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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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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 0.6 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	*	*	*	*	*	*	*	*	*	*	*	*

[R]Estimates 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.

[1] See "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).

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

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-2001
(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**

[R] Estimates 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).

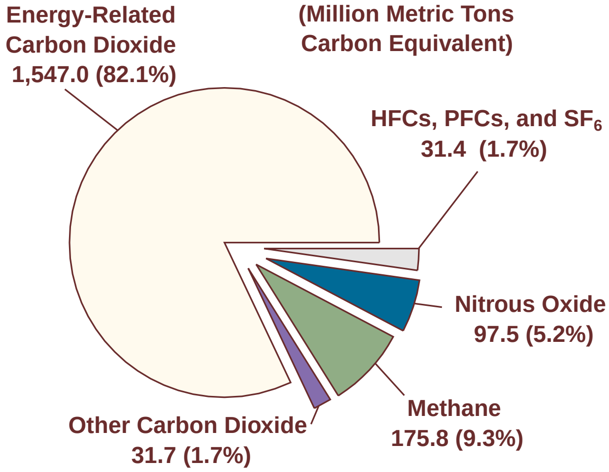
Sources: **Emissions:** Estimates presented in this report. **Global Warming Potentials:** Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 38 and 388-389.

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 (SF_6), 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

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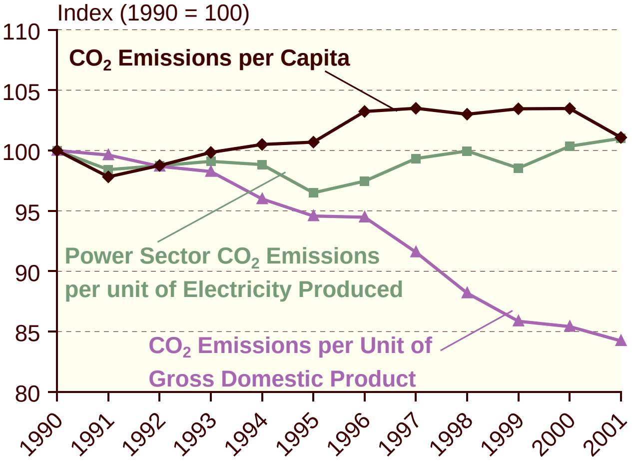
[3] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

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.

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

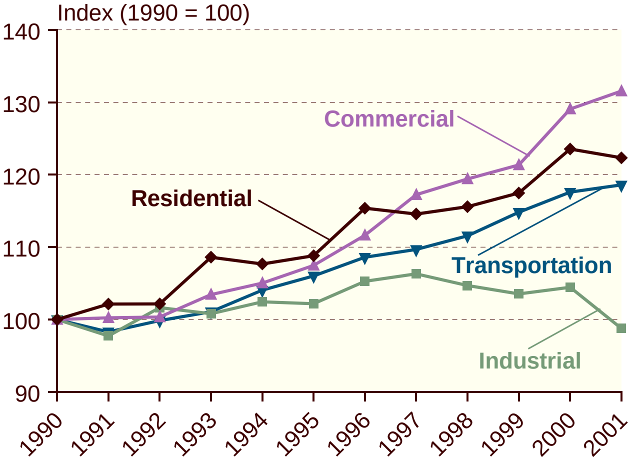


Sources: Estimates presented in this report.

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



Sources: Estimates presented in this report.

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[4] As 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.

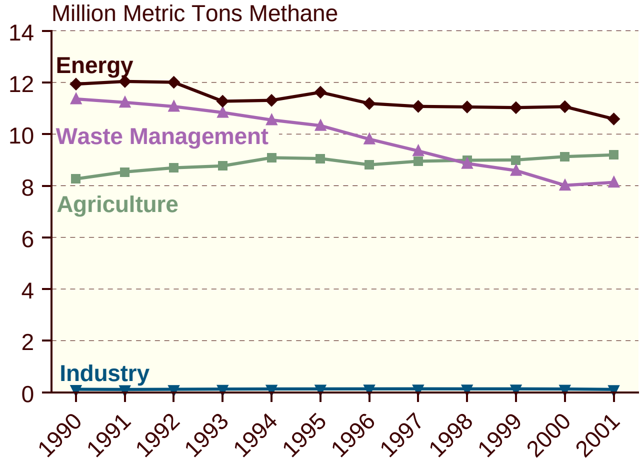
The estimates for methane emissions are more uncertain than those for carbon dioxide. U.S. methane emissions do not necessarily increase with growth in energy consumption or the economy. Energy-related methane emissions are strongly influenced by coal production from a relatively restricted number of 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.

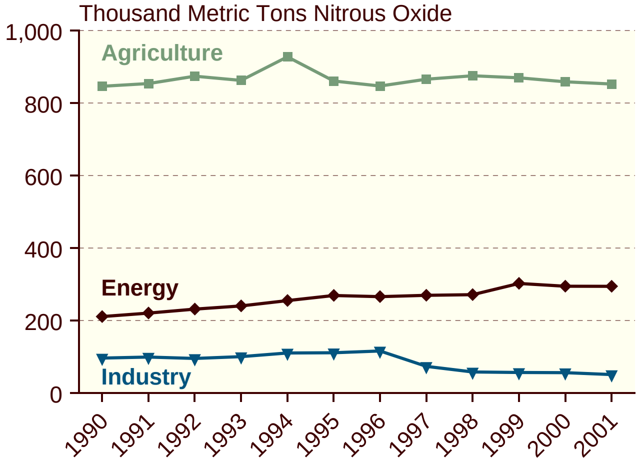
U.S. nitrous oxide emissions include two large categories of sources, agriculture and energy use, and two smaller categories, industrial processes and waste management (Figure ES5). Agricultural sources, at 852.5

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 SF_6 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 SF_6 (6.7 percent). At 21.0 million metric tons carbon equivalent, emissions of HFCs make up the majority of this category, followed by SF_6 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 SF_6 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 SF_6) have atmospheric lifetimes measured in the thousands of years, and consequently they are potent greenhouse gases with GWPs thousands of times higher than that of carbon dioxide per unit of molecular weight. Some of the commercially produced HFCs (134a, 152a, 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^{o} Celsius, rather than the $+14^{o}$ 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.

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

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

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

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

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

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

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 CO_2). 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° ± 0.2°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 CO_2 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 countervailing effect of increased cloud formation, which can act to cool the planet by absorbing and reflecting solar radiation or warm the planet through the emission of

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

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

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

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

[7] Intergovernmental 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 SF_6) 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 SF_6 Emissions Reduction Partnership and new information on world sales of SF_6 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 SF_6 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 SF_6 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 CF_4 and C_2F_6 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 SF_6 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 SF_6 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

[a] Carbon 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.

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

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

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

long-wave radiation. According to the IPCC, increases in atmospheric temperatures would not necessarily result in increased concentrations of water vapor, because most of the atmosphere today is undersaturated.

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

Records from Antarctic ice cores indicate that the carbon cycle has been in a state of imbalance for the past 200 years, with emissions of carbon dioxide to the atmosphere exceeding absorption. Consequently, carbon dioxide concentrations in the atmosphere have been steadily rising. 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

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

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

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

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

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

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

[14] Intergovernmental 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 (CF_4) and perfluoroethane (C_2F_6). PFCs are emitted as byproducts of aluminum smelting and are increasingly being used in the manufacture of semiconductors. They are powerful greenhouse gases and extremely long-lived. Perfluoromethane has 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 (SF_6) 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. SF_6 has a 100-year GWP of 22,200 and a lifetime of 3,200 years. Like perfluoromethane, SF_6 occurs naturally in fluorites, which produce a natural abundance of 0.01 parts per trillion in the atmosphere. Current atmospheric concentrations (3.0 parts per trillion) can be traced to anthropogenic emissions, which grew by approximately 7 percent annually during the 1980s and 1990s. Also like PFCs, sinks for SF_6 are photolysis and ion reactions in the mesosphere.[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 (SF_5CF_3) as a new anthropogenic

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

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

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

[18] Intergovernmental 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 SF_5CF_3 is created by the breakdown of SF_6 in high-voltage equipment, which produces CF_3 that reacts with SF_5 radicals resulting from high-voltage discharges. Its atmospheric concentration has grown from near zero in 1960 to 0.12 parts per trillion in 1999. To date, SF_5CF_3 has the largest radiative forcing on a per-molecule basis of any gas found in the atmosphere.[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 SF_6).

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

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

Ozone (O_3) is present in both the troposphere and the stratosphere. Tropospheric ozone is not directly emitted into the atmosphere but instead forms through the photochemical reactions of various ozone precursors (primarily, nitrogen oxides and volatile organic compounds). In the troposphere, ozone acts as a direct greenhouse gas. The lifetime of ozone in the atmosphere varies from weeks to months, which imparts an element of uncertainty in estimating tropospheric ozone’s radiative forcing effects. The IPCC estimates that the radiative forcing of tropospheric ozone is 0.35 ± 0.2 watts per square meter.[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 affects 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 NO_2, influence climate by their impacts on other greenhouse gases. Nitrogen oxides not only promote ozone formation, they also impact (negatively) methane and HFC concentrations in the atmosphere. The deposition of nitrogen oxides could also reduce atmospheric carbon dioxide concentrations by fertilizing the biosphere.[24]

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

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

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

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

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

[24] Intergovernmental 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 (SO_2), which is emitted largely as a byproduct from the combustion of sulfur-containing fossil fuels, particularly coal. Sulfur dioxide reacts in the air to form sulfate compounds. The major source of anthropogenic black soot and organic carbon aerosols is the burning of fossil fuels, primarily coal and diesel fuels. Biomass-burning aerosols are formed by the incomplete combustion of forest products. The IPCC estimates the direct radiative forcing for aerosols as follows: sulfates, -0.4 watts per square meter; black soot, +0.2 watts per square meter; fossil fuel organic carbon, -0.1 watts per square meter; and biomass-burning aerosols, -0.2 watts per square meter.[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

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

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

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

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

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

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

[31] Intergovernmental 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 “CO_2 equivalent” units for this report, 100-year GWPs are used.

The GWPs discussed above are direct GWPs in that they consider only the direct impact of the emitted gas. The IPCC has also devoted effort to the study of indirect GWPs. Indirect GWPs are based on the climatic impacts of the atmospheric decomposition of a gas into other gases. A number of gases—including methane, carbon monoxide, halocarbons, and nitrogen oxides—are thought to have indirect climatic effects. Methane indirectly influences the climate through ozone formation and the production of carbon dioxide. Carbon monoxide can promote ozone formation and extend the lifetime of methane in the atmosphere, which results in a positive indirect GWP. Some 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_2F_6)	10,000	8,000	11,900	18,000
Sulfur Hexafluoride (SF_6)	3,200	15,100	22,200	32,400

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

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

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

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[32] Intergovernmental 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 (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO_2. The GWP provides a construct for converting emissions of various gases into a common measure, which allows climate analysts to aggregate the radiative impacts of various greenhouse gases into a uniform measure denominated in carbon or carbon dioxide equivalents. The table at the right compares the GWPs published in the Second and Third Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC).

In compiling its greenhouse gas emission estimates, EIA attempts to employ the most current data sources. For that reason, 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 GWPs from the Third Assessment report for informational purposes.

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

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

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

The table below shows 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 SF_6 are lower for some years and higher for others, depending on the relative shares of the three gases.

Gas	IPCC GWP		Annual GWP-Weighted Emissions (Million Metric Tons Carbon Equivalent)								
			1990			2000			2001		
	1996	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]

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:

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

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

[35] The 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.

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

- **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

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[37] Several 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.

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

[39] Article 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 . . . ."

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

[41] Remarks 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:

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

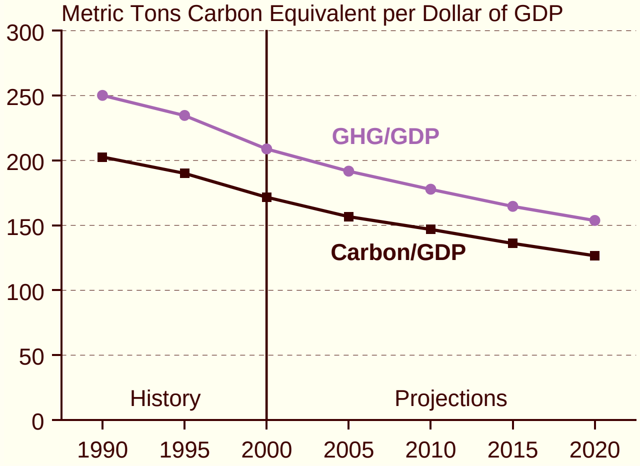
or, algebraically,

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

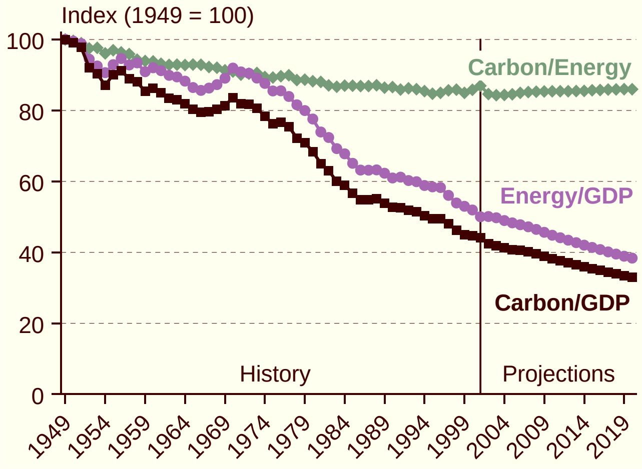
meant that over the second half of the 20th century economic growth was less tied to growth in energy demand than it was during the period of industrialization in the 19th and early 20th century. Other factors contributing to decreases in energy intensity include:

- 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 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:

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.

- 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.

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

[43] Letter 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.climatescience.gov / Library / climateletter.htm (September 9, 2002).

[44] See 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).

[46] Pew 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.

[47] United 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%*

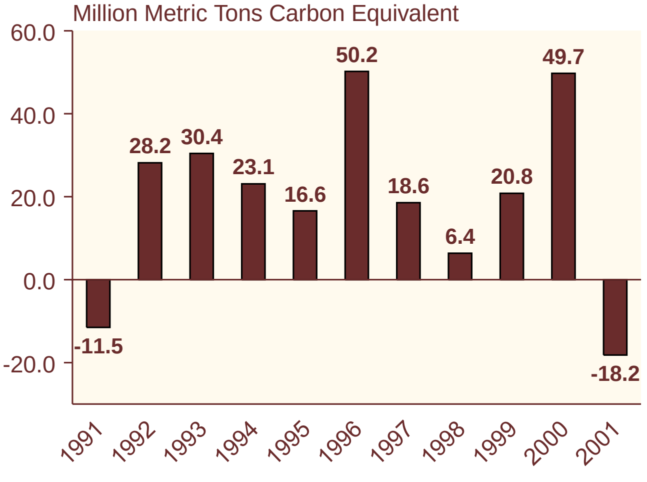
Total emissions of carbon dioxide in the United States and its territories were 1,578.7 million metric tons carbon equivalent in 2001, 18.2 million metric tons carbon equivalent (1.1 percent) less than the 2000 total (Table 4). The decrease in emissions from 2000 to 2001 was the first since 1991, when 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.

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[48] As 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

	Million Metric Tons Carbon Equivalent		*Percent Change*	
Sector	**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,

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[49] Sectoral (residential, commercial, and industrial) energy-related carbon dioxide emissions include the share of total electric power sector carbon dioxide emissions that can be attributed to each end-use sector. The share is based on the percentage of total electricity sales purchased by the sector. 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).

[a] Appendixes for this report are available on web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html.

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

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

Fuel	Million Metric Tons Carbon Equivalent 1990	Million Metric Tons Carbon Equivalent 2001	*Percent Change* 1990-2001	*Percent Change* 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%*

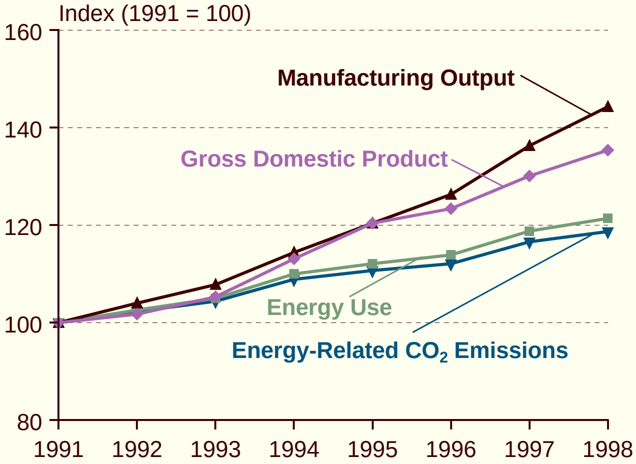
Preliminary estimates indicate that carbon dioxide emissions from the electric power sector decreased by 1.5 percent (9.6 million metric tons carbon equivalent), from 621.2 million metric tons in 2000 to 611.7 million metric tons in 2001 (Table 10). Emissions from natural-gas-fired generation increased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

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.

(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

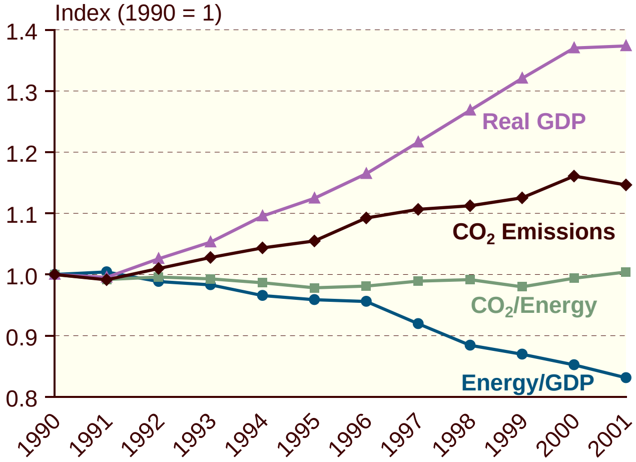
In 2001, 81.0 million metric tons carbon equivalent was sequestered through nonfuel uses of fossil fuels (Table 11). The vast majority of this sequestered carbon was in petroleum-based products (75.9 million metric tons), with smaller amounts in natural-gas-based products (4.6 million metric tons) and 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)

[a] Combined 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).

[b] The 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—Nonutility," 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
CO_2 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
Electric Power Percent of Total	*36.2%*	*36.5%*	*36.1%*	*36.9%*	*36.8%*	*36.7%*	*36.8%*	*37.5%*	*39.0%*	*38.7%*	*39.4%*
CO_2 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
Electric Power Percent of Total	*37.5%*	*37.9%*	*37.7%*	*38.4%*	*38.4%*	*38.2%*	*38.2%*	*39.0%*	*40.6%*	*40.4%*	*41.1%*
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
Electric Power Percent of Total	*-1.3*	*-1.4*	*-1.6*	*-1.5*	*-1.5*	*-1.4*	*-1.4*	*-1.5*	*-1.7*	*-1.6*	*-1.7*

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
CO_2 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**
CO_2 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:

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

[51] Based 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.

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**

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

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 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**

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

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 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 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.

[a] Share 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.

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

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 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.

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.

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[52] Based 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.

[53] Wherever possible, estimates of methane emissions are based on measured data. In some cases, however, measured data are incomplete or unavailable. In the absence of measured data, emissions are indexed to some known activity data, such as coal production or natural gas throughput, and multiplied by an emissions factor derived from a small sample of the relevant emissions source or through laboratory experiments. For a more detailed discussion of where measured data were used and how emissions factors were developed, see 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

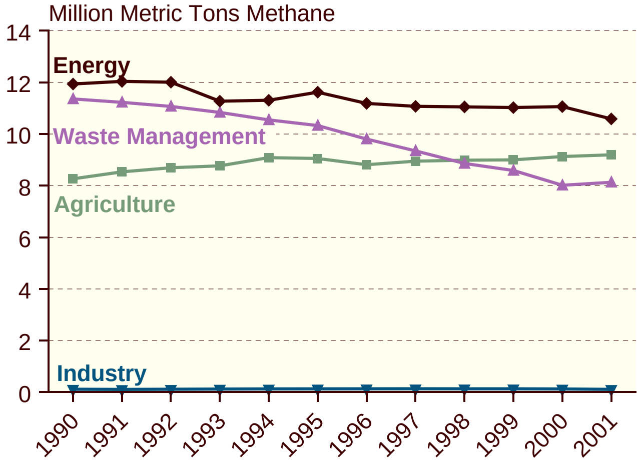
Principal Sources of U.S. Anthropogenic Methane Emissions, 1990-2001

Source	Million Metric Tons Methane 1990	Million Metric Tons Methane 2001	Percent Change 1990-2001	Percent Change 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

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[54] Further 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 *(Percent)*	*-3.9%*
Change Compared to 1990 (Million Metric Tons Methane)	0.5
Change from 1990 *(Percent)*	*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 portion of methane emissions from petroleum systems can be traced to refineries and transportation of crude oil.

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 *(Percent)*	*-0.2%*
Change Compared to 1990 (Million Metric Tons Methane)	-0.3
Change from 1990 *(Percent)*	*-20.7%*

*Less than 0.05 million metric tons.

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 *(Percent)*	*-5.7%*
Change Compared to 1990 (Million Metric Tons Methane)	-0.2
Change from 1990 *(Percent)*	*-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

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

[56] The 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).

