equivalent per year to net emissions of 3 million metric tons carbon equivalent per year from land use and forestry activities.

Other global studies also provide a wide range of estimates of carbon sequestration. A working paper developed by the CICERO Center for International Climate and Environmental Research indicates that, globally, the area available for forest plantations could range from 345 million to 510 million hectares, and that an estimated 2.9 billion metric tons of carbon per year can be removed from the atmosphere in forest plantations.^c In contrast, a 1991 study by Nordhaus^d suggests that approximately 0.3 billion metric tons of carbon could be captured annually over a period of 75 years. The fact that the estimates from the two studies differ by a full order of magnitude illustrates the difficulties and uncertainties involved in estimating carbon sequestration.

The table on the opposite page shows estimates of annual carbon sequestration totals for Annex I and non-Annex I countries that could result from LULUCF activities under the Kyoto Protocol. According to those estimates, more than 300 million metric tons of carbon sequestration "credits" could be made available annually through LULUCF activities in the Annex I countries, and the potential for sequestration is much greater in the non-Annex I countries. The greatest potential for carbon sequestration is in forestry-related activities.^e

(continued on page 75)

^aIntergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 4, web site www.ipcc.ch/pub/srlulucf-e.pdf.

^bAs designated in the United Nations Framework Convention on Climate Change (UNFCCC).

^cH. Kolshus, *Carbon Sequestration in Sinks: An Overview of Potential and Costs*, CICERO Working Paper 2001: 11 (Oslo, Norway: CICERO Center for International Climate and Environmental Research, November 2001), web site www.cicero.uio.no/media/1616.pdf.

^dW.D. Nordhaus, "The Cost of Slowing Climate Change: A Survey," *The Energy Journal*, Vol. 12, No. 1 (1991), pp. 37-65.

^eH. Kolshus, *Carbon Sequestration in Sinks: An Overview of Potential and Costs*, CICERO Working Paper 2001: 11 (Oslo, Norway: CICERO Center for International Climate and Environmental Research, November 2001), web site www.cicero.uio.no/media/1616.pdf.

Global Estimates of Carbon Sequestration Through Land Use and Forestry Activities (Continued)

Estimates of Annual Carbon Sequestration Through LULUCF Activities by 2010 Under Provisions of the Kyoto Protocol

(Million Metric Tons Carbon per Year)

| Activities | Annex I Countries | Non-Annex I Countries |
|--|-------------------|-----------------------|
| Article 3.3 | | |
| Reduced Deforestation | 60 (0-90) | 1,698 |
| Afforestation and Reforestation | 26 (7-46) | 373 (190-538) |
| Article 3.4 | | |
| Croplands (e.g., reduced tillage, erosion control) | 75 | 50 |
| Forests (e.g., enhanced regeneration, fertilization) | 101 | 69 |
| Grazing Lands (e.g., herd, fire, and wood management) | 69 | 168 |
| Agroforests (e.g., management of trees in agriculture) | 12 | 14 |
| Urban land (e.g., tree, waste and wood product management) | 1 | 1 |
| Deforested Land to Agroforest Instead of Pasture/Crop | 0 | 391 |
| Severely Degraded Land to Crop, Grass, or Forest land | 1 | 3 |
| Cropland to Grassland | 24 | 14 |
| Total for Article 3.4 | 300 | 710 |

Notes: Numbers in parentheses represent a range of estimates. Quantities for Articles 3.3 and 3.4 cannot be summed, because they may apply for the same area. Totals may not equal sum of components due to independent rounding.

Sources: H. Kolshus, *Carbon Sequestration in Sinks: An Overview of Potential and Costs*, CICERO Working Paper 2001: 11 (Oslo, Norway: CICERO Center for International Climate and Environmental Research, November 2001), p. 6, web site www.cicero.uio.no/media/1616.pdf; I. Noble and R.J. Scholes, "Sinks and the Kyoto Protocol," *Climate Policy*, Vol. 1 (2001), pp. 5-25; and F. Missfeldt and E. Haites, "The Potential Contribution of Sinks to Meeting Kyoto Protocol Commitments," *Environmental Science and Policy*, Vol. 4, No. 6 (2001), pp. 269-292.

the total), and (4) changes in carbon stocks in landfilled yard trimmings (2 million metric tons carbon equivalent or 0.8 percent of the total).¹³⁴

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 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 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.¹³⁵

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 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 decade 1990-2000, were applied to the entire time series.¹³⁶

¹³⁴U.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.

¹³⁵U.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.

¹³⁶U.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.