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 kilowatthour 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.

[58] See 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.

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.

[a] U.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.

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

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[59] See 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

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

[61] 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), 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.

[a] IPCC 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).

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.

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.

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

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/chief; Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.ipcc.ch/pub/guide.htm; and Energy Information Administration, *State Energy Data Report 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).

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," *Biocycle* (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.

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**

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

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 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

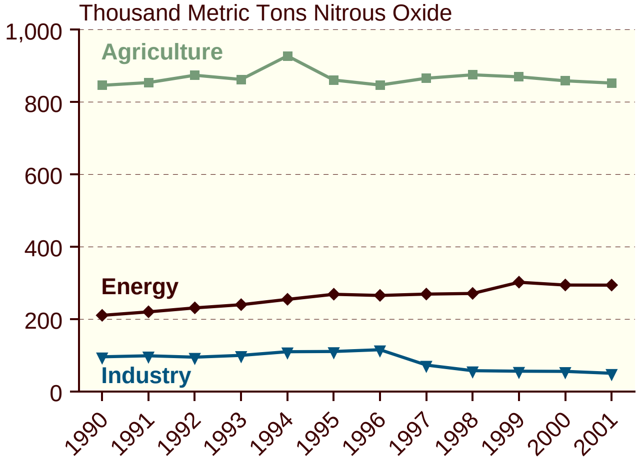
	Nitrous Oxide	Carbon Equivalent
Estimated 2001 Emissions (Thousand Metric Tons)	1,207	97,462
Change Compared to 2000 (Thousand Metric Tons)	-12	-954
Change from 2000 *(Percent)*	*-1.0%*	*-1.0%*
Change Compared to 1990 (Thousand Metric Tons)	37	3,004
Change from 1990 *(Percent)*	*3.2%*	*3.2%*

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

	Thousand Metric Tons Nitrous Oxide		*Percent Change*	
Source	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%*

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

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,

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

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

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

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[65] "Nationwide Survey: The State of Garbage in America 1999," *Biocycle* (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.

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

[67] Biochemical 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 (NH_3) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation.

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

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

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

[71] 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 2.18, web site www.ipcc.ch/pub/guide.htm.

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.

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

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

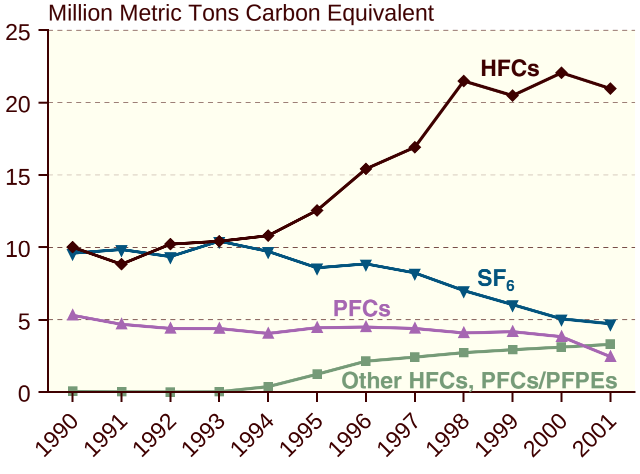
Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2001

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 (SF_6) 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 SF_6 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 SF_6 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.

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[72] Preliminary 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.

[73] In 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 enviornmental 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)

[a] A.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.

[b] 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.

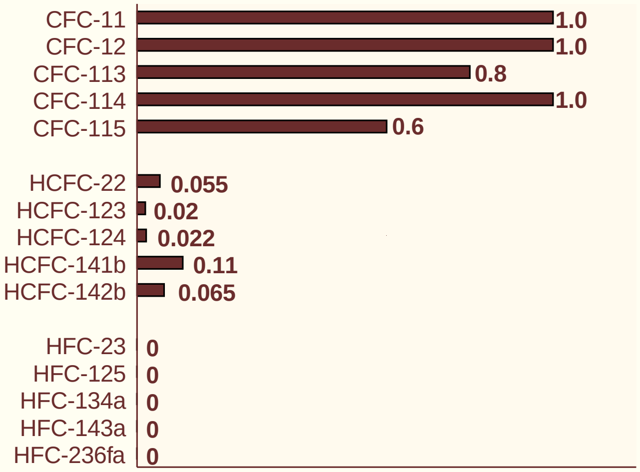
[c] Alternative Fluorocarbons Environmental Acceptability Study, "Atmospheric Chlorine: CFCs and Alternative Fluorocarbons," web site www.afeas.org/atmospheric_chlorine.html.

[d] T.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).

[e] United 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_sbstal19add1.pdf.

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

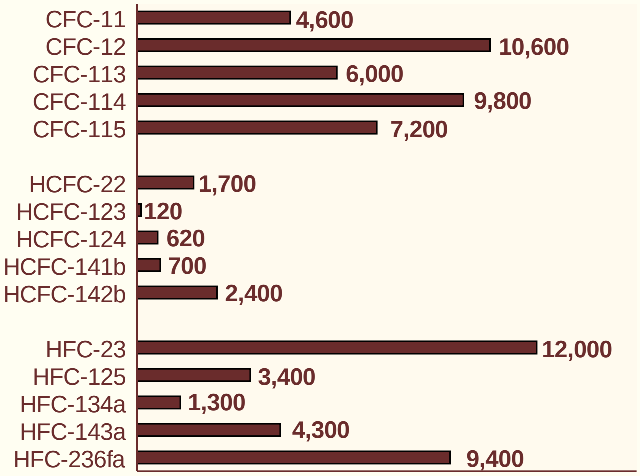
Ozone Depletion Potentials for CFCs and Alternatives (HCFCS and HFCs)



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 SF_6 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 SF_6. 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 SF_6 that are emitted have disproportionate effects on overall emissions because of their large GWPs. PFCs and SF_6 have particularly high GWPs because of their scarcity, stability, strong absorption in the atmosphere, and long atmospheric lifetimes.[76] SF_6 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

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[74] 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.

[75] See Chapter 1, Table 1. Naturally occurring (pre-industrial) emissions of perfluoromethane (CF_4) were 40 parts per trillion. Their concentration had doubled by 1998.

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

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

[78] Preliminary 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 SF_6 (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 SF_6 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 HFCF-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.

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

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[79] Preliminary 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.

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

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

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

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

[84] 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.

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

The EPA Vintaging Model: Estimation Methods and Uncertainty

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

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

[a] 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), Annex J, web site www.epa.gov.

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]

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[86] 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.

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

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

[89] Form 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.

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

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

[92] J. 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).

[94] J. 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 nonflammability, thermal and chemical stability, excellent dielectric properties, high material compatibility, low surface tension and viscosity, and high liquid density. HFC-134a, in particular, is used in special extraction processes to produce important natural active pharmaceuticals, such as taxol for breast cancer treatment, 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 SF_6 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 SF_6 Emissions Reduction Partnership to reduce emissions of SF_6 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 SF_6 to electric power systems from 1990 to 1999, has reduced the uncertainty in estimates of SF_6 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 CF_4 and C_2F_6 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 SF_6 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 SF_6 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 to1998. The revision resulted in an average decrease of less than 0.1 percent in annual HFC-23 emissions from the production of HCFC-22.

[a] 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.

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[95] European 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 SF_6 reported.[104] Emissions of these HFCs are small but growing rapidly, as they continue to find applications as substitutes for

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

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

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

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

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

[101] C. 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).

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

[104] Preliminary 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.

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

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

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

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

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

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

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

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

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

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

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

[115] J. 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 [CF_4] and 11,900 for perfluoroethane [C_2F_6])[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 (C_3F_8, with a GWP of 8,600), perfluorobutane (C_4F10, GWP 8,600), perfluorohexane (C_6F_{14}, GWP 9,000), and nitrogen trifluoride (NF_3, 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 (SF_6)

The most recent EPA estimates show a steady decrease in U.S. emissions of sulfur hexafluoride (SF_6), from a

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[116] Preliminary 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.

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

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

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

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

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

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

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

[124] U.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 SF_6, and the closure of a major U.S. magnesium production facility. Emissions of SF_6 from uses in the semiconductor manufacturing industry have increased. Although it is not emitted in large quantities, SF_6 has a very high GWP of 22,200.[126]

SF_6 is used primarily in electrical applications and metal casting processes. SF_6 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, SF_6 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 SF_6 production is used in electricity transmission and distribution.[129]

Other applications that produce SF_6 emissions include magnesium and aluminum metal casting processes that employ SF_6 to replace toxic and corrosive materials, such as salt fluxes and sulfur dioxide (SO_2). Another important use of SF_6 is as a cover gas during magnesium production and processing to prevent excessive oxidation of molten magnesium in the presence of air. Pre-treating aluminum melt with SF_6 (or an inert gas mixture) prevents porosity and therefore weakening of the metal. It also removes oxides and solid impurities. In addition, mixtures of SF_6 and O_2 are used as feed gases for plasma etching of semiconductor devices.[130] Because of its extremely low atmospheric concentration, SF_6 is also useful as an atmospheric tracer gas for a variety of experimental purposes. Other minor applications include leak detection, loud speakers, lasers, and as a cover gas or fluxing and degassing agent for specialized casting operations in the aluminum industry.[131]

In compiling its estimates, the EPA receives data from participants in the SF_6 Emissions Reduction Partnership for Electric Power Systems and the SF_6 Emissions Reduction Partnership for the Magnesium Industry. The uncertainty associated with SF_6 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 SF_6 neither reacts nor decomposes, adds an element of uncertainty to the estimates.[132]

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

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

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

[128] 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.

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

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

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

[132] 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.

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_2F_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_4F_{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_2F_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_4F_{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]**

[a] Estimate based on historical data.

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

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

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

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[133] 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.

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)

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[a] Intergovernmental 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.

[b] As designated in the United Nations Framework Convention on Climate Change (UNFCCC).

[c] 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), web site www.cicero.uio.no / media / 1616.pdf.

[d] W.D. Nordhaus, “The Cost of Slowing Climate Change: A Survey,” *The Energy Journal*, Vol. 12, No. 1 (1991), pp. 37-65.

[e] 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), 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]

[134] 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.

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

[136] 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.

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]

[a] R. 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

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[137] 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.

[138] 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.

[139] 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.

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**

[a]Estimates based on historical data.

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

Notes: The sums of the annual net stock changes in this table (shown in the "Total" row) represent estimates of the actual net flux between the total forest carbon pool and the atmosphere. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. 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.

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[140] 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), p. 129, web site www.epa.gov.

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

[142] 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.

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]

[a]Estimates based on historical data.

[b]Estimates 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.

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[143] 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.

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

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

[146] 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), web site www.cicero.uio.no/media/1616.pdf.

[147] 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.

[148] 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.

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

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

[151] G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA; Pew Center on Global Climate Change, June 2000), p. 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.

[152] EcoSecurities 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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Glossary

Acid stabilization: A circumstance where the pH of the waste mixture in an animal manure management system is maintained near 7.0, optimal conditions for methane production.

Aerobic bacteria: Microorganisms living, active, or occurring only in the presence of oxygen.

Aerobic decomposition: The breakdown of a molecule into simpler molecules or atoms by microorganisms under favorable conditions of oxygenation.

Aerosols: Airborne particles.

Afforestation: Planting of new forests on lands that have not been recently forested.

Agglomeration: The clustering of disparate elements.

Airshed: An area or region defined by settlement patterns or geology that results in discrete atmospheric conditions.

Albedo: The fraction of incident light or electromagnetic radiation that is reflected by a surface or body. See *Planetary albedo*.

Anaerobes: Organisms that live and are active only in the absence of oxygen.

Anaerobic bacteria: Microorganisms living, active, or occurring only in the absence of oxygen.

Anaerobic decomposition: The breakdown of molecules into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

Anaerobic lagoon: A liquid-based manure management system, characterized by waste residing in water to a depth of at least six feet for a period ranging between 30 and 200 days.

Anode: A positive electrode, as in a battery, radio tube, etc.

Anthracite: The highest rank of coal; used primarily for residential and commercial space heating. It is a hard, brittle, and black lustrous coal, often referred to as hard coal, containing a high percentage of fixed carbon and a low percentage of volatile matter. The moisture content of fresh-mined anthracite generally is less than 15 percent. The heat content of anthracite ranges from 22 to 28 million Btu per ton on a moist, mineral-matter-free basis. The heat content of anthracite coal consumed in the United States averages 25 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter). Note: Since the 1980's, anthracite refuse or mine waste has been used for steam electric power generation. This fuel typically has a heat content of 15 million Btu per ton or less.

Anthropogenic: Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation.

API Gravity: American Petroleum Institute measure of specific gravity of crude oil or condensate in degrees. An arbitrary scale expressing the gravity or density of liquid petroleum products. The measuring scale is calibrated in terms of degrees API; it is calculated as follows: Degrees API = (141.5 / sp.gr.60 deg.F / 60 deg.F) - 131.5.

Asphalt: A dark brown-to-black cement-like material obtained by petroleum processing and containing bitumens as the predominant component; used primarily for road construction. It includes crude asphalt as well as the following finished products: cements, fluxes, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cutback asphalts. Note: The conversion factor for asphalt is 5.5 barrels per short ton.

Associated natural gas: See *Associated-dissolved natural gas* and *Natural gas*.

Associated-dissolved natural gas: Natural gas that occurs in crude oil reservoirs either as free gas (associated) or as gas in solution with crude oil (dissolved gas). See *Natural gas*.

Aviation gasoline (finished): A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D 910 and Military Specification MIL-G-5572. Note: Data on blending components are not counted in data on finished aviation gasoline.

Balancing item: Represents differences between the sum of the components of natural gas supply and the sum of the components of natural gas disposition. These differences may be due to quantities lost or to the effects of data reporting problems. Reporting problems include differences due to the net result of conversions of flow data metered at varying temperature and pressure bases and converted to a standard temperature and pressure base; the effect of variations in company accounting and billing practices; differences between billing cycle and calendar period time frames; and imbalances resulting from the merger of data reporting systems that vary in scope, format, definitions, and type of respondents.

Biofuels: Liquid fuels and blending components produced from biomass (plant) feedstocks, used primarily for transportation.

Biogas: The gas produced from the anaerobic decomposition of organic material in a landfill.

Biogenic: Produced by the actions of living organisms.

Biomass: Organic nonfossil material of biological origin constituting a renewable energy source.

Biosphere: The portion of the Earth and its atmosphere that can support life. The part of the global carbon cycle that includes living organisms and biogenic organic matter.

Bituminous coal: A dense coal, usually black, sometimes dark brown, often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing and to make coke. Bituminous coal is the most abundant coal in active U.S. mining regions. Its moisture content usually is less than 20 percent. The heat content of bituminous coal ranges from 21 to 30 million Btu per ton on a moist, mineral-matter-free basis. The heat content of bituminous coal consumed in the United States averages 24 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

BOD_5: The biochemical oxygen demand of wastewater during decomposition occurring over a 5-day period. A measure of the organic content of wastewater.

Bromofluorocarbons (halons): Inert, nontoxic chemicals that have at least one bromine atom in their chemical makeup. They evaporate without leaving a residue and are used in fire extinguishing systems, especially for large computer installations.

Bunker fuel: Fuel supplied to ships and aircraft, both domestic and foreign, consisting primarily of residual and distillate fuel oil for ships and kerosene-based jet fuel for aircraft. The term "international bunker fuels" is used to denote the consumption of fuel for international transport activities. *Note*: For the purposes of greenhouse gas emissions inventories, data on emissions from combustion of international bunker fuels are subtracted from national emissions totals. Historically, bunker fuels have meant only ship fuel. See *Vessel bunkering*.

Calcination: A process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled.

Calcium sulfate: A white crystalline salt, insoluble in water. Used in Keene's cement, in pigments, as a paper filler, and as a drying agent.

Calcium sulfite: A white powder, soluble in dilute sulfuric acid. Used in the sulfite process for the manufacture of wood pulp.

Capital stock: Property, plant and equipment used in the production, processing and distribution of energy resources.

Carbon black: An amorphous form of carbon, produced commercially by thermal or oxidative decomposition of hydrocarbons and used principally in rubber goods, pigments, and printer's ink.

Carbon budget: Carbon budget: The balance of the exchanges (incomes and losses) of carbon between carbon sinks (e.g., atmosphere and biosphere) in the carbon cycle. See *Carbon cycle* and *Carbon sink*.

Carbon cycle: All carbon sinks and exchanges of carbon from one sink to another by various chemical, physical, geological, and biological processes. See *Carbon sink* and *Carbon budget*.

Carbon dioxide (CO_2): A colorless, odorless, nonpoisonous gas that is a normal part of Earth's atmosphere. Carbon dioxide is a product of fossil-fuel combustion as well as other processes. It is considered a greenhouse gas as it traps heat (infrared energy) radiated by the Earth into the atmosphere and thereby contributes to the potential for global warming. The global warming potential (GWP) of other greenhouse gases is measured in relation to that of carbon dioxide, which by international scientific convention is assigned a value of one (1). See *Global warming potential (GWP)* and *Greenhouse gases*.

Carbon dioxide equivalent: The amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas. Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured (for example, methane) by its estimated global warming potential (which is 21 for methane). “Carbon equivalent units” are defined as carbon dioxide equivalents multiplied by the carbon content of carbon dioxide (i.e., 12/44).

Carbon flux: See *Carbon budget*.

Carbon intensity: The amount of carbon by weight emitted per unit of energy consumed. A common measure of carbon intensity is weight of carbon per British thermal unit (Btu) of energy. When there is only one fossil fuel under consideration, the carbon intensity and the emissions coefficient are identical. When there are several fuels, carbon intensity is based on their combined emissions coefficients weighted by their energy consumption levels. See *Emissions coefficient* and *Carbon output rate*.

Carbon output rate: The amount of carbon by weight per kilowatthour of electricity produced.

Carbon sequestration: The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes.

Carbon sink: A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. The four sinks, which are regions of the Earth within which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels).

Catalytic converter: A device containing a catalyst for converting automobile exhaust into mostly harmless products.

Catalytic hydrocracking: A refining process that uses hydrogen and catalysts with relatively low temperatures and high pressures for converting middle boiling or residual material to high octane gasoline, reformer charge stock, jet fuel, and/or high grade fuel oil. The process uses one or more catalysts, depending on product output, and can handle high sulfur feedstocks without prior desulfurization.

Cesspool: An underground reservoir for liquid waste, typically household sewage.

Chlorofluorocarbon (CFC): Any of various compounds consisting of carbon, hydrogen, chlorine, and fluorine used as refrigerants. CFCs are now thought to be harmful to the earth’s atmosphere.

Clean Development Mechanism (CDM): A Kyoto Protocol program that enables industrialized countries to finance emissions-avoiding projects in developing countries and receive credit for reductions achieved against their own emissions limitation targets. See *Kyoto Protocol*.

Climate: The average course or condition of the weather over a period of years as exhibited by temperature, humidity, wind velocity, and precipitation.

Climate change: A term used to refer to all forms of climatic inconsistency, but especially to significant change from one prevailing climatic condition to another. In some cases, “climate change” has been used synonymously with the term “global warming”; scientists, however, tend to use the term in a wider sense inclusive of natural changes in climate, including climatic cooling.

Clinker: Powdered cement, produced by heating a properly proportioned mixture of finely ground raw materials (calcium carbonate, silica, alumina, and iron oxide) in a kiln to a temperature of about 2,700ºF.

Cloud condensation nuclei: Aerosol particles that provide a platform for the condensation of water vapor, resulting in clouds with higher droplet concentrations and increased albedo.

Coal coke: See *Coke (coal)*.

Coalbed methane: Methane is generated during coal formation and is contained in the coal microstructure. Typical recovery entails pumping water out of the coal to allow the gas to escape. Methane is the principal component of natural gas. Coalbed methane can be added to natural gas pipelines without any special treatment.

Coke (coal): A solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal from which the volatile constituents are driven off by baking in an oven at temperatures as high as 2,000 degrees Fahrenheit so that the fixed carbon and residual ash are fused together. Coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. Coke from coal is grey, hard, and porous and has a heating value of 24.8 million Btu per ton.

Coke (petroleum): A residue high in carbon content and low in hydrogen that is the final product of thermal decomposition in the condensation process in cracking. This product is reported as marketable coke or catalyst coke. The conversion is 5 barrels (of 42 U.S. gallons each) per short ton. Coke from petroleum has a heating value of 6.024 million Btu per barrel.

Combustion: Chemical oxidation accompanied by the generation of light and heat.

Combustion chamber: An enclosed vessel in which chemical oxidation of fuel occurs.

Conference of the Parties (COP): The collection of nations that have ratified the Framework Convention on Climate Change (FCCC). The primary role of the COP is to keep implementation of the FCCC under review and make the decisions necessary for its effective implementation. See *Framework Convention on Climate Change (FCCC)*.

Cracking: The refining process of breaking down the larger, heavier, and more complex hydrocarbon molecules into simpler and lighter molecules.

Criteria pollutant: A pollutant determined to be hazardous to human health and regulated under EPA's National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act require EPA to describe the health and welfare impacts of a pollutant as the "criteria" for inclusion in the regulatory regime.

Crop residue: Organic residue remaining after the harvesting and processing of a crop.

Cultivar: A horticulturally or agriculturally derived variety of a plant.

Deforestation: The net removal of trees from forested land.

Degasification system: The methods employed for removing methane from a coal seam that could not otherwise be removed by standard ventilation fans and thus would pose a substantial hazard to coal miners. These systems may be used prior to mining or during mining activities.

Degradable organic carbon: The portion of organic carbon present in such solid waste as paper, food waste, and yard waste that is susceptible to biochemical decomposition.

Desulfurization: The removal of sulfur, as from molten metals, petroleum oil, or flue gases.

Diffusive transport: The process by which particles of liquids or gases move from an area of higher concentration to an area of lower concentration.

Distillate fuel: A general classification for one of the petroleum fractions produced in conventional distillation operations. It includes diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. Products known as No. 1, No. 2, and No. 4 fuel oils are used primarily for space heating and electric power generation.

Efflux: An outward flow.

Electrical generating capacity: The full-load continuous power rating of electrical generating facilities, generators, prime movers, or other electric equipment (individually or collectively).

EMCON Methane Generation Model: A model for estimating the production of methane from municipal solid waste landfills.

Emissions: Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).

Emissions coefficient: A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., pounds of carbon dioxide emitted per Btu of fossil fuel consumed).

Enteric fermentation: A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

Eructation: An act or instance of belching.

ETBE (ethyl tertiary butyl ether): $(CH_3)_3COC_2H$: An oxygenate blend stock formed by the catalytic etherification of isobutylene with ethanol.

Ethylene: An olefinic hydrocarbon recovered from refinery processes or petrochemical processes. Ethylene is used as a petrochemical feedstock for numerous chemical applications and the production of consumer goods.

Ethylene dichloride: A colorless, oily liquid used as a solvent and fumigant for organic synthesis, and for ore flotation.

Facultative bacteria: Bacteria that grow equally well under aerobic and anaerobic conditions.

Flange: A rib or a rim for strength, for guiding, or for attachment to another object (e.g., on a pipe).

Flared: Gas disposed of by burning in flares usually at the production sites or at gas processing plants.

Flatus: Gas generated in the intestines or the stomach of an animal.

Flue gas desulfurization: Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Also referred to as scrubbers. Chemicals such as lime are used as scrubbing media.

Fluidized-bed combustion: A method of burning particulate fuel, such as coal, in which the amount of air required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of mineral ash in the proportions of 1 part fuel to 200 parts ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid.

Flux material: A substance used to promote fusion, e.g., of metals or minerals.

Fodder: Coarse food for domestic livestock.

Forestomach: See *Rumen*.

Fossil fuel: An energy source formed in the earths crust from decayed organic material. The common fossil fuels are petroleum, coal, and natural gas.

Framework Convention on Climate Change (FCCC): An agreement opened for signature at the "Earth Summit" in Rio de Janeiro, Brazil, on June 4, 1992, which has the goal of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent significant anthropogenically forced climate change. See *Climate change*.

Fuel cycle: The entire set of sequential processes or stages involved in the utilization of fuel, including extraction, transformation, transportation, and combustion. Emissions generally occur at each stage of the fuel cycle.

Fugitive emissions: Unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels.

Gasification: A method for converting coal, petroleum, biomass, wastes, or other carbon-containing materials into a gas that can be burned to generate power or processed into chemicals and fuels.

Gate station: Location where the pressure of natural gas being transferred from the transmission system to the distribution system is lowered for transport through small diameter, low pressure pipelines.

Geothermal: Pertaining to heat within the Earth.

Global climate change: See *Climate change*.

Global warming: An increase in the near surface temperature of the Earth. Global warming has occurred in the distant past as the result of natural influences, but the term is today most often used to refer to the warming that some scientists predict will occur as a result of increased anthropogenic emissions of greenhouse gases. See *Climate change*.

Global warming potential (GWP): An index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time, such as 100 years.

Greenhouse effect: The result of water vapor, carbon dioxide, and other atmospheric gases trapping radiant (infrared) energy, thereby keeping the earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap this radiation, which would otherwise escape into space, and subsequent re-radiation of some of this energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent. See *Greenhouse gases*.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving the Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

Gross gas withdrawal: The full-volume of compounds extracted at the wellhead, including nonhydrocarbon gases and natural gas plant liquids.

Gypsum: Calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), a sludge constituent from the conventional lime scrubber process, obtained as a byproduct of the dewatering operation and sold for commercial use.

Halogenated substances: A volatile compound containing halogens, such as chlorine, fluorine or bromine.

Halons: See *Bromofluorocarbons*.

Heating degree-days (HDD): A measure of how cold a location is over a period of time relative to a base temperature, most commonly specified as 65 degrees Fahrenheit. The measure is computed for each day by subtracting the average of the day's high and low temperatures from the base temperature (65 degrees), with negative values set equal to zero. Each day's heating degree-days are summed to create a heating degree-day measure for a specified reference period. Heating degree-days are used in energy analysis as an indicator of space heating energy requirements or use.

Herbivore: A plant-eating animal.

Hydrocarbon: An organic chemical compound of hydrogen and carbon in either gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simple (e.g., methane, a constituent of natural gas) to the very heavy and very complex.

Hydrochlorofluorocarbons (HCFCs): Chemicals composed of one or more carbon atoms and varying numbers of hydrogen, chlorine, and fluorine atoms.

Hydrofluorocarbons (HFCs): A group of man-made chemicals composed of one or two carbon atoms and varying numbers of hydrogen and fluorine atoms. Most HFCs have 100-year Global Warming Potentials in the thousands.

Hydroxyl radical (OH): An important chemical scavenger of many trace gases in the atmosphere that are greenhouse gases. Atmospheric concentrations of OH affect the atmospheric lifetimes of greenhouse gases, their abundance, and, ultimately, the effect they have on climate.

Intergovernmental Panel on Climate Change (IPCC): A panel established jointly in 1988 by the World Meteorological Organization and the United Nations Environment Program to assess the scientific information relating to climate change and to formulate realistic response strategies.

International bunker fuels: See *Bunker fuels.*

Jet fuel: A refined petroleum product used in jet aircraft engines. It includes kerosene-type jet fuel and naphtha-type jet fuel.

Joint Implementation (JI): Agreements made between two or more nations under the auspices of the Framework Convention on Climate Change (FCCC) whereby a developed country can receive “emissions reduction units” when it helps to finance projects that reduce net emissions in another developed country (including countries with economies in transition).

Kerosene: A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps. Kerosene has a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point, a final boiling point of 572 degrees Fahrenheit, and a minimum flash point of 100 degrees Fahrenheit. Included are No. 1-K and No. 2-K, the two grades recognized by ASTM Specification D 3699 as well as all other grades of kerosene called range or stove oil, which have properties similar to those of No. 1 fuel oil. See *Kerosene-type jet fuel.*

Kerosene-type jet fuel: A kerosene-based product having a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point and a final maximum boiling point of 572 degrees Fahrenheit and meeting ASTM Specification D 1655 and Military Specifications MIL-T-5624P and MIL-T-83133D (Grades JP-5 and JP-8). It is used for commercial and military turbojet and turboprop aircraft engines.

Kyoto Protocol: The result of negotiations at the third Conference of the Parties (COP-3) in Kyoto, Japan, in December of 1997. The Kyoto Protocol sets binding greenhouse gas emissions targets for countries that sign and ratify the agreement. The gases covered under the Protocol include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride.

Ketone-alcohol (cyclohexanol): An oily, colorless, hygroscopic liquid with a camphor-like odor. Used in soapmaking, dry cleaning, plasticizers, insecticides, and germicides.

Leachate: The liquid that has percolated through the soil or other medium.

Lignite: The lowest rank of coal, often referred to as brown coal, used almost exclusively as fuel for steam-electric power generation. It is brownish-black and has a high inherent moisture content, sometimes as high as 45 percent The heat content of lignite ranges from 9 to 17 million Btu per ton on a moist, mineral-matter-free basis. The heat content of lignite consumed in the United States averages 13 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

Liquefied petroleum gases: A group of hydrocarbon-based gases derived from crude oil refining or natural gas fractionation. They include ethane, ethylene, propane, propylene, normal butane, butylene, isobutane, and isobutylene. For convenience of transportation, these gases are liquefied through pressurization.

Lubricants: Substances used to reduce friction between bearing surfaces, or incorporated into other materials used as processing aids in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases.

Methane: A colorless, flammable, odorless hydrocarbon gas (CH4) which is the major component of natural gas. It is also an important source of hydrogen in various industrial processes. Methane is a greenhouse gas. See also *Greenhouse gases.*

Methanogens: Bacteria that synthesize methane, requiring completely anaerobic conditions for growth.

Methanol: A light alcohol that can be used for gasoline blending. See oxygenate.

Methanotrophs: Bacteria that use methane as food and oxidize it into carbon dioxide.

Methyl chloroform (trichloroethane): An industrial chemical (CH_3CCl_3) used as a solvent, aerosol propellant, and pesticide and for metal degreasing.

Methyl tertiary butyl ether (MTBE): A colorless, flammable, liquid oxygenated hydrocarbon containing 18.15 percent oxygen.

Methylene chloride: A colorless liquid, nonexplosive and practically nonflammable. Used as a refrigerant in centrifugal compressors, a solvent for organic materials, and a component in nonflammable paint removers.

Mole: The quantity of a compound or element that has a weight in grams numerically equal to its molecular weight. Also referred to as gram molecule or gram molecular weight.

Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer (1987). An international agreement, signed by most of the industrialized nations, to substantially reduce the use of chlorofluorocarbons (CFCs). Signed in January 1989, the original document called for a 50-percent reduction in CFC use by 1992 relative to 1986 levels. The subsequent London Agreement called for a complete elimination of CFC use by 2000. The Copenhagen Agreement, which called for a complete phaseout by January 1, 1996, was implemented by the U.S. Environmental Protection Agency.

Motor gasoline (finished): A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines. Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 to 158 degrees Fahrenheit at the 10 percent recovery point to 365 to 374 degrees Fahrenheit at the 90 percent recovery point. “Motor Gasoline” includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline, but excludes aviation gasoline. Note: Volumetric data on blending components, such as oxygenates, are not counted in data on finished motor gasoline until the blending components are blended into the gasoline.

Multiple cropping: A system of growing several crops on the same field in one year.

Municipal solid waste: Residential solid waste and some nonhazardous commercial, institutional, and industrial wastes.

Naphtha less than 401 degrees Fahrenheit: A naphtha with a boiling range of less than 401 degrees Fahrenheit that is intended for use as a petrochemical feedstock. Also see *Petrochemical feedstocks*.

Naphtha-type jet fuel: A fuel in the heavy naphtha boiling range having an average gravity of 52.8 degrees API, 20 to 90 percent distillation temperatures of 290 degrees to 470 degrees Fahrenheit, and meeting Military Specification MIL-T-5624L (Grade JP-4). It is used primarily for military turbojet and turboprop aircraft engines because it has a lower freeze point than other aviation fuels and meets engine requirements at high altitudes and speeds.

Natural gas: A mixture of hydrocarbons and small quantities of various nonhydrocarbons in the gaseous phase or in solution with crude oil in natural underground reservoirs.

Natural gas liquids (NGLs): Those hydrocarbons in natural gas that are separated as liquids from the gas. Includes natural gas plant liquids and lease condensate.

Natural gas, pipeline quality: A mixture of hydrocarbon compounds existing in the gaseous phase with sufficient energy content, generally above 900 Btu, and a small enough share of impurities for transport through commercial gas pipelines and sale to end-users.

Nitrogen oxides (NO_x): Compounds of nitrogen and oxygen produced by the burning of fossil fuels.

Nitrous oxide (N_2O): A colorless gas, naturally occurring in the atmosphere. Nitrous oxide has a 100-year Global Warming Potential of 310.

Nonmethane volatile organic compounds (NMVOCs): Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Octane: A flammable liquid hydrocarbon found in petroleum. Used as a standard to measure the antiknock properties of motor fuel.

Oil reservoir: An underground pool of liquid consisting of hydrocarbons, sulfur, oxygen, and nitrogen trapped within a geological formation and protected from evaporation by the overlying mineral strata.

Organic content: The share of a substance that is of animal or plant origin.

Organic waste: Waste material of animal or plant origin.

Oxidize: To chemically transform a substance by combining it with oxygen.

Oxygenates: Substances which, when added to gasoline, increase the amount of oxygen in that gasoline blend. Ethanol, Methyl Tertiary Butyl Ether (MTBE), Ethyl Tertiary Butyl Ether (ETBE), and methanol are common oxygenates.

Ozone: A molecule made up of three atoms of oxygen. Occurs naturally in the stratosphere and provides a protective layer shielding the Earth from harmful ultraviolet radiation. In the troposphere, it is a chemical oxidant, a greenhouse gas, and a major component of photochemical smog.

Ozone precursors: Chemical compounds, such as carbon monoxide, methane, nonmethane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone.

Paraffinic hydrocarbons: Straight-chain hydrocarbon compounds with the general formula C_nH_{2n+2}.

Perfluorocarbons (PFCs): A group of man-made chemicals composed of one or two carbon atoms and four to six fluorine atoms, containing no chlorine. PFCs have no commercial uses and are emitted as a byproduct of aluminum smelting and semiconductor manufacturing. PFCs have very high 100-year Global Warming Potentials and are very long-lived in the atmosphere.

Perfluoromethane: A compound (CF_4) emitted as a byproduct of aluminum smelting.

Petrochemical feedstocks: Chemical feedstocks derived from petroleum principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics.

Petroleum: A broadly defined class of liquid hydrocarbon mixtures. Included are crude oil, lease condensate, unfinished oils, refined products obtained from the processing of crude oil, and natural gas plant liquids. Note: Volumes of finished petroleum products include nonhydrocarbon compounds, such as additives and detergents, after they have been blended into the products.

Petroleum coke: See *Coke (petroleum)*.

Photosynthesis: The manufacture by plants of carbohydrates and oxygen from carbon dioxide and water in the presence of chlorophyll, with sunlight as the energy source. Carbon is sequestered and oxygen and water vapor are released in the process.

Pig iron: Crude, high-carbon iron produced by reduction of iron ore in a blast furnace.

Pipeline, distribution: A pipeline that conveys gas from a transmission pipeline to its ultimate consumer.

Pipeline, gathering: A pipeline that conveys gas from a production well / field to a gas processing plant or transmission pipeline for eventual delivery to end-use consumers.

Pipeline, transmission: A pipeline that conveys gas from a region where it is produced to a region where it is to be distributed.

Planetary albedo: The fraction of incident solar radiation that is reflected by the Earth-atmosphere system and returned to space, mostly by backscatter from clouds in the atmosphere.

Pneumatic device: A device moved or worked by air pressure.

Polystyrene: A polymer of styrene that is a rigid, transparent thermoplastic with good physical and electrical insulating properties, used in molded products, foams, and sheet materials.

Polyvinyl chloride (PVC): A polymer of vinyl chloride. Tasteless. odorless, insoluble in most organic solvents. A member of the family vinyl resin, used in soft flexible films for food packaging and in molded rigid products, such as pipes, fibers, upholstery, and bristles.

Post-mining emissions: Emissions of methane from coal occurring after the coal has been mined, during transport or pulverization.

Radiative forcing: A change in average net radiation at the top of the troposphere (known as the tropopause) because of a change in either incoming solar or exiting infrared radiation. A positive radiative forcing tends on average to warm the earth's surface; a negative radiative forcing on average tends to cool the earth's surface. Greenhouse gases, when emitted into the atmosphere, trap infrared energy radiated from the earth's surface and therefore tend to produce positive radiative forcing. See *Greenhouse gases*.

Radiatively active gases: Gases that absorb incoming solar radiation or outgoing infrared radiation, affecting the vertical temperature profile of the atmosphere. See *Radiative forcing*.

Ratoon crop: A crop cultivated from the shoots of a perennial plant.

Redox potential: A measurement of the state of oxidation of a system.

Reflectivity: The ratio of the energy carried by a wave after reflection from a surface to its energy before reflection.

Reforestation: Replanting of forests on lands that have recently been harvested or otherwise cleared of trees.

Reformulated gasoline: Finished motor gasoline formulated for use in motor vehicles, the composition and properties of which meet the requirements of the reformulated gasoline regulations promulgated by the U.S. Environmental Protection Agency under Section 211(k) of the Clean Air Act. Note: This category includes oxygenated fuels program reformulated gasoline (OPRG) but excludes reformulated gasoline blendstock for oxygenate blending (RBOB).

Renewable energy resources: Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

Residual fuel oil: A general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. It conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore powerplants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

Rumen: The large first compartment of the stomach of certain animals in which cellulose is broken down by the action of bacteria.

Sample: A set of measurements or outcomes selected from a given population.

Sequestration: See *Carbon sequestration*.

Septic tank: A tank in which the solid matter of continuously flowing sewage is disintegrated by bacteria.

Sinter: A chemical sedimentary rock deposited by precipitation from mineral waters, especially siliceous sinter and calcareous sinter.

Sodium silicate: A grey-white powder soluble in alkali and water, insoluble in alcohol and acid. Used to fireproof textiles, in petroleum refining and corrugated paperboard manufacture, and as an egg preservative. Also referred to as liquid gas, silicate of soda, sodium metasilicate, soluble glass, and water glass.

Sodium tripolyphosphate: A white powder used for water softening and as a food additive and texturizer.

Stabilization lagoon: A shallow artificial pond used for the treatment of wastewater. Treatment includes removal of solid material through sedimentation, the decomposition of organic material by bacteria, and the removal of nutrients by algae.

Still gas (refinery gas): Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. The principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Still gas is used as a refinery fuel and a petrochemical feedstock. The conversion factor is 6 million Btu per fuel oil equivalent barrel.

Stratosphere: The region of the upper atmosphere extending from the tropopause (8 to 15 kilometers altitude) to about 50 kilometers. Its thermal structure, which is determined by its radiation balance, is generally very stable with low humidity.

Stripper well: An oil or gas well that produces at relatively low rates. For oil, stripper production is usually defined as production rates of between 5 and 15 barrels of oil per day. Stripper gas production would generally be anything less than 60 thousand cubic feet per day.

Styrene: A colorless, toxic liquid with a strong aromatic aroma. Insoluble in water, soluble in alcohol and ether; polymerizes rapidly; can become explosive. Used to make polymers and copolymers, polystyrene plastics, and rubber.

Subbituminous coal: A coal whose properties range from those of lignite to those of bituminous coal and used primarily as fuel for steam-electric power generation. It may be dull, dark brown to black, soft and crumbly, at the lower end of the range, to bright, jet black, hard, and relatively strong, at the upper end. Subbituminous coal contains 20 to 30 percent inherent moisture by weight. The heat content of subbituminous coal ranges from 17 to 24 million Btu per ton on a moist, mineral-matter-free basis. The heat content of subbituminous coal consumed in the United States averages 17 to 18 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

Sulfur dioxide (SO_2): A toxic, irritating, colorless gas soluble in water, alcohol, and ether. Used as a chemical intermediate, in paper pulping and ore refining, and as a solvent.

Sulfur hexafluoride (SF_6): A colorless gas soluble in alcohol and ether, and slightly less soluble in water. It is used as a dielectric in electronics. It possesses the highest 100-year Global Warming Potential of any gas (23,900).

Sulfur oxides (SO_x): Compounds containing sulfur and oxygen, such as sulfur dioxide (SO_2) and sulfur trioxide (SO_3).

Tertiary amyl methyl ether ($(CH_3)_2(C_2H_5)COCH_3$): An oxygenate blend stock formed by the catalytic etherification of isoamylene with methanol.

Troposphere: The inner layer of the atmosphere below about 15 kilometers, within which there is normally a steady decrease of temperature with increasing altitude.

Nearly all clouds form and weather conditions manifest themselves within this region. Its thermal structure is caused primarily by the heating of the earth's surface by solar radiation, followed by heat transfer through turbulent mixing and convection.

Uncertainty: A measure used to quantify the plausible maximum and minimum values for emissions from any source, given the biases inherent in the methods used to calculate a point estimate and known sources of error.

Vapor displacement: The release of vapors that had previously occupied space above liquid fuels stored in tanks. These releases occur when tanks are emptied and filled.

Ventilation system: A method for reducing methane concentrations in coal mines to non-explosive levels by blowing air across the mine face and using large exhaust fans to remove methane while mining operations proceed.

Vessel bunkering: Includes sales for the fueling of commercial or private boats, such as pleasure craft, fishing boats, tugboats, and ocean-going vessels, including vessels operated by oil companies. Excluded are volumes sold to the U.S. Armed Forces.

Volatile organic compounds (VOCs): Organic compounds that participate in atmospheric photochemical reactions.

Volatile solids: A solid material that is readily decomposable at relatively low temperatures.

Waste flow: Quantity of a waste stream generated by an activity.

Wastewater: Water that has been used and contains dissolved or suspended waste materials.

Wastewater, domestic and commercial: Wastewater (sewage) produced by domestic and commercial establishments.

Wastewater, industrial: Wastewater produced by industrial processes.

Water vapor: Water in a vaporous form, especially when below boiling temperature and diffused (e.g., in the atmosphere).

Wax: A solid or semi-solid material derived from petroleum distillates or residues by such treatments as chilling, precipitating with a solvent, or de-oiling. It is a light-colored, more-or-less translucent crystalline mass, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Includes all marketable wax, whether crude scale or fully refined. The three grades included are microcrystalline, crystalline-fully refined, and crystalline-other. The conversion factor is 280 pounds per 42 U.S. gallons per barrel.