Satellite Data Indicate That Forests Store 700 Million Metric Tons of Carbon Annually

In a recent study, investigators have used satellite data from the National Aeronautics and Space Administration (NASA) to construct detailed maps of forest carbon pools, sources, and sinks in North America, Europe, and Russia. Their findings indicate that approximately 700 million metric tons of carbon is stored in those forests annually—equivalent to approximately 11.5 percent of global energy-related carbon dioxide emissions in 1999. The data indicate that, with the exception of Canada's boreal forests, which were

found to be losing carbon, most northern forests are actively storing carbon. Russia, which contains the most forest land, accounted for approximately 40 percent of the biomass carbon sink. The researchers reported that about 61 billion tons of carbon is contained in the wood components of these northern forests, with American and European forests containing more carbon per unit of area than either Canadian or Russian forests (56 versus 41 tons of carbon per hectare).^a

^aR. Myneni et. al, "Forests Storing 700 Million Tons of Carbon Per Year," *UniSci Daily University Science News* (December 12, 2001), web site <http://unisci.com/stories/20014/1212012.htm>.

Changes in Forest Carbon Stocks

Worldwide, the most significant anthropogenic activity that affects forest carbon sequestration is deforestation, particularly that of tropical forests. During the 1980s, tropical deforestation is projected to have resulted in approximately 6 billion metric tons of carbon dioxide emissions to the atmosphere annually. This value represents approximately 23 percent of global carbon dioxide emissions resulting from anthropogenic activities during the 1980s. Approximately 7 percent of global carbon dioxide emissions were compensated for by carbon sequestration as a result of forest re-growth in the Northern Hemisphere.¹³⁷ 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.¹³⁸ 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 within 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.¹³⁹

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 practically nonexistent 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

¹³⁷U.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.

¹³⁸U.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.

¹³⁹U.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.

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.¹⁴⁰

According to the EPA (Table 32), between 1990 and 2000, U.S. forest and harvested wood components accounted for an average annual net sequestration of 210 million metric tons carbon 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 22 percent in the overall rate of annual sequestration.

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 2.8 percent of total tree cover. The

EPA's carbon sequestration estimates for urban trees are derived from estimates by Nowak and Crane,¹⁴¹ based on data collected from 1990 through 2000. Net carbon dioxide flux from urban trees is estimated at 16 million metric tons carbon equivalent annually from 1990 through 2000 (Table 31).¹⁴²

Changes in Agricultural Soil Carbon Stocks

The amount of organic carbon in soils depends on the balance between addition of organic materials and loss of carbon through decomposition. The quantity and quality of organic matter within soils, as well as decomposition rates, are determined by the interaction of climate, soil properties, and land use. Agricultural practices—including clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, and flooding—can alter organic matter inputs and decomposition, causing a net flux of carbon to or from soils. The IPCC methodology, which is used by the EPA to estimate the net flux from agricultural soils (Table 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

Table 32. Net Carbon Dioxide Sequestration in U.S. Forests, 1990 and 1995-2000
(Million Metric Tons Carbon Equivalent)

| Description | 1990 ^a | 1995 ^a | 1996 ^a | 1997 ^b | 1998 ^b | 1999 ^b | 2000 ^b |
|---|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Forest Carbon Stocks | 211 | 211 | 211 | 149 | 149 | 149 | 149 |
| Trees | 128 | 128 | 128 | 122 | 122 | 122 | 122 |
| Understory | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| Forest Floor | 7 | 7 | 7 | -8 | -8 | -8 | -8 |
| Down Dead Wood | 15 | 15 | 15 | 16 | 16 | 16 | 16 |
| Forest Soils | 58 | 58 | 58 | 15 | 15 | 15 | 15 |
| Harvested Wood Carbon Stocks . . | 57 | 56 | 56 | 58 | 56 | 59 | 61 |
| Wood Products | 13 | 15 | 15 | 16 | 14 | 17 | 18 |
| Landfilled Wood | 44 | 41 | 41 | 42 | 42 | 42 | 43 |
| Total | 268 | 267 | 267 | 207 | 205 | 208 | 210 |

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

¹⁴⁰U.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 www.epa.gov.

¹⁴¹D.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.

¹⁴²U.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.

use and management of mineral soils is estimated to be the most significant contributor to total flux from 1990 through 2000.¹⁴³

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 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). 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.¹⁴⁴

Land Use and International Climate Change Negotiations

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

Many of the countries involved in climate change negotiations have agreed that implementation of LULUCF activities under an international climate change agreement may be complicated by a lack of clear definitions for words such as "reforestation" and "forest." Further, implementation may be hindered by the lack of effective accounting rules. According to researchers at the Pew Center on Global Climate Change,¹⁴⁵ 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 uncertainty and verifiability be addressed?
- How will the issues of (non) permanence and leakage be addressed?
- Which activities beyond afforestation, reforestation and deforestation (ARD), if any, should be included, and what accounting rules should apply?
- Which carbon pools and which greenhouse gases should be considered?