Weanling system: A cattle management system that places calves on feed starting at 165 days of age and continues until the animals have reached slaughter weight.

Wellhead: The point at which the crude (and / or natural gas) exits the ground. Following historical precedent, the volume and price for crude oil production are labeled as "wellhead," even though the cost and volume are now generally measured at the lease boundary. In the context of domestic crude price data, the term "wellhead" is the generic term used to reference the production site or lease property.

Wetlands: Areas regularly saturated by surface or groundwater and subsequently characterized by a prevalence of vegetation adapted for life in saturated-soil conditions.

Wood energy: Wood and wood products used as fuel, including roundwood (cordwood), limbwood, wood chips, bark, sawdust, forest residues, charcoal, pulp waste, and spent pulping liquor..

Yearling system: A cattle management system that includes a stocker period from 165 days of age to 425 days of age followed by a 140-day feedlot period.

Appendix A

Estimation Methods

Overview

The organization of this appendix generally follows the organization of the body of the report: the discussion is divided by greenhouse gas and by emissions source.

Carbon Dioxide

Most U.S. anthropogenic carbon dioxide emissions result from energy consumption. Energy production contributes a small amount from the flaring of natural gas at oil and gas wells and the scrubbing of carbon dioxide from natural gas, and a number of industrial processes also emit carbon dioxide through non-combustion processes. The largest single source of emissions from these processes is the calcination of limestone in cement production. Other sources include lime manufacture, limestone and dolomite consumption, soda ash manufacture and consumption, industrial carbon dioxide manufacture, and aluminum production. Lastly, some small adjustments are made to reach the total for national emissions as stipulated by the United Nations Framework Convention on Climate Change. This appendix describes each carbon dioxide emissions source, the estimation methods used, and the data sources.

Several emissions sources are excluded from the carbon dioxide emissions presented in this report, due either to the uncertainty of estimates or because they are based on biomass combustion (which is assumed to be consumed sustainably with a net flux of carbon dioxide to the atmosphere equal to zero). Should the energy use of biomass fuels result in a long-term decline in the total carbon embodied in standing biomass (e.g., forests), the net release of carbon would be treated as a land use issue (see Chapter 6).

Energy Consumption

Emissions Sources

Most U.S. commercial energy is produced through the combustion of fossil fuels, such as coal, natural gas, and petroleum. Chemically, the main components of fossil fuels are hydrocarbons, made up of molecules containing hydrogen and carbon atoms. When these fuels are burned, atmospheric oxygen combines with the hydrogen atoms to create water vapor and with the carbon atoms to create carbon dioxide. In principle, if the amount of fuel burned and the amount of carbon in the fuel are known, the volume of carbon dioxide emitted into the atmosphere can be computed with a high degree of precision. In practice, however, a combination of real-world complexities can reduce the precision of the estimate. These complexities are discussed further in this appendix. Nonetheless, energy-related carbon dioxide emissions are known with greater reliability than are other greenhouse gas emissions sources, and the uncertainty of the estimate is probably in the 3 to 5 percent range. Appendix C, “Uncertainty in Emissions Estimates,” contains an extended discussion of the nature and sources of uncertainty in the estimates.

One real-world complexity is that not all the carbon in fuel is perfectly combusted. About 1.5 percent of the carbon in fossil fuels is emitted in the form of carbon monoxide, which swiftly decays into carbon dioxide in the atmosphere. Another 1 percent is emitted in the form of non-methane volatile organic compounds, which also eventually decay into carbon dioxide. The carbon dioxide emissions reported in Chapter 2 include all “potential” carbon dioxide emissions from the sources covered, including both carbon dioxide emitted directly and carbon emitted in other forms (such as carbon monoxide) that rapidly decay into carbon dioxide in the atmosphere.

Estimation Methods

Carbon emissions in this report were calculated by multiplying energy consumption for each fuel type by an associated carbon emissions coefficient. The result was then modified by subtracting carbon sequestered by nonfuel use. This section describes the derivation of information on energy consumption, emissions coefficients, and carbon sequestered by nonfuel use.

Consumption Data

The Energy Information Administration (EIA) collects a wide variety of information from primary suppliers on a frequent basis and from energy consumers less often, but still in a timely manner. Thus, levels of energy consumption in the United States are fairly well known by end-use sector and detailed fuel type.[1] To estimate carbon dioxide emissions, EIA uses annual data from the four end-use sectors (residential, commercial, industrial, and transportation) and for all the fossil fuels (coal, natural gas, and the full slate of petroleum products). The petroleum products include asphalt and road oil, aviation gasoline, distillate fuel, jet fuel, kerosene, liquefied petroleum gases (LPG), lubricants, motor gasoline, residential fuel, and other petroleum products. Definitions and heating values of the fossil fuels are documented in the appendixes of EIA's recurring reports: the *Annual Energy Review (AER)* and *State Energy Data Report (SEDR)*, as well as the *Petroleum Supply Annual*, *Coal Industry Annual*, and *Natural Gas Annual*. This approach to estimating emissions enables EIA to provide detailed information about trends in sources of emissions.

Information about consumption of "other petroleum" is derived from unpublished EIA data. In recent years, these products have included crude oil, naphtha with a boiling temperature $<401^{o}$F, petrochemical feedstocks with a boiling temperature $\geq 401^{o}$F, motor gasoline blending components, miscellaneous products, petroleum coke, pentanes plus, still gas, special naphthas, waxes, and unfinished oils.

Emission Coefficients

The amount of carbon released when a fossil fuel is burned depends on the density, carbon content, and gross heat of combustion of the fuel.[2] Most of the coefficients for major fuels are assumed to be constant over time. However, for motor gasoline, LPG, jet fuel, and crude oil, EIA developed annualized carbon emission coefficients to reflect changes in chemical composition or product mix over the years. Appendix B contains a more detailed discussion of the methods employed for developing the coefficients. Table B1 in Appendix B presents a full listing of emissions factors for crude oil, natural gas, and the complete slate of petroleum products.

Data Series Revisions Underlying Changes in Electric Power Fuel Use Estimates

Chapter 2 provides information on resulting changes to the emissions estimates brought about by EIA revisions to key data series. Presented in table A1 below are the underlying changes to the fuel consumption values from one Annual Energy Review to the next.

Revisions resulting from changing the source of fuel consumption data for nonutilities and from EIA's data review affect data beyond the category of nonutilities. For example, the revised estimate of natural gas consumption for 2000 is 3 percent higher in the *Annual Energy Review 2001* than in *Annual Energy Review 2000* (Table A1*).*

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[1] Although some of EIA's detailed sectoral surveys are conducted only every 4 years on a sample basis, EIA collects information about apparent consumption of petroleum products (taken as "petroleum product supplied") in mandatory monthly surveys of primary suppliers (e.g., refiners, pipeline operators, importers/exporters, and bulk terminal operators).

[2] Combustion of hydrocarbons results in the production of carbon dioxide, water vapor, and heat. In the United States, the heat resulting from combustion is generally measured as the heat associated with production of water vapor and carbon dioxide. This is commonly referred to as the "higher" or "gross" heating value and is used in EIA statistics on thermal energy. The estimates in this report consistently employ coefficients that reflect the higher heating value assumption. Internationally, however, the "lower" heating value is used. If the lower heating value were used, the Btu content of the fuel would be 5 to 10 percent lower, and the coefficients would be 5 to 10 percent larger, but the carbon emissions estimate would be unchanged. This is sometimes a source of discrepancy. See 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.

Table A1. Revisions to Selected Estimates: AER 2001 and AER 2000 Electricity Net Generation: Total (All Sectors)
(Billion Kilowatthours)

Year	AER 2000	AER 2001	Percent Difference
1998	3,618	3,620	0.1
1999	3,706	3,695	-0.3
2000	3,792	3,802	0.3
Total Natural Gas Consumption			
(Trillion Cubic feet)			
Year	**AER 2000**	**AER 2001**	**Percent Difference**
1998	21.26	22.24	4.6
1999	21.70	22.40	3.2
2000	22.71	23.46	3.3
Total Coal Consumption			
(Million Short Tons)			
Year	**AER 2000**	**AER 2001**	**Percent Difference**
1998	1,038.3	1,037.1	-0.1
1999	1,045.3	1,038.6	-0.6
2000	1,079.7	1,084.1	0.4
Total Petroleum Consumption			
(Million Barrels Per Day)			
Year	**AER 2000**	**AER 2001**	**Percent Difference**
1998	18.92	18.92	0.0
1999	19.52	19.52	0.0
2000	19.48	19.70	1.1
Total Renewable Energy Consumption			
(Trillion Btu)			
Year	**AER 2000**	**AER 2001**	**Percent Difference**
1998	6,977	6,782	-2.8
1999	7,226	6,790	-6.0
2000	6,823	6,465	-5.2

Sources: Electricity Net Generation, Table 8.1 of *AER 2000* and *AER 2001.* Natural Gas, Consumption, Table 6.5 of *AER 2000* and *AER 2001.* Coal Consumption, Table 6.5 of *AER 2000* and *AER 2001.* Petroleum Consumption, Table 5.12 of *AER 2000* and *AER 2001.* Renewable Energy Consumption, Table 10.2b of *AER 2000* and *AER 2001.*

Changes to Energy Consumption Data

While, in general, emissions can be estimated simply by multiplying fuel consumption by the appropriate emissions coefficients, several small adjustments to EIA energy statistics are necessary to eliminate double counting or miscounting of emissions. Usually the adjustments amount to less than 0.1 percent of energy-related carbon emissions. They include:

- **Ethanol.** About 70 million barrels of ethanol are included in annual U.S. gasoline consumption after 1992. Because ethanol is a biofuel, the carbon it contains should not be counted as an emission. Hence, carbon from ethanol is deducted from transportation gasoline consumption. Ethanol consumption is reported in EIA's *Renewable Energy Annual* and the *Petroleum Supply Annual*.

- **Synthetic gas from coal.** Small amounts of "supplemental gas," particularly, gas from the Great Plains Coal Gasification Plant in North Dakota, are manufactured from coal. The coal is counted in industrial energy consumption, and the gas is shipped into the pipeline system. EIA deducts the carbon in synthetic gas (as reported in the *Natural Gas Annual*) from industrial coal emissions.

- **Still gas to pipelines.** Several refineries sell small volumes of "still gas" as supplemental gas to pipelines. EIA deducts the carbon in still gas sales to pipelines (as reported in the *Natural Gas Annual*) from industrial "other petroleum" consumption.

- **Biogas.** The *Natural Gas Annual* reports that small volumes of "supplemental gas" of biological origin (probably landfill gas) are incorporated in U.S. pipeline gas supplies. In keeping with the accounting rule of excluding carbon of biological origin, these supplies are deducted from U.S. natural gas consumption.

- **Carbon dioxide in geothermal steam.** Geothermal steam at The Geysers in Guerneyville, California, where most U.S. geothermal electric power is generated, contains carbon dioxide dissolved in the steam, which is released into the atmosphere when the steam is brought to the Earth's surface for power production. EIA includes emissions from this source, at a rate of about 0.1 million metric tons of carbon per year.

Carbon Sequestration: Nonfuel Use of Fossil Fuels

Gross emissions can be estimated by multiplying fossil fuel consumption by an emissions factor embodying the estimated carbon content of the fuel. However, portions of the fossil fuels consumed are not actually combusted but are used as chemical feedstocks, construction materials, lubricants, solvents, or reducing agents (Table A2). EIA estimates "nonfuel" use of fossil fuels annually in Table 1.15 of the *Annual Energy Review*.[3] For this report, EIA has estimated the fate of the carbon in fuels used for nonfuel purposes (see Table 5 in Chapter 2), based on the rates of sequestration shown in Table A3. Some but not all of the carbon is emitted to the atmosphere. The principal nonfuel uses of fossil fuels, the methods of estimating nonfuel consumption, and the fate of the carbon are listed below.

Table A2 Fossil Fuel Consumption for Nonfuel Use, 1990-2001 (Quadrillion Btu)

Year	Asphalt & Road Oil	LPG	Pentanes Plus	Lubricants	Petrochem Feedstocks	Petroleum Coke	Special Naphtha	Other Petroleum	Total Petroleum	Natural Gas	Coal	Total Energy
1990	1.17	1.20	0.08	0.36	1.12	0.18	0.11	0.23	4.45	0.59	0.02	5.06
1991	1.08	1.38	0.04	0.32	1.15	0.15	0.09	0.26	4.47	0.59	0.02	5.08
1992	1.10	1.39	0.06	0.33	1.20	0.23	0.10	0.20	4.63	0.61	0.04	5.28
1993	1.15	1.35	0.28	0.34	1.22	0.12	0.10	0.20	4.76	0.61	0.03	5.40
1994	1.17	1.55	0.26	0.35	1.26	0.14	0.08	0.20	5.01	0.69	0.03	5.73
1995	1.18	1.59	0.30	0.35	1.21	0.13	0.07	0.20	5.03	0.67	0.03	5.72
1996	1.18	1.65	0.32	0.34	1.21	0.15	0.07	0.20	5.11	0.68	0.03	5.82
1997	1.22	1.67	0.30	0.35	1.40	0.12	0.07	0.21	5.34	0.70	0.03	6.07
1998	1.26	1.60	0.27	0.37	1.40	0.21	0.11	0.23	5.45	0.79	0.03	6.27
1999	1.32	1.81	0.33	0.37	1.33	0.28	0.15	0.22	5.81	0.69	0.03	6.53
2000	1.28	1.86	0.31	0.37	1.35	0.14	0.10	0.22	5.62	0.71	0.03	6.35
2001	1.26	1.69	0.24	0.34	1.19	0.18	0.08	0.23	5.20	0.67	0.02	5.89

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).
Source: Energy Information Administration, *Annual Energy Review 2001*, DOE/EIA-0384(2001) (Washington, DC, November 2002), Table 1.15, p. 33, and underlying estimates.

- **Natural Gas.** Nonfuel use of natural gas is based on periodic (1985, 1988, 1991, 1994 and 1998) reports in EIA's Manufacturing Energy Consumption Survey (MECS). Based on MECS, nonfuel use is divided into three categories: nitrogenous fertilizers, other chemical use, and all other nonfuel uses. Feedstock use of natural gas to make nitrogenous fertilizers is a nonsequestering use, because the underlying chemical in nitrogenous fertilizers is ammonia (NH_3), which is manufactured by steam reforming of natural gas and reacting the synthesis gas with atmospheric nitrogen, leaving the carbon in the feedstock literally "up in the air." In many cases, the carbon dioxide is recovered to make urea or for industrial use. However, carbon in urea and industrial carbon dioxide are generally only temporarily delayed on their way to the atmosphere. EIA assumes that other nonfuel uses in the chemical industry result in 100-percent carbon sequestration. Natural gas is used as a feedstock for a range of chemical products other than ammonia, particularly methanol. Although the methanol used to make methyl tertiary butyl ether (MTBE) winds up in the gasoline pool and is combusted, EIA already counts the carbon in MTBE in gasoline emissions, and to count it again in the feedstock would be double counting. Future research on the fate of the carbon in feedstocks for other chemical industry uses will probably gradually reduce the 100-percent sequestration share currently assumed.

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[3] Energy Information Administration, *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, August 2001), p. 33.

- **Liquefied Petroleum Gases.** Nonfuel use of LPG (ethane, propane, and butane) through 1996 is estimated on the basis of sales of these products to the chemical industry, as reported in the American Petroleum Institute (API) survey, *Sales of Natural Gas Liquids and Liquefied Refinery Gases*, from which EIA deducts chemical industry fuel use of LPG as reported periodically in the MECS. For 1997-2000 the sales to the chemical industry are estimated based on the 1996 ratio of the API's data to EIA's *Petroleum Supply Annual* (PSA) value for LPG, which is then multiplied by the PSA data for 1997-2000. Most of the ethane, propane, and butane used by the chemical industry is used to manufacture ethylene, propylene, and butadiene, respectively, all of which are intermediate products for plastics. Following the recommendation of the Intergovernmental Panel on Climate Change (IPCC), EIA assumes that 80 percent of nonfuel use is sequestered in plastics, synthetic rubber, and related products.[4]

- **Asphalt and Road Oil.** EIA assumes that asphalt and road oil use is nonfuel use by definition, and that all carbon in asphalt and road oil is sequestered.

- **Pentanes Plus.** "Pentanes plus" are hydrocarbons heavier than butane extracted from natural gas at gas processing plants. Their principal uses are as contributors to the gasoline pool and as petrochemical feedstocks. Nonfuel use of pentanes plus is estimated on the basis of the API's annual survey of natural gas liquids and refinery gases sold to the chemical industry. Following IPCC practice for LPG, EIA assumes that 80 percent of the carbon in pentanes plus used by the chemical industry is sequestered.

- **Petrochemical Feedstocks.** EIA's petroleum surveys recognize two categories of products called "petrochemical feedstocks." These are presumably naphtha and gas oils destined for ethylene crackers, and probably some mix of aromatic hydrocarbons (benzene, toluene, and xylene) and feedstocks used to make aromatic hydrocarbons. All petrochemical feedstock supplies are included in nonfuel use by definition, and, following the practice of the IPCC, EIA assumes that 75 percent of the carbon in synthetic feedstocks and 50 percent of the carbon in gas oil feedstock is sequestered in plastics, synthetic fibers, and related products.

- **Distillate and Residual Fuels.** The MECS reports small volumes (10 million barrels and 1 million barrels, respectively) of distillate and residual oils used for nonfuel purposes in the chemical industry. Following the practice for gas oil petrochemical feedstocks, EIA assumes 50-percent sequestration. Future research may shed more light on the industrial processes that use these fuels.

- **Petroleum Coke.** Petroleum coke is a coal-like solid, about 90 percent carbon by weight, created after intensive extraction of lighter hydrocarbons from petroleum feedstocks by oil refiners. Most petroleum coke is used in the refineries as fuel or as a catalyst. EIA estimates nonfuel use by taking the quantity of petroleum coke supplied and deducting all known fuel uses (refinery use from the *Petroleum Supply Annual*, electric utility use from the *Electric Power Annual*, and industrial use from the MECS). EIA assumes that 50 percent of the carbon in petroleum coke for nonfuel use is sequestered. It should be noted, however, that significant sequestering nonfuel uses of petroleum coke in the United States are difficult to identify. In conjunction with the Environmental Protection Agency this estimate is currently under evaluation and it may yield a downward estimation in the sequestering amounts allocated to petroleum coke. The principal identified nonfuel use is for sacrificial anodes in primary aluminum smelting, a nonsequestering use that EIA counts separately under process emissions (see the next section). It appears that petroleum coke is also used in small quantities by many different industries as a reducing agent (a source of carbon monoxide that, in turn, can be used to scour oxygen from products such as lead oxide (to produce lead) or iron oxide (to produce iron). These are, however, nonsequestering uses.

- **Still Gas.** Still gas is the gas that floats to the top of distillation columns in oil refineries. Its chemical composition is a highly variable blend of free hydrogen, methane, carbon monoxide, and heavier hydrocarbons, depending on the refinery process, the feedstock, and process conditions. EIA estimates nonfuel use by deducting all known fuel uses (refinery fuel use from the *Petroleum Supply Annual* and pipeline gas supplies from the *Natural Gas Annual*). The remainder is assumed to be dispatched to chemical plants as a feedstock. Following the IPCC practice for LPG, EIA assumes that 80 percent of the carbon in still gas is sequestered.

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[4] 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. 1.28, web site www.ipcc.ch/pub/guide.htm.

Table A3. Rates of Sequestration for U.S. Fossil Fuel Consumption

Fuel Type	Fraction of Fuel Combusted	Fraction of Nonfuel Use of Energy Sequestered
Petroleum		
Motor Gasoline	0.99	--
LPG	0.995	0.8
Jet Fuel	0.99	--
Distillate Fuel	0.99	0.5
Residual Fuel	0.99	0.5
Asphalt and Road Oil	0.99	1
Lubricants	0.99	0.5
Petrochemical Feed	0.99	0.75
Aviation Gas	0.99	--
Kerosene	0.99	--
Petroleum Coke	0.99	0.5
Special Naphtha	0.99	0
Other		
Aviation Gas		
Blending Components	0.99	--
Crude Oil	0.99	--
Naphtha <401oF	0.99	0.75
Other Oil 401oF	0.99	0.5
Petrochemical Feed		
Still Gas	0.99	0.8
Motor Gasoline		
Blending Components	0.99	--
Miscellaneous	0.99	1
Natural Gasoline	0.99	--
Plant Condensate	0.99	--
Pentanes Plus	0.99	0.8
Still Gas	0.995	--
Special Naphthas	0.99	0
Unfinished Oils	0.99	--
Unfractionated Stream	0.99	--
Waxes	0.99	1
Coal		
Residential and Commercial	0.99	--
Industrial Coking	0.99	0.75
Industrial Other	0.99	--
Electric Utility	0.99	--
Natural Gas		
Flare Gas	1	--
Natural Gas	0.995	0.29-0.52
Crude Oil	0.99	--

Sources: EIA estimates documented in this chapter; 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), pp. 1.28-1.29, web site.

- **Special Naphtha.** “Special naphtha” is a catch-all for an array of hydrocarbon-based solvents, such as hexane and the volatile oils used in petroleum-based paint. In general, solvents evaporate into the atmosphere as “nonmethane volatile organic compounds” after use and swiftly weather into atmospheric carbon dioxide. EIA assumes that all special naphthas are for nonfuel use and that no carbon in special naphtha is sequestered.

- **Lubricants.** The most common petroleum-based lubricant is motor oil, but the category also includes numerous other products, such as industrial greases. Following the IPCC, EIA assumes that 50 percent of the carbon in lubricants is sequestered. The ultimate fate of lubricants is not easy to determine. For example, it is often the case that “recycling” motor oil means burning it as boiler fuel.

- **Waxes and Polishes.** The principal use of waxes is to make wax paper and food packaging materials, which usually end up in landfills. Following the IPCC, EIA assumes 100-percent nonfuel use and 100-percent carbon sequestration for these materials.

- **Miscellaneous.** EIA assumes 100-percent nonfuel use and 100-percent carbon sequestration for this category.

- **Coal.** The manufacture of coke is the largest nonfuel use of coal. By convention, however, coke manufacture is treated as a fuel use. This is not unreasonable, because coke is almost always ultimately combusted. Coke is manufactured by “cooking” high-grade coal in huge ovens in the absence of oxygen. Volatile materials, moisture, and certain categories of impurities are driven off, leaving behind a high-carbon material suitable for metallurgical use. Among the byproducts of the process are “coal tars” or “coal liquids,” which typically are rich in aromatic hydrocarbons, such as benzene. Coal tars generally are used as feedstocks in the chemical industry. “Nonfuel use” of coal, as defined for this report, consists of the coal tars driven off during the manufacture of coke. Coal tar production was obtained, for years prior to 1995, from the International Trade Commission’s *Synthetic Organic Chemicals*. Since 1995, production has been estimated on the basis of the ratio of 1994 coke production to coal tar production. Following the IPCC guidelines, EIA assumes that 75 percent of the carbon in coal tars is sequestered.

Carbon Sequestration: Fraction Combusted

A small amount of carbon sequestration is associated with the combustion of fossil fuels. Using IPCC assumptions, EIA assumes that oxidation of liquid and solid fuels during combustion is 99 percent complete, and that 1 percent of the carbon remains sequestered. Oxidation of gaseous fuels (LPG and natural gas) is assumed to be 99.5 percent complete.[5] Conceptually, fuel may be “lost” before combustion due to evaporation, leaks, or spills; it may be subject to incomplete combustion and vented to the atmosphere in the form of volatile organic compounds or particulates; or it may remain at the site of combustion in the form of carbon-containing ash or soot.

Data Sources

Fossil Fuel Consumption: (1990-1997), Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(97) (Washington, DC, September 1999). (1998-2001), Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384(2001) (Washington, DC, November 2002); *Petroleum Supply Annual 2001*, DOE/EIA-0340(2001)/1 (Washington, DC, June 2002); *Natural Gas Annual 2000*, DOE/EIA-0131(2000) (Washington, DC, October 2001); and *Renewable Energy Annual 2001*, DOE/EIA-0603(2001) (Washington, DC, December 2001).

Nonfuel Use of Energy and Biofuels Consumption: Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384(2001) (Washington, DC, November 2002); ; Energy Information Administration, *Manufacturing Consumption of Energy*, DOE/EIA-0512(various years) (Washington, DC); American Petroleum Institute, *Sales of Natural Gas Liquids and Liquefied Refinery Gas* (various years); U.S. International Trade Commission, *Synthetic Organic Chemicals*, USITC Publication 2933 (various years through 1994); 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. 1.28,www.ipcc.ch/pub/guide.htm

Adjustments to U.S. Energy Consumption

In recent years, there have been several estimates of U.S. carbon emissions, some of which differ by as much as 5 percent. Two significant reasons for the differences in emissions estimates (beyond those associated with differences in coefficients) are the definitions of “energy consumption” and “the United States” employed by researchers. Subtle differences in definition can produce variations of several percentage points in reported energy consumption and, hence, in carbon emissions. Some estimates include U.S. territories while others exclude them. If consumption is estimated as “apparent consumption” based on production plus imports minus exports plus stock change, then statistical discrepancies will be included in consumption. International bunker fuels are sometimes counted as domestic consumption and sometimes as exports. This section describes how each adjustment is accommodated in the EIA estimates.

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[5] 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. 1.29, web site www.ipcc.ch/pub/guide.htm.

U.S. Territories

Emissions Sources

EIA's energy data for the United States cover only the 50 States and the District of Columbia. In contrast, energy data produced by the International Energy Agency for the United States cover the 50 States plus U.S. territories, including Puerto Rico, the U.S. Virgin Islands, and Guam. Annual energy consumption in the U.S. territories is only about 0.5 quadrillion Btu (Table A4). For the territories as a group, oil consumption ranges between 220,000 and 325,000 barrels per day, and coal consumption averages 315,000 to 425,000 short tons per year, in the U.S. Virgin Islands and Puerto Rico.

Estimation Methods

Energy consumption for U.S. territories is converted to carbon emissions by using the same emissions coefficients applied to U.S. energy data. Carbon emissions for U.S. territories range from 9 to 12 million metric tons per year (see Table 4 in Chapter 2). Because a large portion of reported energy consumption in U.S. territories is from "other petroleum," there is a degree of uncertainty about the correct emissions factor to be used in this area, as well as the reliability of underlying data.

Data Sources

1990-2000: Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (various years), and unpublished data included in "Other" countries in the Asia/Pacific region. Data are shown in tables of "Apparent Consumption of Petroleum Products." Data for 2001 based on unpublished preliminary information.

Table A4. U.S. Territories Primary Energy Consumption (Btu), 1990, 1992-2001
(Quadrillion Btu)

Territory	1990	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
Puerto Rico	0.30	0.33	0.35	0.35	0.35	0.33	0.33	0.34	0.33	0.35	0.38
Virgin Islands, U.S.	0.12	0.12	0.12	0.12	0.19	0.16	0.20	0.26	0.31	0.31	0.32
American Samoa	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Guam	0.03	0.04	0.05	0.07	0.05	0.04	0.05	0.04	0.05	0.05	0.05
Hawaiian Trade Zone	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
U.S. Pacific Islands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.004
Wake Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	**0.47**	**0.52**	**0.54**	**0.57**	**0.62**	**0.57**	**0.61**	**0.68**	**0.71**	**0.75**	**0.78**

*Less than 5 trillion Btu.
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).
Sources: Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (various years), and unpublished data included in "Other" countries in the Asia/Pacific region. Data are shown in tables of "Apparent Consumption of Petroleum Products." Data for 2001 based on unpublished preliminary information.

International Bunker Fuels

Emissions Sources

The term "international bunker fuels" refers to fuels sold to and consumed by air or marine vessels engaging in international transport activities. By convention, trade statistics treat the sale of bunker fuels as a form of export by the selling country, because the purchaser promptly hauls the fuel outside national boundaries. This convention is followed by organizations that prepare international energy statistics, such as the United Nations and the International Energy Agency.

Bunker fuels, however, are an export without a corresponding import, because the purchasing vessel generally combusts the fuel during transport. EIA energy statistics, which are based on domestic sales of products, treat bunker fuels sales in the same manner as the sale of other fuels, i.e. as domestic energy consumption. Therefore, carbon emissions from bunker fuels are already incorporated in the domestic energy consumption statistics of the

United States, primarily as transportation-related consumption of residual and distillate fuel oil by cargo and passenger vessels and kerosene-based jet fuel by commercial aircraft. Table A5 shows U.S. international bunker fuel usage. Beginning with the 1999 data year, we have included estimates for military bunker fuels that make up about 10 percent of the total category.

Estimation Methods

Carbon coefficients are applied to annual consumption estimates for each of the relevant international bunker fuels, namely residual and distillate fuel oil to account for international marine bunkers, and kerosene-based jet fuel for international aviation bunkers. It is assumed that 99 percent of the fuel is combusted. Consumption estimates for distillate and residual fuel oil are each taken as the sum of oil laden on American and foreign ocean-going vessels in the United States. Since the data available for jet fuel consumption by U.S. air carriers reflects total fuel consumed on international routes, EIA estimates assume that domestic fuel purchases for outgoing international flights are 50 percent of this total. Jet fuel consumption by foreign air carriers fueled in the United States are based on the share of total expenses by these air carriers in U.S. ports that account for fuel and oil purchases, multiplied by the average annual price of jet fuel in U.S. ports. The estimate of military bunker fuels is obtained from the EPA inventory of the previous year. The 1999 estimate is used as a proxy for 2000 emissions.

Data Sources

1990-2001: U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division, “Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries” (unpublished, various years); EIA estimate. (1988-2001): U.S. Department of Commerce, Bureau of Economic Analysis, unpublished BE-36 survey data (various years); Air Transportation Association, *Monthly Fuel Cost and Consumption* (various years), web site www.air-transport.org/public/industry/16.asp. Military Bunker Fuels: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*(Washington, DC 20460) April 2002.

Table A5. Consumption and Carbon emissions from International Bunker Fuels Supplied in the United States, 1990,1992-2001

Item	1990	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
Carbon Emissions (MMTCE)											
Marine Bunkers											
Distillate	1.7	1.5	1.7	1.4	1.6	1.2	1.2	1.7	0.8	0.8	0.6
Residual	15.2	14.3	11.4	11.2	11.1	11.4	12.2	12.7	10.4	9.4	9.1
Total Marine	*16.9*	*15.8*	*13.0*	*12.6*	*12.7*	*12.7*	*13.4*	*14.4*	*11.3*	*10.2*	*9.7*
Aviation Bunkers											
US Carriers	5.0	5.3	5.3	5.5	5.7	6.0	6.3	6.6	6.8	7.1	6.8
Foreign Carriers	5.3	5.6	5.8	6.0	6.6	6.8	7.6	7.6	8.5	7.8	7.9
Total Aviation	*10.4*	*11.0*	*11.1*	*11.5*	*12.4*	*12.8*	*13.9*	*14.2*	*15.3*	*14.9*	*14.6*
Total	27.3	26.7	24.2	24.1	25.1	25.4	27.3	28.6	26.6	25.1	24.2
Internat'l Bunker Fuels Consumed (Quadrillion Btu)											
Marine	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.7	0.5	0.5	0.5
Aviation	0.5	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8
Total	**1.3**	**1.3**	**1.2**	**1.2**	**1.2**	**1.3**	**1.4**	**1.4**	**1.3**	**1.3**	**1.2**

P = preliminary data.

Source: Distillate and Residual Fuels (1980-1987): Energy Information Administration, International Energy Annual, DOE/EIA-0219 (Washington, DC). (1988-2000); U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division, "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries", (Unpublished). Jet Fuels (1980-1987): Oak Ridge National Laboratory, Transportation Energy Data Book (Oak Ridge, TN, various years). (1988-2000): U.S. Department of Commerce, Bureau of Economic Analysis, Unpublished BE-36 survey data (various years). Air Transportation Association, Monthly Fuel Cost and Consumption (various years), see web site http://www.air-transport.org/public/industry/31.asp

Other Carbon Dioxide Emissions

Other carbon dioxide emissions include emissions from energy production and industrial emissions that are not caused by the combustion or feedstock use of commercial fossil fuels. These emissions typically are created either by the combustion of waste products containing fossil carbon (natural gas flaring) or by chemical reactions with carbon-containing minerals (for example, calcining sodium carbonate [limestone] to make lime or cement).

Energy Production

Emissions Sources

U.S. energy production also generates small volumes of carbon dioxide emissions. The two principal sources are the flaring of natural gas and the venting of carbon dioxide produced in conjunction with natural gas.[6] When a field is developed for petroleum extraction, any natural gas associated with that field may be flared if its use is not economically justifiable. This is typically the case for remote sites or when the gas is of poor quality or minimal volume. During natural gas production, flaring may be used for disposal of waste products (e.g., hydrogen sulfide), capacity testing, or as a result of process upsets.

Emissions from the second source, carbon dioxide produced in conjunction with natural gas, occur during production activities. Natural gas is actually a mixture of several different gases including carbon dioxide. If the carbon dioxide content of natural gas is large enough to reduce the heating value of the gas below the specification for pipeline gas (870 Btu per standard cubic foot), the carbon dioxide is typically extracted by amine scrubbing. The extracted carbon dioxide generally is released to the atmosphere.

Estimation Methods

The method for estimating emissions from natural gas flaring is based on the volume of vented and flared gas reported to EIA (assuming that all gas is flared). To calculate carbon emissions, the figures are aggregated, converted into Btu, and then multiplied by an emissions coefficient of 14.92 million metric tons of carbon per quadrillion Btu.

As estimates presented in Chapter 2 indicate, natural gas flaring is a minor source of emissions, accounting for only about 2 to 5 million metric tons of carbon annually. There is some uncertainty associated with this estimate, given that operators in the field are not required to meter gas that is vented or flared.

The carbon dioxide produced in conjunction with natural gas is estimated by multiplying regional natural gas production data by regional carbon dioxide contents from a Gas Research Institute (GRI) study. The estimates of carbon dioxide emitted during transmission and distribution are derived by multiplying pipeline and end-use consumption data by the carbon dioxide content of natural gas delivered to consumers from a second GRI study. Emissions associated with production activities are calculated by subtracting consumption-related emissions from the total carbon dioxide initially produced. For 1999 through 2001 the 1998 value was moved by production of dry gas in quadrillion Btu as it appears in Table 1.3 of the *Monthly Energy Review July 2002*.

Data Sources

Flaring (1980-2000): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). (2001): *Natural Gas Monthly*, DOE/EIA-0130(2002/08) (Washington, DC, August 2002). Carbon Dioxide Produced with Natural Gas: Composition (1980-1998): Gas Research Institute, *Chemical Composition of Discovered and Undiscovered Natural Gas in the United States: 1993 Update*, GRI-93/0456.1; Gas Research Institute, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*, GRI-92/0123. Production (1980-1996): Dwight's Energy Data Lease/Well Production File. (1997-1998): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, 1999). (1999, 2000) Energy Information Administration, *Monthly Energy Review*, DOE/EIA-035(2001/07) (Washington, DC, July 2001). Transmission and End-Use Consumption (1980-1998): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). (1999): Energy Information Administration, *Natural Gas Monthly*, DOE/EIA-0130(2000/06) (Washington, DC, June 2000).

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[6] See discussion of carbon dioxide manufacture for the treatment of vented carbon dioxide.

Industrial Processes

In addition to energy-related emissions, carbon dioxide is also produced during certain industrial processes. The primary source of industrial emissions is the calcination of limestone ($CaCO_3$) to create lime (CaO). These two compounds are basic materials in a variety of manufacturing processes, particularly cement, iron and steel, and glass. Other sources of industrial emissions include the production and use of soda ash (Na_2CO_3), the manufacture of carbon dioxide, and aluminum production.

For this source category, emissions estimates are based on the compound used in the industrial process. Table A6 shows activity data for industrial processes. By multiplying the amount of production or consumption of the compound by a carbon coefficient (the relative amount of carbon in that compound), a process-specific estimate is derived. During the period 1990 through 2000, carbon dioxide emissions from industrial sources have ranged from 16 to 19 million metric tons of carbon annually. Each industrial process, emissions source, and estimation method is discussed below.

Cement Manufacture

More than half (60 percent) of the carbon dioxide emissions from industrial sources originate from cement manufacturing (see Chapter 2).

Emissions Sources. Four basic materials are required to make cement: calcium, silicon, aluminum, and iron. Substrates of these materials are ground into a powder and heated in a kiln. While in the kiln, limestone (the predominant source of calcium) is broken down into carbon dioxide and lime. The carbon dioxide is driven off into the atmosphere. After the kilning process has been completed, cement clinker is left.

Estimation Methods. One mole of calcined limestone produces one mole of carbon dioxide and one mole of lime. Since virtually all of the lime produced is absorbed into the clinker, the lime content of clinker is assumed to be representative of the amount of carbon dioxide emitted. In order to estimate emissions from cement manufacture, a carbon coefficient must be calculated. EIA has adopted the IPCC recommendation that 64.6 percent of cement clinker is lime.[7] Multiplying this lime content factor by the ratio of carbon produced to lime produced yields the coefficient for cement clinker. A separate coefficient is necessary for estimating emissions from the additional lime used to produce masonry cement. In this case, the amount of lime not accounted for as clinker is assumed to be 3 percent.[8] This factor is then multiplied by the same production ratio of carbon to lime, generating the carbon coefficient for masonry cement. It should also be noted that during clinker production, some of the clinker materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The carbon dioxide emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker production emission factor. In keeping with the IPCC/OECD/IEA 1999 draft meeting report on emissions from industrial processes and the new gases (appearing in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories)*, EIA estimates that an additional increment of carbon dioxide emissions from clinker production equal to 2-percent of direct emissions from clinker production are attributable to cement kiln dust.

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[7] 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. 2.6,www.ipcc.ch/pub/guide.htm

[8] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999* (Washington, DC, April 2001), p. 3-5.

Table A6. Production and Consumption Data for U.S. Carbon Dioxide Emissions from Industrial Processes, 1990-2001.

(Thousand Metric Tons)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
Cement Clinker Production	63,326	61,608	62,184	65,745	69,787	69,983	70,361	72,686	74,523	76,003	78,138	78,900
Masonry Cement Production	2,911	2,592	2,806	2,962	3,613	3,603	3,469	3,634	3,989	4,000	5,000	4,000
Lime Production	15,832	15,667	16,199	16,700	17,400	18,500	19,200	19,700	20,100	19,700	19,600	18,700
Limestone Consumed in Iron Smelting	3,955	3,635	3,098	2,561	2,538	2,615	2,538	2,549	2,477	2,379	2,461	2,271
Limestone Consumed in Steelmaking	682	738	612	1,087	1,225	1,126	949	750	798	612	1,029	1,416
Limestone Consumed in Glass Manufacture	272	269	354	439	680	754	450	203	443	443	443	443
Limestone Consumed in FGD Units	4,369	4,552	4,479	4,274	4,621	5,815	6,125	6,595	6,322	6,835	7,607	7,607
Limestone Consumed in Dolomite Manufacture	986	732	641	549	526	428	691	673	654	295	658	658
Soda Ash Production (from Trona)	8,147	8,152	8,269	8,056	8,111	9,167	9,056	9,500	9,167	8,833	8,722	8,556
Soda Ash Consumed in Glass Manufacture	3,177	2,997	3,082	3,095	3,150	3,130	3,040	3,130	3,220	3,270	3,170	3,170
Soda Ash Consumed in FGD Units	179	155	156	146	191	211	206	295	296	210	235	235
Sodium Silicate Production	740	789	827	913	914	1,091	1,002	1,101	1,096	992	1,034	1,036
Sodium Tripolyphosphate Production	451	419	419	419	419	419	419	419	205	181	181	181
Aluminum Manufacture	4,048	4,121	4,042	3,695	3,299	3,375	3,577	3,603	3,713	3,779	3,668	2,600
Copper Primary Smelting	1,577	1,580	1,710	1,790	1,840	1,930	2,010	2,070	2,140	1,890	1,590	1,600

P = preliminary data.

Sources: U.S. Department of the Interior, United States Geological Survey, *Mineral Commodity Summaries* (Washington, DC, various years). *Cement Annual Report* (Washington, DC, various years). *Soda Ash Annual Report* (Washington, DC, various years) (soda ash production calculated from quantity of trona ore production). *Crushed Stone Annual Report* (Washington, DC, various years). *Iron and Steel Annual Report* (Washington, DC, various years). *Copper Annual Report* (Washington, DC, various years). *Aluminum Annual Report* (Washington, DC, various years). Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1999* (Washington, DC, August 1999). Energy Information Administration unpublished survey data, *Steam Electric Plant Operation and Design Report, Form EIA-767* (Washington, DC, various years). Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), and *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994). American Iron and Steel Institute, *Annual Statistical Report* (Washington, DC, various years).

Lime Manufacture

Lime is an important chemical with a variety of industrial, chemical, and environmental applications.

Emissions Sources. Lime production involves three main stages: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone is roasted at high temperatures, just as it is released during clinker production. The carbon dioxide is driven off as a gas and normally exits the system with the stack gas.

Estimation Methods. Based on the ratio of the molecular weight of carbon dioxide to the weight of calcium carbonate, EIA assumes that 785 metric tons of carbon dioxide, or 214 metric tons of carbon, are released for every 1,000 metric tons of lime produced. This factor is applied to annual levels of lime manufacture to estimate potential emissions. EIA does not account for the instances in which the carbon dioxide is recovered or reabsorbed. Representatives of the National Lime Association believe that 10 to 20 percent of the carbon dioxide emitted in lime manufacture is recovered for industrial use or reabsorbed from the atmosphere by chemical reactions induced by the use of lime.

Limestone Consumption

These are basic raw materials used by a wide variety of industries, including the construction, agriculture, chemical, and metallurgical industries.

Emissions Sources. Limestone (including dolomite) can be used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems in utility and industrial plants, as a raw material in glass manufacturing, or as an input for the production of dead-burned dolomite. Limestone is heated during these processes, generating carbon dioxide as a byproduct.

Estimation Methods. Assuming that limestone has a carbon content of 12 percent and dolomite 13.2 percent, EIA applies the appropriate factor to the annual level of consumption in the iron smelting, steelmaking, and glass manufacture industries, and in flue gas desulfurization systems that use this sorbent. This amounts to 120 metric tons of carbon for every 1,000 metric tons of limestone consumed, or 132 metric tons of carbon for every 1,000 tons of dolomite consumed (when dolomite is distinguished in the data). In the case of limestone (including dolomite) used in flue gas desulfurization units, the estimate of carbon emitted was adjusted based on the application of a capacity utilization rate from the calcination process of sorbents used, typically limestone (including dolomite). According to information obtained in May 1999 from the U.S. Geological Survey regarding the characterization of limestone consumed in fluidized-bed combustion systems and flue gas desulfurization units, the utilization rate of calcium obtained from the calcination process, ranges from approximately 30 to 40 percent.