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

The most recent UNFCCC climate negotiations, which took place at the Conference of the Parties (COP) in Bonn, Germany, in July 2001 (COP-6.5) and Marrakech, Morocco, in November 2001 (COP-7) led to an agreement called the Marrakech Accords. LULUCF activities were debated throughout the negotiations, and it is believed that the LULUCF issue was one of the main

Table 33. Net Carbon Dioxide Sequestration in U.S. Agricultural Soils, 1990 and 1995-2000
(Million Metric Tons Carbon Equivalent)

| Description | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| Mineral Soils | 18.9 ^a | 25.1 ^a | 25.1 ^a | 25.1 ^a | 27.2 ^b | 27.2 ^b | 27.2 ^b |
| Organic Soils | -6.1 ^a | -6.2 ^a | -6.2 ^a | -6.2 ^a | -6.2 ^b | -6.2 ^b | -6.2 ^b |
| Liming of Soils | -2.6 ^a | -2.4 ^a | -2.4 ^a | -2.4 ^a | -2.6 ^a | -2.5 ^a | -2.6 ^a |
| Total | 10.2^a | 16.4^a | 16.4^a | 16.5^a | 18.3^a | 18.5^a | 18.4^a |

^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.

¹⁴³U.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.

¹⁴⁴U.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.

¹⁴⁵G. 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/projects/land_use.cfm.

reasons that the negotiations at COP-6 in November 2000 failed. Consensus on including carbon sinks in the Kyoto Protocol was reached only at the very end of the climate change negotiations at COP-7.¹⁴⁶ Should the Kyoto Protocol eventually be ratified, specific implementation rules for LULUCF would have to be developed.

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).¹⁴⁷

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.¹⁴⁸

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.¹⁴⁹ 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.

Accounting for carbon sequestration through land use and forestry practices also raises the issues of “permanence” and “leakage.” Carbon sequestration occurring at one time and place presents the issue of whether the carbon will be lost at a later time (permanence) or result in offsetting losses elsewhere (leakage). For example, suppose an international climate change agreement is developed in which changes in carbon stocks within a certain commitment period are used to meet targets. If there is a gap between commitment periods, there will be a possibility for unaccounted losses (or gains) in certain countries. A similar possibility of unaccounted losses will arise if countries in one geographic area receive “credits” for carbon that is sequestered in countries in a different geographic area but subsequent carbon losses remain unaccounted.¹⁵⁰

Leakage is defined as the unexpected loss of expected carbon sequestration benefits when the displacement of activities or market effects leads to carbon losses elsewhere. For example, avoiding deforestation in one geographic location may accelerate the rate of deforestation in another geographic location. Leakage may also occur through the impact of a large reforestation program on timber prices. Increased availability of timber could result in lower prices, which in turn could cause reduced rates of planting in other locations. Reduced timber prices may also result in the conversion of existing forests for agriculture.¹⁵¹

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

¹⁴⁶H. Kolshus, *Carbon Sequestration in Sinks: An Overview of Potential and Costs*, CICERO Working Paper 2001: 11 (Oslo, Norway: CICERO Center for International Climate and Environmental Research, November 2001), web site www.cicero.uio.no/media/1616.pdf.

¹⁴⁷U.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.

¹⁴⁸U.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.

¹⁴⁹G. 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/projects/land_use.cfm.

¹⁵⁰G. 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/projects/land_use.cfm.

¹⁵¹G. 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. 32, web site www.pewclimate.org/projects/land_use.cfm.

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. 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.

In response to the findings presented by Drs. Lichter and Shlesinger, EcoSecurities Ltd., an established environmental finance company that specializes in advising on global warming issues, maintains that their research has been consistently misinterpreted. The company believes that the study's conclusions are inappropriate for two reasons. First, it was never the carbon fertilization effect

alone that climate change policymakers considered to be the greenhouse gas mitigation value of forests. Second, because more than 20 percent of all anthropogenic greenhouse gas emissions come from forest conversion and degradation, the avoidance of deforestation should also be viewed as a prime emission reduction measure.¹⁵²

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.

¹⁵²EcoSecurities Ltd. "'Sinks' and Climate Change. Comment on Recent Reporting on Last Week's *Nature Journal*," Press Release (June 2001), web site www.ecosecurities.com/200about_us/223press_releases/223press_release_sinks_climate.html.

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<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.
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- Global Change.
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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 Program.
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.
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U.S. Global Change Research Office.
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U.S. National Aeronautics and Space Administration
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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 = $(141.5 / \text{sp.gr.} \cdot 60 \text{ deg.F} / 60 \text{ deg.F}) - 131.5$.

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.