Soda Ash Manufacture and Consumption

Commercial soda ash (sodium carbonate) is used in many familiar consumer products, such as glass, soap and detergents, paper, textiles, and food.

Emissions Sources. Two methods are used to manufacture natural soda ash in the United States. The majority of production comes from Wyoming, where soda ash is manufactured by calcination of trona ore in the form of naturally occurring sodium sesquicarbonate. For every mole of soda ash created in this reaction, one mole of carbon dioxide is also produced and vented to the atmosphere. The other process used to manufacture soda ash is carbonation of brines; however, the carbon dioxide driven off in this process is captured and reused.

Once manufactured, most soda ash is consumed in glass and chemical production. Other uses include water treatment, flue gas desulfurization, soap and detergent production, and pulp and paper production. As soda ash is processed for these purposes, additional carbon dioxide may be emitted if the carbon is oxidized. Because of the limited availability of specific information about such emissions, only certain uses of soda ash are considered in this report. Sodium silicate and sodium tripolyphosphate are included as chemicals manufactured from soda ash and components of detergents.

Estimation Methods. For soda ash manufacture, in order to ensure that carbon dioxide from the carbonation of brines is not included in emissions estimates, the calculations in this report are derived solely from trona ore production figures. Approximately 1.8 metric tons of trona ore are required to yield 1 metric ton of soda ash. This amounts to 97 metric tons of carbon dioxide for every 1,000 tons of trona ore produced annually. For soda ash consumption, EIA applies a factor of 113 metric tons of carbon for every 1,000 metric tons of soda ash consumed in glass manufacturing or in flue gas desulfurization.

Carbon Dioxide Manufacture

Emissions Source. Carbon dioxide is produced from a small number of natural wells and as a byproduct of chemical (i.e., ammonia) manufacturing. The Freedonia Group has determined that, in the United States, there is an 80 percent to 20 percent split between carbon dioxide produced as a byproduct and carbon dioxide produced from wells.[9] Emissions of byproduct carbon dioxide are incorporated into the natural gas energy consumption estimates as nonfuel, nonsequestered carbon and therefore are not included here to avoid double counting. Most carbon dioxide produced from wells is injected back into the ground for enhanced oil recovery. This process sequesters the carbon dioxide, at least in the short run. Conceptually, only carbon dioxide produced from wells and diverted to industrial use is emitted to the atmosphere.

Estimation Methods. The Freedonia Group estimates that non-sequestering industrial use of carbon dioxide resulted in emissions of 1.3 million metric tons of carbon in 1993.[10] If 20 percent of this industrial use is supplied by wells, emissions can be estimated at 0.26 million metric tons of carbon. Based on the Freedonia report, the 2000 estimate is calculated by assuming an annual 4.2-percent increase, implying emissions of 0.35 million metric tons of carbon.

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[9] The Freedonia Group, Inc., *Carbon Dioxide, Business Research Report B286* (Cleveland, OH, November 1991), p. 46.

[10] The Freedonia Group, Inc., *Carbon Dioxide, Industry Study 564* (Cleveland, OH, February 1994), p. 37.

Aluminum Manufacture

Aluminum is an element used in alloys. Because it is light in weight, malleable, and not readily corroded or tarnished, it is used as a principal material for kitchen utensils, aircraft, some automobiles, bicycles, and other manufactured products. The United States is a major producer of aluminum and also an importer, depending on market conditions.

Emissions Sources. As part of the primary aluminum smelting process, alumina (aluminum oxide, Al_2O_3) is vaporized by a powerful electric current. Emissions from the electricity used to generate the current are included with emissions from industrial electricity consumption and are not counted separately. The current also vaporizes a carbon "sacrificial anode," typically manufactured from petroleum coke. This is a nonsequestering nonfuel use of a fossil fuel. To avoid double counting, 50 percent of nonfuel use of petroleum coke is carried as "sequestering." Thus, process emissions from aluminum smelting can be considered as a deduction from the sequestering portion of nonfuel use of petroleum coke.

Estimation Methods. The 1994 MECS indicated that nonfuel use of fuels by aluminum smelters (SIC 3334) totaled 40 trillion Btu in 1994.[11] The composition of nonfuel use by fuel type has been withheld for confidentiality purposes, but it is probable that most of the 40 trillion Btu consists of petroleum coke, which would imply an emissions factor of about 0.338 metric tons of carbon per metric ton of aluminum smelted (0.04 quadrillion Btu of coke × 27.85 million metric tons of carbon per quadrillion Btu / 3.295 million metric tons of aluminum smelted in 1994). EIA now uses an emissions factor of 0.4 metric tons carbon per metric ton of aluminum smelted, which is at the low end of Abrahamson's range and also equals the mass balance for a "typical" aluminum smelter from another source.[12]

Municipal Solid Waste

A portion of the municipal solid waste(MSW) that is burned contains plastics. The carbon that goes into plastics is subtracted from the inventory. Therefore, when those plastics are burned they must be accounted for as additions to the atmosphere of carbon. The U.S. EPA accounted for MSW for the first time in the 1998 official inventory. This document uses the EPA estimate for 1990 through 2000 and uses the 2000 estimate for 2001. This number is currently reported under "waste" as it includes for example emissions from the burning of toxic wastes in addition to the MSW, much of which is burned in the generation of electrical energy.

Data Sources for Industrial Processes

The U.S. Geological Survey reports listed below can be found on the Internet at http://minerals.usgs.gov/minerals/pubs/mcs/.

Cement and Clinker Production (1980-2000): U.S. Department of the Interior, U.S. Geological Survey, *Cement Annual Report* (Washington, DC, various years). **(2001):** U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries* (Washington, DC, 2002).

Lime Manufacture: (1980-2001): U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries* (Washington, DC, various years).

Limestone Consumption in Iron Smelting, Steelmaking, and Glass Manufacture: (1980-2000): U.S. Department of the Interior, U.S. Geological Survey, *Crushed Stone Report* (Washington, DC, various years). **(2001):** EIA estimate. **Limestone Consumption in Flue Gas Desulfurization: (1980-2000):** Energy Information Administration, unpublished survey data, Form EIA-767, "Steam Electric Plant Operation and Design Report" (Washington, DC, various years). **(2001):** EIA estimate.

Soda Ash Manufacture and Soda Ash Consumption in Glass Making (1980-2001): U.S. Department of the Interior, U.S. Geological Survey, *Soda Ash Report* (Washington, DC, various years). **Soda Ash Consumption in Flue Gas Desulfurization (1980-2000):** Energy Information Administration, unpublished survey data, Form EIA-767, "Steam Electric Plant Operation and Design Report" (Washington, DC, various years). **(2001):** EIA estimate. **Sodium Silicate and Sodium Tripolyphosphate: (1980-1996):** Chemical Manufacturers Association, *U.S.*

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[11] Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), Table A3, p. 49.

[12] Drexel University Project Team, *Energy Analysis of 108 Industrial Processes* (Lilburn, GA: The Fairmont Press, 1996), p. 282.

Chemical Industry Statistical Handbook 1998 (Washington, DC, September 1998), pp. 37-38. **(1997-2001):** data published by the U.S. Department of Commerce, Bureau of the Census, in its annual and quarterly *Current Industrial Reports* on inorganic materials.

Carbon Dioxide: Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), and *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994).

Aluminum (1980-2001): U.S. Department of the Interior, U.S. Geological Survey, *Aluminum Report* (Washington, DC, various years).

Municipal Solid Waste (1990-2000, 2001 estimate): U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000* (Washington, DC, April 2002).

Methane

Energy Sources

Coal Mining

Emissions Sources

As coal is formed from organic material by natural chemical and physical processes, methane is also produced. The methane is stored in the pores (open spaces) of the coal itself and in cracks and fractures within the coalbed. As coal is mined, the pressure surrounding the stored methane decreases, allowing much of it to be released into the operating coal mine (in the case of an underground mine) or into the atmosphere (in the case of a surface mine). The methane remaining in the coal pores is emitted when the coal is transported and pulverized for combustion. There are five avenues for methane emissions from coal mines:

- **Ventilation Systems in Underground Mines.** Methane in concentrations over 5 percent is explosive and presents a mortal danger to coal miners. To meet safety standards set by the Mine Safety and Health Administration (MSHA) requiring levels of methane concentration to be maintained well below the 5-percent threshold, mine operators use large fans to provide a steady airflow across the mine face and ventilate the mine shaft. Typically, these ventilation systems release substantial quantities of methane in the fan exhaust.

- **Degasification Systems in Underground Mines.** When the volume of gas in underground mines is too high to be practically reduced to safe levels by standard ventilation techniques, degasification systems are employed. Degasification may take place before mining or may take the form of gob-wells or in-mine horizontal boreholes. Methane captured by degasification systems may be vented, flared, or recovered for energy.

- **Surface Mines.** Because coal mined from the surface has formed at lower temperature and pressure than coal from underground mines, its methane content is lower. Further, because the coal is located near the surface, methane has had ample opportunity to migrate to the atmosphere before mining. Thus, while methane emissions from surface mines are heterogeneous in nature, they are systematically smaller than emissions from underground mines.

- **Post-Mining Emissions.** Methane that remains in coal pores after either underground or surface mining will desorb slowly as the coal is transported (typically by train) to the end user. Because coal that is consumed in large industrial or utility boilers is pulverized before combustion, methane remaining in the coal pores after transport will be released prior to combustion.

- **Methane Recovery for Energy.** In some cases (for example, in some mining degasification systems), methane is emitted from coal mines in sufficiently high volumes and concentrations to permit commercial recovery of the gas as either pipeline gas, power generation fuel, or for mine site uses. Because coal mine methane recovered commercially is combusted, the quantities recovered are subtracted from estimates of total coal mine methane emissions.

Estimation Methods

Ventilation Systems in Underground Mines. Emissions from this source are segregated into two classes: emissions from “gassy” mines and emissions from “nongassy” mines.[13] Because methane concentrations and airflows in gassy mines are carefully monitored by the MSHA, a fairly reliable set of data can be derived for emissions from ventilation systems in gassy mines. Prior to 1993, MSHA data are available for only a subsample of years (1980, 1985, 1988, 1990, 1993). Thus, EIA developed a methodology that uses available MSHA data in conjunction with coal production data to develop emissions factors per ton of coal mined on a basin-by-basin level.[14] Emissions factors for nonsample years are interpolated. MSHA data are available for all years after 1993 and estimates of emissions from ventilation systems are based on a compilation of MSHA data by the U.S. EPA Office of Air and Radiation.

Emissions from nongassy mines make up less than 2 percent of all emissions from underground mines.[15] Basin-level emissions factors for nongassy mines were established by dividing 2 percent of each basin’s estimated emissions from nongassy mines for 1988 by that year’s production levels. The resulting emissions factors are applied to annual production data for the period through 1998. For 1999 through2001, emissions from nongassy mines are based on calculations from the U.S. EPA Office of Air and Radiation.

Degasification Systems in Underground Mines. Degasification emissions are not monitored by any regulatory agency. Where degasification does occur, the method of disposition may not be tabulated. Estimated emissions from degasification systems during the period 1993 through 2001 are based on data collected by the EPA’s Office of Air and Radiation, Coalbed Methane Outreach Program. For years prior to 1993, emissions from degasification systems are estimated by multiplying annual production in mines known to have degasification systems in place by a per-ton emissions factor.

Surface Mines. Emissions from U.S. surface mines have not been systematically measured. However, studies on surface coal mines in the United States, England, France, and Canada suggest a range of 0.3 to 2.0 cubic meters per metric ton of coal mined.[16] This report adopts the central value of that range and multiplies it by U.S. surface coal production.

Post-Mining Emissions. Like emissions from surface mines, post-mining emissions are not measured systematically. Thus, global average emissions factors must be applied. Post-mining emissions for coal mined from the surface are estimated to be very low, between 0.0 and 0.2 cubic meters per metric ton of coal mined. In contrast, post-mining emissions from underground coal are estimated to be more significant, between 0.9 and 4.0 cubic meters of methane per metric ton of coal mined.[17] The central values of these ranges are adopted and multiplied by annual production data for this report.

Methane Recovery for Energy. Methane recovery for energy is restricted to a small sample of mines that typically meter their gas sales. Thus, total methane recovery can be estimated from the volume and heat content of sales. The EIA adopts a time series of methane recovery prepared by the EPA Coalbed Methane Outreach Program for all years through 2001.

Data Sources

Ventilation Systems in Underground Mines. Coal mine ventilation data for the gassiest U.S. mines were drawn from a database prepared by the Department of Interior’s Bureau of Mines for the years 1980, 1985, 1988, 1990, and 1993. Ventilation data for 1994-2001 were obtained from the EPA, Climate Protection Partnerships Division, Coalbed Methane Outreach Program. Coal production data for years prior to 1998 are reported to EIA on Form EIA-

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[13] Gassy mines are defined as those underground coal mines with measured emissions from ventilation exhaust in excess of 100,000 cubic feet of methane per day.

[14] For purposes of this analysis, the U.S. has five distinct coal basins: Northern Appalachia includes Pennsylvania, Northern West Virginia, Maryland, and Ohio; Central Appalachia includes Eastern Kentucky, Virginia, Southern West Virginia, and Tennessee; the Warrior basin includes Alabama; the Illinois basin includes Illinois, Indiana, Western Kentucky, Iowa, and Oklahoma; and the Western basin includes Colorado, New Mexico, Utah, and Wyoming.

[15] M.A. Trevits, G.L. Finfinger, and J.C. LaScola, “Evaluation of U.S. Coal Mine Emissions,” in Society for Mining, Metallurgy and Exploration, *Proceedings of the Fifth U.S. Mine Ventilation Symposium* (Littlejohn Co., 1991), p. 2.

[16] 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. 1.98-1.112,www.ipcc.ch/pub/guide.htm

[17] 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. 1.98-1.112,www.ipcc.ch/pub/guide.htm

7A, “Coal Production Report.” Coal production data for 1998 based on Form 7000-2, “Quartely Mine Employment and Coal Report,” collected by the Mine Safety and Health Administration. Basin-level emissions for non-gassy mines in 1988 were calculated by the EPA’s Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-19–3-24.

Degasification Systems in Underground Mines. Data on drainage from degasification systems from 1993 through 2001 are from the EPA’s Office of Air and Radiation, Climate Protection Partnerships Division, Coalbed Methane Outreach Program. Emissions factors for this source are derived from estimates of 1988 emissions from degasification systems prepared by the EPA’s Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-19B–3-24. Annual production figures for years prior to 1998 are reported to EIA on Form EIA-7A, “Coal Production Report.” Coal production data for 1998 based on Form 7000-2, “Quartely Mine Employment and Coal Report,” collected by the Mine Safety and Health Administration.

Surface Mines. Emissions factors for surface mines are found in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997),www.ipcc.ch/pub/guide.htm Coal production data for years prior to 1998 are reported to EIA on Form EIA-7A, “Coal Production Report.” Coal production data for 1998 based on Form 7000-2, “Quartely Mine Employment and Coal Report,” collected by the Mine Safety and Health Administration.

Post-Mining Emissions. Emissions factors for post-mining emissions are found in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997),www.ipcc.ch/pub/guide.htm Coal production data for years prior to 1998 are reported to EIA on Form EIA-7A, “Coal Production Report.” Coal production data for 1998 based on Form 7000-2, “Quartely Mine Employment and Coal Report,” collected by the Mine Safety and Health Administration.

Methane Recovery for Energy. Methane recovery estimates the EPA’s Office of Air and Radiation, Climate Protection Division, Coalbed Methane Outreach Program.

Natural Gas Production, Processing, and Distribution

Emissions Sources

Because methane is the principal constituent of natural gas (representing about 95 percent of the mixture), releases of natural gas result in methane emissions. Methane emissions can be grouped into three categories: (1) fugitive or unintentional leaks emitted from sealed surfaces such as pipelines, gaskets, and flanges; (2) vented or intentional releases from process vents, maintenance blowdowns, and pneumatic devices; and (3) releases from incomplete combustion in compressor engines, burners, and flares.[18] The natural gas industry can be divided into four source segments:

- **Gas Production.** This segment consists of gas and oil wells, surface equipment to produce gas, and gathering pipeline. Leakage occurs from valves, meters, and flanges. Pneumatic valves release gas when they are reset. Gathering pipeline may be emptied for maintenance or may have fugitive emissions.

- **Gas Processing.** When gas is processed, liquefied petroleum gases and natural gasoline are removed for sale or further refining. Water is also removed, and gas is conformed to commercial pipeline quality and heat content. Methane is released during maintenance, via leaks, and during system upsets when sudden increases in pressure require a gas release or result in a system rupture.

- **Transmission and Storage.** High-pressure transmission pipelines transport natural gas from production fields and gas processing facilities to distribution pipelines. Natural gas may escape through leaky pipes and valves. Methane may be emitted as part of compressor exhaust. Gas is often stored near consumption centers to meet peak demand during periods of high consumption. These storage facilities emit methane in compressor exhaust and from dehydrators.

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[18] 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), p. 19.

- **Distribution.** The pressure of gas received from the transmission system is lowered at the gate station and is forwarded to distribution pipeline for delivery to residential, commercial, and industrial consumers. Leaks may occur at gate stations, through leaky pipes, and at customer meters.

Estimation Methods

Estimates of emissions from the natural gas system are scaled to commonly available activity data such as number of wells in operation, miles of gathering pipeline, gas throughput, gas volumes processed, miles of transmission pipeline and miles of distribution pipeline. The activity data are multiplied by emissions factors derived from point-in-time emissions estimates for 1992 developed in a study sponsored jointly by the U.S. Environmental Protection Agency (EPA) and the Gas Research Institute (EPA/GRI).[19] The EPA/GRI study provides activity data and disaggregated emissions factors for 86 separate gas industry process components. In an effort to take advantage of this level of detail, this report estimates the number of each process component for the years 1990-2001. Each process component is scaled to a widely available metric, such as gas withdrawals or pipeline miles most related to the process activity. The derived activity data are then applied to the component emissions factor from the EPA/GRI report.

Data Sources

Natural Gas Systems. Emission factors and activity data for 1992 are from the joint EPA/GRI study: 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). Activity data for all other years are scaled to data from the following sources: gas wellheads, gross gas withdrawals, gas processing and gas removed from storage can be found in EIA's *Natural Gas Annual* (various years), *Natural Gas Monthly* (various years), *Monthly Energy Review* (July issue, various years); transmission and distribution pipeline mileage are published annually by the American Gas Association in *Gas Facts*; gas processing plants are published in the *Oil & Gas Journal*, special issue for "Worldwide Gas Production" (various years); oil wells are published in the World Oil Magazine (February issue, various years); crude oil production is published in the *Petroleum Supply Annual and Petroleum Supply Monthly* (various years).

Petroleum Systems

Emissions Sources

The vast preponderance of emissions from petroleum systems occur during crude oil exploration and production. Much smaller emissions occur during crude transportation and crude refining. Emissions from petroleum systems can be divided into four types: 1) vented emissions; 2) fugitive emissions; 3) combustion emissions and 4) upset emissions.

- vented emissions are intentional releases to the atmosphere by facility design or operational practice.
- fugitive emissions are accidental and often ongoing releases associated with a leak source within the system
- combustion emissions are the result of fuel use to drive compressors or flares
- upset emissions are typically the result of safety measures such as emergency pressure releases or oil platform shutdowns[20]

The largest single emissions source is the venting at crude oil storage tanks.

Estimation Methods

Estimates of emissions from petroleum systems are derived by multiplying emission factors for approximately 90 separate components of the petroleum system by an estimate of the total number of components on the national system. To produce a time-series of estimates, the number of components for 1990 - 2001 are scaled to readily available industry activity data such as number of oil wells, refinery input, and crude transported by pipeline, marine vessel or truck.

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[19] 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), p. 19.

[20] U.S. Environmental Protection Agency, Office of Air and Radiation, *Estimates of Methane Emissions from the U.S. Oil Industry*, (Draft Report, Washington, D.C.)

Data Sources

Emission factors are from the U.S. Environmental Protection Agency, Office of Air and Radiation, Draft Report, *Estimates of Methane Emissions from the U.S. Oil Industry*. Activity data are from EIA's *Monthly Energy Review* (July, various years), EIA's *Petroleum Supply Annual* (various years), Oil and Gas Journal's *Worldwide Refining Issue and Pipeline Economics Issue*.

Stationary Combustion

Emissions Sources

The principal products of fuel combustion are carbon dioxide and water vapor. When fuel combustion is incomplete, methane may also be released. The volume of methane released varies according to the efficiency and temperature of the combustion process. Most stationary sources are large, comparatively efficient boilers, such as those found in the industrial and utility sectors, and thus have low levels of methane emissions. However, a significant amount of wood is consumed in residential woodstoves and fireplaces, which are typically inefficient combustion chambers. Wood combustion in these devices produces most of the U.S. methane emissions from stationary sources.

Estimation Methods

An emissions factor based on fuel type (for example, coal, wood, natural gas) and combustion technology (for example, utility boiler, industrial boiler, woodstove) is applied to consumption data for each fuel and technology type.

Data Sources

Emissions coefficients for stationary fuel were obtained from the EPA's Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, 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), www.ipcc.ch/pub/guide.htm. Fuel consumption data were drawn from the Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(99) (Washington, DC, September 1999) for 1980-1997; and *Monthly Energy Review*, DOE/EIA-0035(02/07)(Washington, DC, July 2002) for 1998-2001. Residential woodfuel consumption data were derived from EIA's *Annual Energy Review 2001*, DOE/EIA-0384(01) (Washington, DC, November 2002).

Mobile Combustion

Emissions Sources

Methane emissions from mobile combustion are, like those from stationary combustion, the result of incomplete fuel combustion. In automobiles, methane emissions result when oxygen levels in the combustion chamber drop below levels sufficient for complete combustion. The effects of incomplete combustion in automobiles may be moderated somewhat by post-combustion emissions controls, such as catalytic converters. Methane emissions are also generated by fuel combustion in other modes of transport. Other sources include aircraft, ships and locomotives, in addition to methane emissions from farm and construction equipment. There is, however, some evidence that jet airplane engines may consume ambient methane during flight, thereby reducing their net emissions.

Estimation Methods

Methane emissions from highway vehicles are estimated by applying emissions factors (per vehicle mile traveled) to vehicle use data. Research indicates that emissions rates differ among motor vehicles by vehicle type and by type of catalytic converter (associated with the vintage of the motor vehicle) for light duty vehicles. Consequently, EIA partitions vehicle use data by vehicle type (i.e. by passenger cars, light-duty trucks, buses, motorcycles, and heavy-duty trucks), as well as by motor vehicle vintage (model year) for passenger cars and light duty trucks. Due to improvements in technology and increasing stringency of environmental regulations, motor vehicle methane emissions have generally declined over time. For non-highway sources, emissions coefficients are applied directly to annual fuel consumption data.

Data Sources

Emissions factors for all vehicles are provided in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997),www.ipcc.ch/pub/guide.htm. EIA collected data on miles traveled in personal transportation vehicles (cars and light-duty trucks) as part of its triennial Residential Transportation Energy Consumption Survey (RTECS): Energy Information Administration, *Household Vehicles Energy Consumption 1994*, DOE/EIA-0464 (Washington, DC, July 1996, and previous years). This survey contains data for the years 1983, 1985, 1988, 1991, and 1994. Vehicle miles traveled for other years are estimated using weighted averages from survey data in conjunction with statistics on the U.S. fleet of cars and trucks by model year, provided by provided by the American Automobile Manufacturers Association*, AAMA Vehicle Facts and Figures* (Detroit, MI, various years) and by Ward's Communications Inc., *Ward's Automotive Yearbook* (Southfield, MI, 1999) and Ward's Automotive Report (Southfield, MI, various years). Vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks were obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics* (Washington, DC, various years), web site www.fhwa.dot.gov/ohim/ohimstat.htm.

Fuel consumption for ships, locomotives, farm and construction equipment is based on data from EIA's *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, various years). Jet and piston-powered aircraft fuel consumption data are contained in the Energy Information Administration's *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years). Data on fuel consumption by recreational boats are taken from Oak Ridge National Laboratory, Center for Transportation Analysis, *Transportation Energy Data Book* (Oak Ridge, TN, various years), web site www-cta.ornl.gov/publications/tedb.html.

Landfill Methane Emissions

Emissions Sources

After organic wastes (e.g., food, paper, yard waste) are placed in landfills, they begin to decompose. Aerobic bacteria, consuming oxygen, convert organic material to carbon dioxide, heat, and water. When available oxygen is depleted, anaerobic bacteria, including methanogens, begin digesting the waste and producing methane. Methanogenic anaerobes are highly sensitive to temperature, pH, and moisture levels. Because U.S. sanitary landfills are essentially closed systems designed to minimize entry and exit of moisture, conditions within a landfill are largely a product of the composition of the waste it contains. Thus, methane is likely to be produced at different rates and volumes both across different landfills and within a single landfill.

The biogas produced in a landfill is typically between 50 and 60 percent methane. When emitted, biogas mixing with air can result in methane concentrations within the explosive range of 5 to 15 percent. Often, landfill operators put methane control systems in place to prevent migration of high concentrations to buildings. Methane captured by control systems may be vented to the atmosphere or flared, but it is also a potentially valuable energy resource. Where landfills produce steady, large volumes of methane and landfill gas-to-energy prices are competitive with other energy alternatives, recovered gas may be used as an energy resource. In most cases, the gas is converted to electricity and used for on-site energy needs or sold to local utilities. In some cases, the gas is transported via pipeline to a local end user.

Estimation Methods

Data on methane emissions from landfills are limited to those landfills with methane recovery systems in place. For more than 100 U.S. landfills with gas recovery systems in place, Thorneloe et al. measured or estimated methane emissions at 2.1 million metric tons for 1992.[21] Methane emissions from landfills without gas recovery systems have not been measured, and even the number of landfills is subject to considerable uncertainty. Emissions from a given landfill are largely the product of the composition of the waste it contains and an array of site-specific factors. Waste composition data on a landfill-specific basis are nonexistent; however, national-level waste flow and waste composition data are available, and their reliability has improved over time. Thus, for this report, all waste not disposed of in a landfill with measured emissions is treated as if it has flowed to one very large national landfill.

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[21] S.A. Thorneloe, M.R.J. Doorn, L.A. Stefanski, M.A. Barlaz, R.L. Peer, and D.L. Epperson, "Estimate of Methane Emissions From U.S. Landfills," Prepared for U.S. Environmental Protection Agency, Office of Research and Development (April 1994), p. 1087.

To estimate methane emissions from all waste not disposed of in a landfill with measured emissions, waste volumes are subjected to a slightly modified version of the EMCON Methane Generation Model.[22] This model divides the waste into three categories: readily decomposable, moderately decomposable, and slowly decomposable, each with its own set of emissions characteristics. The EMCON model provides both a high methane yield scenario and a low methane yield scenario. For each category of decomposable waste, a time lag until methane generation begins is estimated, as well as a time constant during which the methane yield of the waste is realized. The methane yield represents the total amount of methane that a given amount of waste will produce over its lifetime. For example, under a low methane yield scenario, slowly decomposing waste will begin producing methane after a 5-year lag and will continue emitting over a 40-year period. Table A7 shows the EMCON methane generation model parameters.

Waste flows were estimated from 1940 through 2001. Waste in place in the Nation's landfills was assumed to represent the waste stream for all previous years plus the current year's additions. The landfills examined by Thorneloe et al. contained 9.2 percent of the waste estimated to be in place in the Nation's landfills during 1992. This report assumes that the share of waste in these landfills and the share in all other landfills remained constant over time. Thus, the EMCON model was applied to 90.8 percent of the waste generated each year.

To estimate emissions from those landfills with measured data for 1992 but no data for other years, the EMCON model was recalibrated to produce the 2.1 million metric tons of measured emissions in 1992. The recalibrated model, with methane yields almost twice as large as the original, was then applied to 9.2 percent of the waste stream for all years. These much higher yields are not unexpected, as gas recovery systems are most economically employed in high-emitting landfills.

Table A7. EMCON Methane Generation Model Parameters

Waste Category	Decomposable Portion (Percent by Dry Weight)	Methane Yield (Cubic Feet per Pound)	Lag Time (Years)	Time Constant
High Yield (Default)				
Readily Decomposable	4.0	4.5	0.2	3
Moderately Decomposable	45.0	3.6	1.5	10
Slowly Decomposable	5.2	0.5	5.0	20
Low Yield (Default)				
Readily Decomposable	4.0	2.8	0.3	4
Moderately Decomposable	45.0	2.0	2.0	20
Slowly Decomposable	5.2	0.3	5.0	40
High Yield (Modified)				
Readily Decomposable	4.0	8.8	0.0	3
Moderately Decomposable	45.0	7.0	2.0	10
Slowly Decomposable	5.2	1.0	5.0	20
Low Yield (Modified)				
Readily Decomposable	4.0	5.4	0.0	4
Moderately Decomposable	45.0	3.8	2.0	20
Slowly Decomposable	5.2	0.6	5.0	40

Source: D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," Global Environmental Change (December 1992), pp. 311-328.

Data Sources

Data on waste generated and landfilled for the period 1988 through 2000 (Table A8) were drawn from "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-2001). These data were not collected by *Biocycle* before 1988. Waste generated and landfilled for the period 1960 through 1987 was estimated from data produced by Franklin Associates. On behalf of the EPA's Office of Solid Waste and Emergency Response, Franklin Associates have estimated municipal solid waste (MSW) generated and landfilled for the years 1960 through 1997. See Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States*, Worksheets, 1992 update, Prepared for the U.S. Environmental Protection Agency, Municipal Solid and Industrial Solid Waste Division (July 1992) and U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1998 Update*, EPA-530-S-99-021 (Washington DC, July 1999). In contrast to the *Biocycle* data, which include all waste going to landfills, including construction and

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[22] D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environment Change* (December 1992), pp. 311-328.

demolition (C&D) waste and sludge, the Franklin data include only MSW going to landfills. For 2001, waste generation data were not yet available so 2000 estimates were scaled up by GDP growth of 0.3 percent to provide an estimate of waste generation in 2001. The volume of waste recycled or combusted rather than landfilled was assumed to have remained stable at 40% in 2000.

Table A8. U.S. Solid Waste Generated and Landfilled, 1990-2001
(Million Metric Tons)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Waste Generated	266.4	254.6	264.7	278.4	292.9	296.4	297.1	308.9	339.9	353.7	371.1	372.2
Waste Landfilled	205.2	193.6	190.6	197.7	196.3	186.8	184.2	188.5	207.4	215.8	222.7	223.3
Waste In Place	6868.7	7062.3	7252.9	7450.6	7646.9	7833.7	8017.9	8206.4	8413.7	8629.6	8852.3	9075.7

Source: "Nationwide Survey: The State of Garbage in America," Biocycle (1988-2001).

In order to account for categories of waste other than MSW going to landfills between 1960 and 1987, an average ratio of waste generation estimated by *Biocycle* and waste generation estimated by Franklin Associates for 1988 through 1997 was calculated. The annual average ratio during this period was 1.47 to 1. Thus, all Franklin estimates for 1960 through 1987 were multiplied by 1.47 to estimate overall waste generation and landfilling for those years. To further extend waste generation estimates back to 1940, a regression equation relating waste generation to GNP and population was developed. Annual methane recovery data are from the U.S. Environmental Protection Agency's Landfill Methane Outreach Program database.[23]

Domestic and Commercial Wastewater Treatment

Emissions Sources

Emissions of methane from the treatment of wastewater occur when liquid waste streams containing high concentrations of organic materials are treated anaerobically (in the absence of oxygen). Treatment processes used in the United States are anaerobic digestion, aerobic, and facultative (combining aerobic and anaerobic processes) stabilization lagoons, septic tanks, and cesspools.[24] Treatment of wastewater solids using anaerobic digestion is the most obvious potential source of methane emissions; however, emission of significant quantities of methane from this process requires that the digester gas be vented rather than recovered or flared. Anaerobic and facultative lagoons involve retention of wastewater in impoundments, where the organic materials in the wastewater undergo bacterial decomposition. The growth of algae, which absorb carbon dioxide and release oxygen as a result of photosynthesis, sustains aerobic conditions at least near the surface of the lagoon. Bacteria deplete oxygen at the bottom of the lagoon, producing conditions suitable for methanogenic bacteria. The extent of the resulting anaerobic zone and the associated methane generation depend on such factors as organic loadings and lagoon depth. In facultative lagoons, unlike anaerobic lagoons, a significant aerobic zone persists.

Nearly 75 percent of U.S. households are served by sewers that deliver domestic wastewater to central treatment plants. Septic tanks or cesspools treat domestic wastewater from most of the remaining households.[25] Anaerobic digestion is frequently used to treat sludge solids at U.S. municipal wastewater treatment plants; however, anecdotal evidence suggests that neither recovery nor flaring of digester gas is common in the United States and that equipment for recovery and flaring of digester gas is poorly designed or maintained, allowing most of the methane produced to be released to the atmosphere.[26]

Estimation Methods

Insufficient information is available to develop separate estimates of methane emissions from each of the sources discussed above. Information on the type of treatment used by the thousands of municipal and industrial treatment facilities is not available. For instance, no reliable statistics were found for the use of anaerobic digestion at municipal treatment facilities. Knowledge regarding the emissions of methane from lagoons, septic systems, and cesspools is limited. Another difficulty is the overlap between municipal and industrial treatment systems. Many industrial concerns discharge wastewater, which may or may not have been treated, into municipal systems.

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[23] See web site www.epa.gov/lmop.

[24] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *International Anthropogenic Methane Emissions: Estimates for 1990*, EPA-230-R-93-010 (Washington, DC, January 1994), p. 10-9.

[25] U.S. Census, 1980, 1990, 2000.

[26] William Hahn, Science Applications International Corporation, personal communication, May 23, 1996.

Therefore, EIA bases its current estimate of methane emissions from wastewater treatment on the highly simplified approach recommended by the IPCC,[27] which assumes that each person in a developed nation contributes 0.05 kilogram of BOD_5 to domestic wastewater annually, and 15 percent of this wastewater is treated anaerobically, yielding 0.22 kilogram of methane per kilogram of BOD_5 in the wastewater.[28] The EIA assumes that recovery of methane at municipal wastewater treatment facilities is negligible.

Data Sources

Estimates of the U.S. resident population on July 1 of each year were obtained from the U.S. Census Bureau.

Agricultural Sources

Enteric Fermentation in Domesticated Animals

Emission Sources

The breakdown of carbohydrates in the digestive track of herbivores (including insects and humans) results in the production of methane.[29] The volume of methane produced from this process (enteric fermentation) is largest in those animals that possess a rumen, or forestomach, such as cattle, sheep, and goats. The forestomach allows these animals to digest large quantities of cellulose found in coarse plant material. This digestion is accomplished by microorganisms in the rumen, some of which are methanogenic bacteria. These bacteria produce methane while removing hydrogen from the rumen. The majority (about 90 percent) of the methane produced by the methanogenic bacteria is released through normal animal respiration and eructation (belching). The remainder is released as flatus.

Estimation Method

The level of methane emissions from enteric fermentation in domesticated animals is a function of several variables, including quantity and quality of feed intake, the growth rate of the animal, its productivity (reproduction and/or lactation), and its mobility. To estimate emissions from enteric fermentation, the animals are divided into distinct, relatively homogeneous groups. For a representative animal in each group, feed intake, growth rate, activity levels, and productivity are estimated. An emissions factor per animal is developed based on these variables. The factor is then multiplied by population data for that animal group to calculate an overall emissions estimate. Because emissions from cattle represent about 95 percent of U.S. emissions from enteric fermentation, the estimation method for cattle is more complex and detailed.

Cattle. The U.S. cattle population is separated into dairy and beef cattle. Dairy cattle are then divided into replacement heifers 0-12 months old, replacement heifers 12-24 months old, and mature cows. Dairy cattle are further subdivided into regional populations in an effort to capture variations in diet and feed quality. Beef cattle are divided into six classes: replacements 0-12 months old, replacements 12-24 months old, mature cows, bulls, steers and heifers raised for slaughter under the weanling system, and steers and heifers raised for slaughter under the yearling system. These populations are then multiplied by emissions factors developed for each category of cattle based on their energy intake requirements.[30] Because characteristics critical in determining energy intake, and thus emissions rates, for cattle—such as growth rates and milk production— change annually, an effort to scale emission factors to these changes is made. For dairy cattle, emission factors are scaled to average milk production per cow on a regional basis. For beef cattle, emissions rates were pegged to average pre-slaughter live weights for the calves and adult cattle, respectively (Table A9).

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[27] 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. 6.23,www.ipcc.ch/pub/guide.htm

[28] Biological oxygen demand (BOD) represents the oxygen consumed by bacteria to decompose organic matter contained in a wastewater stream. It provides a measure of the organic loading of wastewater, which is the primary determinant of its potential to produce methane. BOD_5 is a standardized measurement of BOD that measures the oxygen consumed over a 5-day period.

[29] 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), p. 272.

[30] 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. 5-3; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. G-2, web site www.epa.gov/globalwarming/publications/emissions/us2000.

Table A9. Average Pre-Slaughter Live Weights for U.S. Cattle and Calves, 1990 - 2001 (Pounds)

Animal Class	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Cattle	1,136	1,163	1,169	1,161	1,189	1,183	1,169	1,173	1,203	1,210	1220	1221
Calves	281	346	376	388	384	372	341	339	285	291	316	320

P = preliminary data.
Source: U.S. Department of Agriculture, web site www.usda.gov/nass/

Other Animals. For sheep, pigs, goats, and horses, populations are not desegregated below the species level. Emissions factors for each animal group are multiplied by their respective populations. Emission factors are drawn from the work of Crutzen et al.[31]

Data Sources

Population and slaughter weight data for cattle and population data for sheep and swine were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch web site at www..usda.gov/nass/. Population data for goats and horses are extrapolated from the USDA's *Census of Agriculture* for the years 1987, 1992 and 1997.[32] Emissions factors for dairy cattle scaled to milk production 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 2000) p. H-2.

Solid Waste of Domesticated Animals

Emission Sources

When the solid waste of animals is allowed to decompose under anaerobic conditions, methane is produced. The volume of methane produced varies according to the amount of organic material susceptible to decomposition within the waste (volatile solids) and the manner in which the waste is managed. Liquid-based waste management systems, in addition to providing a suitable anaerobic environment, provide the moisture necessary for methanogenic bacterial cell production and acid stabilization.[33] Thus, they result in the greater methane emissions.

Estimation Method

Methane emissions from the solid waste of domesticated animals are estimated by linking emissions to the volume of solid waste produced by a given animal, the volatile solids in that waste, and the manner in which the waste is handled. The volume of waste produced is controlled by the animal's size, diet, and energy requirements. As a proxy for these variables, typical animal mass as estimated in a 1990 inventory of livestock and poultry prepared by the U.S. Environmental Protection Agency[34] is used to determine emissions per animal. Animal sizes are adopted directly for all animals except cattle, for which masses are adjusted annually based on live pre-slaughter weights as reported by the U.S. Department of Agriculture. Volatile solids produced per kilogram of animal weight, maximum methane-producing capacity of each animal's waste and the share of waste handled in each management system are adopted from the work of Safley et al.[35] For all animals except dairy cattle, the share of waste handled in each management system is also drawn from Safley et al.

Methane conversion factors for dairy cattle are adopted on a State-by-State basis and are calculated from a weighted average of each State's manure management technique. Dairy cattle size and volatile solid production are drawn from the EPA. Resulting emissions factors are applied to State population data acquired from the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch.

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[31] 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. 274-275.

[32] U.S. Department of Agriculture, National Agricultural Statistics Service, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Series," Part 51 (Washington, DC, 1987, 1992, and 1997).

[33] U.S. Environmental Protection Agency, Office of Air and Radiation, Anthropogenic Methane Emissions in he United States: Estimates for 1990 (Washington, DC, April 1993).

[34] U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in he United States: Estimates for 1990* (Washington, DC, April 1993).

[35] L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions from Livestock and Poultry Manure* (Washington, DC: U.S. Environmental Protection Agency, February 1992), p. 18.

Data Sources

Population and slaughter weight data for cattle, and population data sheep, poultry, and swine were provided by the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), Livestock, Dairy, and Poultry Branch and were obtained via the Internet at www.usda.gov/nass/. Average broiler chicken populations for each year were estimated by multiplying the estimated number of broiler chickens hatched annually by 0.1425 based on their 7 week life cycle as recommended by the USDA's Economic Research Service.[36] Population data for goats and horses were extrapolated from USDA, NASS, *Census of Agriculture, United States Summary and State Data,* Vol. 1, "Geographic Area Studies," Part 51 (Washington, DC, 1987, 1992, 1997). Methane conversion factors weighted on a state-by-state basis are 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 2000) p. I-4.

Rice Cultivation

Emissions Sources

Methane is produced when organic material in flooded rice fields decomposes in the absence of oxygen (anaerobically). Between 60 and 90 percent of the methane generated is oxidized by bacteria in the soil, while an additional portion leaches into the groundwater. The majority of the methane that remains is transported through rice plants and is transpired into the atmosphere. A smaller amount of methane reaches the atmosphere by bubbling from the soil and by diffusing through the water column.

Estimation Methods

A range of daily emissions rates has been developed from studies of rice fields in California,[37] Louisiana,[38] and Texas.[39] The high and low ends of the range, 0.1065 and 0.5639 grams of methane per square meter of land cultivated, are applied to the growing season length and the harvested area for each State that produces rice. In states with a second ("ratoon") crop, the additional area harvested is incorporated into the estimates.

Data Source

The area of rice harvested and the length of growing season data were obtained from the U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (annual reports). For 1990-2000, data on Florida rice harvests are from University of Florida, Institute of Food and Agricultural Sciences, Cooperative Extension Service, " Florida's 2000 Rice Variety Census," "An Overview of the Florida Rice Industry", web site, http://edis.ifas.ufl.edu. For 2001, data on Florida rice harvests are from the University of Florida Everglades Research and Education Center. For states with ratoon crop, the percentages of rice harvested in this crop were taken from the U.S. EPA *U.S. Inventory of Greenhouse Gas Emissions* (various years).

Burning of Crop Residues

Emissions Sources

Between 40 and 50 percent of dry matter in crop residue is carbon.[40] When crop residues are burned for fodder, land supplementation, or fuel, incomplete combustion produces methane emissions.

Estimation Methods

This report assumes that 3 percent of all crop residues are burned, with the exception of rice, which is combusted at various levels over time. The share of rice crop residues in California estimated to be combusted declines from 75

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[36] Personal communication (May 1993).

[37] R. Sass, F. Fisher, S.Lewis, M. Jund, and F. Turner, "Methane Emissions From Rice Fields: Effect of Soil Properties," *Global Biogeochemical Cycles*, Vol. 8 (1994), p. 135.

[38] R.J. Cicerone, J.D. Shetter, and C.C. Delwiche, "Seasonal Variation of Methane Flux From a California Rice Paddy," *Journal of Geophysical Research*, Vol. 88 (1983), pp. 7203-7209.

[39] C.W. Lindau and P.K. Bolich, "Methane Emissions From Louisiana First and Ratoon Rice Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48.

[40] A. Strehler and W. Stutzle, "Biomass Residues," in D.O Hall and R.P. Overend (eds.), *Biomass: Regenerable Energy* (Chichester, UK: John Wiley and Sons, 1987), p. 85.

percent in 1990 to 23 percent in 2001. The share of rice combusted throughout the remainder of the U.S. declines from 16 percent in 1990 to 9 percent in 2001.[41] To derive methane emissions, the dry weight and carbon content of each crop were determined and then multiplied by estimated combustion efficiencies (Table A10).

Table A10. Factors Used in Estimating Methane and Nitrous Oxide Emissions from Crop Residue Burning

Crop Type	Residue/Crop Ratio	Dry Matter Content (Percent)	Carbon Content (Percent)	Nitrogen Content (Percent)
Barley	1.2	0.93	0.4485	0.0077
Beans	2.1	0.8535	0.45	0.023
Corn	1	0.91	0.4478	0.0058
Oats	1.3	0.901	0.42	0.0084
Peas	1.5	0.902	0.45	0.023
Peanut	1	0.86	0.45	0.0106
Potatoes	0.4	0.867	0.4226	0.011
Rice	1.4	0.91	0.3806	0.0072
Rye	1.6	0.9	0.4853	0.007
Sorghum	1.4	0.88	0.34	0.0085
Soybean	2.1	0.867	0.45	0.023
Sugarbeet	0.2	0.9	0.4072	0.0228
Sugarcane	0.8	0.62	0.4235	0.004
Wheat	1.3	0.93	0.4428	0.0062

Sources: A. Strehler and W. Stutzle, "Biomass Residues," in D. Hall and R. Overend (eds.), Biomass: Regenerable Energy (Chichester, UK: John Wiley and Sons, 1987), C. Li, S. Frolking and R. Harriss, "Modeling Carbon Biogeochemistry in Agricultural Soils," Global Biogeochemical Cycles, Vol. 8 (September 1994), E. Darley, "Emission Factors from Burning Agricultural Wastes Collected in California," Final Report, CAL/ARB Project 4-011 (Riverside, CA: University of California, 1977), 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), and G. Barnard, "Use of Agricultural Residues as Fuel," in J. Pasztor and L. Kristoferson (eds.), Bioenergy and the Environment (Boulder, CO: Westview Press, 1990)

Data Sources

Crop harvest sizes were obtained from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (Annual Reports).

Industrial Processes

Chemical Production

Emissions Sources

A wide variety of organic compounds (those containing carbon) are used as feedstocks in chemical production. High temperatures are often used to “crack” the molecular bonds of the compounds, with different temperatures producing specific chemicals. The process of cracking produces a number of chemical byproducts, including methane.

Estimation Methods

The IPCC has published emissions factors for methane emitted during the manufacture of ethylene, ethylene dichloride, styrene, methanol, and carbon black (Table A11). Production figures for the chemicals are multiplied by those emissions factors.

Data Source

Chemical production figures for 1990-2000 were obtained from the Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years); and for 2001 were obtained from the American Chemistry Council, *Guide to the Business of Chemistry* (Table 3.12).

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[41] 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) p.5-23.

Table A11. Methane Emissions Factors for Industrial Processes (Grams of Methane Emitted per Kilogram of Product Produced)

Industrial Product	Methane Emissions Factor
Coke	0.5
Sinter	0.5
Pig Iron	0.9
Carbon Black	11.0
Ethylene	1.0
Dichloroethylene	0.4
Styrene	4.0
Methanol	2.0

Source: 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. 2.6, web site www.ipcc.ch/pub/guide.htm.

Iron and Steel Production

Emissions Sources

Coke, sinter, and pig iron are the principal material inputs for the production of iron and steel. Coke is produced by heating coal in the absence of oxygen. One of the gaseous byproducts of this process is methane. During the next step in the production process, coke, iron ore, and flux materials are combined to form sinter. The coke is burned to create heat, causing the sinter to agglomerate. During agglomeration, methane is released. Coke and iron are then added to flux materials in a blast furnace and reduced to iron, slag, and exhaust gases. Methane is one of the exhaust gases.

Estimation Methods

The IPCC has published emissions factors for methane emitted during the production of coke, sinter, and pig iron.[42] Production figures for iron and steel inputs are multiplied by those emissions factors.

Data Source

Coke, sinter, and pig iron production data are published annually by the American Iron and Steel Institute in its *Annual Statistical Report* (Washington, DC, various years).

Nitrous Oxide

Most anthropogenic nitrous oxide emissions in the United States can be attributed to agricultural and energy sources. In particular, 51 percent of estimated emissions of nitrous oxide were attributable to nitrogen fertilization of agricultural soils. Motor vehicle fuel combustion accounts for another 19 percent of 2001 emissions. It should be noted that the range of uncertainty associated with emissions from mobile combustion and fertilizer use is large. Emissions estimates in this report include: mobile source combustion from passenger cars, buses, motorcycles, trucks, and other mobile sources; stationary source combustion from the commercial, residential, industrial, and electrical utility sectors; fertilizer application; burning of crop residues; livestock manure management; human sewage; waste combustion; and industrial production of adipic acid and nitric acid.

Energy Use

Mobile Combustion

Emissions Sources

Nitrous oxide emissions are produced as a byproduct of fuel combustion. During combustion, nitrous oxide (N_2O) is produced as a result of chemical interactions between nitrogen oxides (NO, NO_2 and NO_3) and other combustion products. Since nitrous oxide decomposes at high temperatures, most stationary combustion systems (such as

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[42] 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,www.ipcc.ch/pub/guide.htm

electric power generation) emit little nitrous oxide. However, under some conditions, the catalytic converters fitted as pollution control devices on most U.S. vehicles will convert nitrogen oxides into nitrous oxide. The relevant conditions appear to be when the catalytic converter is just warming up, but before it reaches normal operating temperature, if the catalytic converter is not working properly, or if the catalyst is affected by excessive levels of sulfur in the gasoline.

Estimation Methods

In general, EIA estimates nitrous oxide emissions from highway vehicles by multiplying emissions factors (grams of nitrous oxide per mile driven) by national-level vehicle miles traveled. Research indicates that emissions rates differ among motor vehicles by vehicle type, and by type of catalytic converter (associated with the vintage of the motor vehicle) for light duty vehicles. Consequently, EIA partitions national-level vehicle miles traveled by vehicle type (i.e. by passenger cars, light-duty trucks, buses, motorcycles, and heavy-duty trucks), as well as by motor vehicle vintage (model year) for cars and light duty trucks.

For non-highway sources, an emissions factor in grams of nitrous oxide per unit of fuel consumed is applied to fuel consumption data. Since off-road vehicles rarely have catalytic converters (and vintage data is scarce) no attempt is made to track vehicle vintages for the non-highway sources.

Data Sources

Emissions factors for motor vehicle nitrous oxide have been the subject of considerable discussion and research. The IPCC's *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (Paris, France, 1997)included revised nitrous oxide emissions factors for motor vehicles that were four times higher those used in the previous reference manual. The EPA's Office of Mobile Sources, stimulated by the IPCC report, undertook an automotive testing program in the summer of 1998. The Office of Mobile Sources results were published in U.S. Environmental Protection Agency, *Emissions of Nitrous Oxide from Highway Mobile Sources*, EPA-420-R-98-009 (Washington, DC, August 1998), and have been used in this report. These emissions factors are considerably lower than the emissions factors in the IPCC report but somewhat higher than emissions factors used in EIA's *Emissions of Greenhouse Gases in the United States* reports for 1996 and before, and higher than the emissions factors suggested by the IPCC for use with European vehicles.

EIA collected data on miles traveled in personal transportation vehicles (cars and light-duty trucks) as part of its triennial Residential Transportation Energy Consumption Survey (RTECS): Energy Information Administration, *Household Vehicles Energy Consumption 1994*, DOE/EIA-0464(94) (Washington, DC, July 1996, and previous years). This survey contains data for the years 1983, 1985, 1988, 1991, and 1994. Vehicle miles traveled for other years are estimated using weighted averages from survey data in conjunction with statistics on the U.S. fleet of cars and trucks by model year, provided by the American Automobile Manufacturers Association, *AAMA Vehicle Facts and Figures* (Detroit, MI, various years) and by Ward's Communications Inc., *Ward's Automotive Yearbook* (Southfield, MI, 2000) and Ward's Automotive Report (Southfield, MI, various years). Vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks were obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics* (Washington, DC, various years), web site www.fhwa.dot.gov/ohim/ohimstat.htm.

Fuel consumption for ships, locomotives, farm and construction equipment is based on data from the Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, various years). Jet and piston-powered aircraft fuel consumption data are contained in the Energy Information Administration's *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years). Data on fuel consumption by recreational boats are taken from Oak Ridge National Laboratory: Center for Transportation Analysis, *Transportation Energy Data Book* (Oak Ridge, TN, various years), web site www-cta.ornl.gov/publications/tedb.html.

Stationary Combustion

Emissions Sources

As with mobile sources, nitrous oxide emissions are produced as a byproduct of fuel combustion. The three fuels of primary importance burned by stationary sources are coal, fuel oil, and natural gas. Combustion systems powered by coal produce the most nitrous oxide, approximately 62 percent of annual emissions. Since 1990, electric utilities as a sector, have consistently accounted for more than one-half of total nitrous oxide emissions from stationary combustion. Other important sources are commercial facilities, industrial facilities, and residences.

Estimation Methods

Nitrous oxide emissions from stationary combustion are estimated by multiplying fuel consumption figures for each fuel type and stationary source by emissions factors for each type of fuel. Nitrous oxide emissions from stationary combustion include emissions from the consumption of wood in the residential, commercial, industrial, and electric utility sectors. Emissions are estimated by applying emissions factors for coal, oil, natural gas, and wood, to EIA's consumption data for each fuel in the commercial, residential, industrial, and electric utility sectors.

Data Sources

Emissions coefficients for stationary fuel were obtained 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),www.ipcc.ch/pub/guide.htm Fuel consumption data were drawn from the Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(99) (Washington, DC, September 1999) for 1980-1997; and *Monthly Energy Review*, DOE/EIA-0035(02/07)(Washington, DC, July 2002) for 1998-2001. Residential woodfuel consumption data were derived from EIA's *Annual Energy Review 2001*, DOE/EIA-0384(01) (Washington, DC, October J 2002).

Agriculture

Nitrogen Fertilization of Agricultural Soils

Emissions Sources

Nitrous oxide is a waste product of certain classes of bacteria normally present in soil. When nitrogen (in the form of natural or artificial fertilizers) is added to natural or agricultural soils, the action of these bacteria is stimulated. However, the extent to which adding nitrogen stimulates nitrous oxide emissions is highly uncertain. The bacteria that emit nitrous oxide have natural competitors, which may be more or less successful in particular settings. In addition, conditions may be more or less propitious for bacterial action: the soil may be too moist or too dry, too compacted, too acid or alkaline, too warm or too cold. The form in which nitrogen is applied may be subject to faster or slower release to the waiting bacteria. Further, excess nitrogen will escape from the location of application through runoff and will be subject to decomposition in diverse natural environments. Thus, measured emissions from even large numbers of specific sites are exceptionally difficult to generalize into an estimate of national emissions.

Estimation Methods

Following the IPCC *Reference Manual*, this report estimates nitrogen applications to soils from the following sources:

- Use of nitrogen fertilizers (computed directly from fertilizer data)
- Nitrogen in animal manure applied to agricultural soils (estimated from animal populations)
- Nitrogen in crop residues applied to agricultural soils (estimated from crop production statistics)
- Biological fixation of nitrogen in agricultural soils (estimated from crop production statistics)

For estimating nitrous oxide emissions from the first three sources, following the IPCC guidelines EIA assumes that 1.25 percent of the nitrogen applied is emitted to the atmosphere as nitrous oxide and 30 percent escapes into the environment. Some 2.5 percent of the nitrogen that escapes is ultimately converted into nitrous oxide in the form of emissions from streams and bodies of water. A further 10 percent of the nitrogen applied to soils is assumed to be released as gas in the form of nitrogen oxides and ammonia, and 1 percent of that nitrogen is assumed to be ultimately converted into nitrous oxide.[43]

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[43] 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. 1.53,www.ipcc.ch/pub/guide.htm

To estimate nitrous oxide emissions from the biological fixation of nitrogen in crops, annual production statistics for nitrogen-fixing crops (alfalfa, beans, lentils, peanuts, and soybeans) were obtained from the U.S. Department of Agriculture's *Crop Production* annual reports. Crop product values for these crops were then converted to total crop (crop product plus crop residue) dry biomass in mass units of dry matter, by applying residue-to-crop ratios and dry matter fractions. The total crop values in dry biomass units were then used to calculate the crop nitrogen content that is released in the form of nitrous oxide. Finally, nitrous oxide emissions factors were then applied to calculate nitrous oxide emissions from the biological fixation of nitrogen in crops.[44]

Data Sources

Estimates of total U.S. fertilizer consumption were obtained from reports by the Tennessee Valley Authority Fertilizer Research Center for various years through 1994: J.T. Berry et al., *Commercial Fertilizers* (Muscle Shoals, AL: Tennessee Valley Authority, Fertilizer Research Center, Reports for 1986-1991 and 1993-1994) and The Fertilizer Institute for 1995 through 2001. Estimates of nitrous oxide from the biological fixation of nitrogen in crops, were based on crop production statistics obtained from the U.S. Department of Agriculture's *Crop Production* annual reports. For nitrogen in animal manure, see the section on "Solid Waste of Domesticated Animals." For nitrogen in crop residues, see the section on "Crop Residue Burning" under methane or nitrous oxide.

Crop Residue Burning

Emissions Sources

Crop residues are commonly disposed of by incorporation into the soil, spreading over the soil surface to prevent erosion, as animal bedding, or through burning. Burning crop residues releases nitrous oxide into the atmosphere. The burning of crop residues occurs throughout the United States, although it is illegal in certain areas. There are no accurate estimates of the amount of crop residue burned in the United States.

Estimation Methods

This report assumes that 3 percent of all crop residues are burned, with the exception of rice, which is combusted at various levels over time.The share of rice crop residues in California estimated to be combusted declines from 75 percent in 1990 to 23 percent in 2001. The share of rice combusted throughout the remainder of the U.S. declines from 16 percent in 1990 to 9 percent in 2001.[45] The amount of crop residue burned is discounted by an assumed combustion efficiency, multiplied by its dry matter content and nitrogen content, and then converted to nitrous oxide using a standard ratio of nitrous oxide to nitrogen content.

Data Sources

Crop harvest sizes were obtained from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (Annual Reports).

Solid Waste of Domesticated Animals

Emissions Sources

Nitrous oxide is emitted as part of the denitrification of animal manure. The volume of nitrous oxide emissions is a function of the amount of manure produced, the nitrogen content of the manure, and the method for handling the animal waste. Waste managed by a solid storage or pasture range method may emit 20 times the nitrous oxide per unit of nitrogen content that is emitted from anaerobic lagoon or other liquid systems.

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[44] 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. 4.85-4.94,www.ipcc.ch/pub/guide.htm

[45] 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) p.5-23.

Estimation Methods

Nitrous oxide emissions from the solid waste of domesticated animals are estimated by linking emissions to the volume of solid waste produced by a given animal, the volatile solids in that waste, the nitrogen content of the waste, and the manner in which the waste is managed. Animal populations are divided into distinct, relatively homogeneous groups. The U.S. cattle population is separated into dairy and beef cattle. Emissions of nitrous oxide from poultry, sheep, pigs, goats, and horses are also estimated. For each group of animals, a per-head volatile solids production and an associated nitrogen content within the volatile solids are assigned. These values are multiplied by animal populations to derive total nitrogen excreted. For each animal group, excretions are distributed among the manure management systems used. The ratio of nitrous oxide production to nitrogen content for each management technique is applied to provide an emissions estimate for each animal group, broken down by manure management system. The emissions are then summed to calculate an overall emissions estimate.

Data Sources

Population and slaughter weight data for cattle and population data for sheep, poultry, and swine were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch, web site www.usda.gov/nass/. Average broiler chicken populations for each year were estimated by multiplying the estimated number of broiler chickens slaughtered annually by 0.1425, based on their 7-week life cycle as recommended by the USDA's Economic Research Service.[46] Population data for goats and horses were extrapolated from U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, *Census of Agriculture, United States Summary and State Data*, (Washington, DC, 1982, 1987, 1992, and 1997). Volatile solids content, nitrogen content of wastes by species, manure management systems, and nitrogen to nitrous oxide conversion rates were taken 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. 4.88-4.93, www.ipcc.ch/pub/guide.htm

Waste Management

Waste Combustion

Emissions Sources

Like other stationary and mobile combustion processes, the burning of garbage and nonhazardous solid waste produces nitrous oxide emissions. There are 160 municipal waste combustion plants in the United States, with 114 plants generating energy. Emission levels are dependent on the composition of waste burned and combustion temperatures.[47] Very high temperatures reduce nitrous oxide emissions.

Estimation Methods

The total annual volume of municipal solid waste generated in the United States was multiplied by the share of waste incinerated. Total waste incinerated was then multiplied by a factor of 30 grams of nitrous oxide per metric ton of waste incinerated to calculate total nitrous oxide emissions from this source.

Data Sources

Waste generation data and share incinerated were drawn from *Biocycle* magazine, "The State of Garbage in America" (various years). Waste generation data for 2001 were based on 2000 data scaled to GDP growth of 0.3 percent with the share of waste combusted held steady. The emissions factor was taken from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-0010 (Washington, DC, April 2000), web site www.epa.gov/publications/emissions/index.html.

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[46] Personal communication, May 1993.

[47] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), p. 7-5.

Human Sewage in Wastewater

Emissions Sources

When human sewage is treated in wastewater systems, the nitrogen-based organic matter in the waste generates nitrous oxide through nitrification and denitrification. Under aerobic conditions, ammonia is converted to nitrate. As oxygen dissipates and an anaerobic environment governs, nitrate is converted to nitrous oxide.

Estimation Methods

Nitrous oxide emissions are estimated as a function of national population, per capita protein consumption, and the fraction of nitrogen in protein. The fraction of nitrogen in protein is assumed to be 16 percent, and 1 kilogram of nitrous oxide is assumed to be emitted per 100 kilograms of nitrogen in wastewater.

Data Sources

U.S. population data are from the Bureau of Census. Per-capita protein intake is from the Food and Agriculture Organization, *FAOSTAT Statistical Database*. Nitrogen content and nitrous oxide conversion factor are from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-0010 (Washington, DC, April 2000), web site www.epa.gov/publications/emissions/index.html.

Industrial Processes

Adipic Acid Production

Emissions Sources

Manufacture of adipic acid is one of the two principal sources of nitrous oxide from industrial processes. Adipic acid is used primarily in the manufacture of nylon fibers and plastics in carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizers 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. Creation of nitrous oxide is an intrinsic byproduct of this chemical reaction.

Estimation Methods

Emissions of nitrous oxide from production of adipic acid are calculated by multiplying adipic acid production figures by nitrous oxide emissions coefficients. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.[48] Currently, three plants control emissions by thermally decomposing the nitrous oxide, and 98 percent of the potential emissions from the production of adipic acid, subject to abatement controls, are eliminated by this technique.[49] By 2001, 97.4 percent of total estimated U.S. production of adipic acid was subject to abatement control measures.

Data Sources

Adipic acid production figures were obtained from *Chemical and Engineering News*, annual report on the “Top 50 Industrial Chemicals” (April issue, various years). For 1996 through 2001, estimated U.S. total adipic acid production was obtained from the American Chemical Council (formerly the Chemical Manufacturers Association). The adipic acid emissions coefficient was taken from M. Thiemens and W. Trogler, “Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide,” *Science*, Vol. 251, No. 4996 (February 22, 1991), p. 932.

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[48] M.H. Thiemens and W.C. Trogler, “Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide,” *Science*, Vol. 251, No. 4996 (February 22, 1991), p. 932.

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

Nitric Acid Production

Emissions Sources

Nitric acid is a primary ingredient in fertilizers. The process for manufacturing this acid involves oxidizing ammonia (NH_3) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation.

Estimation Methods

The IPCC guidelines indicate emissions factors of 2 to 9 grams of nitrous oxide per kilogram of nitric acid manufactured.[50] The emissions estimates presented in this report are calculated by multiplying the annual quantity of nitric acid produced by the midpoint (5.5 grams nitrous oxide per kilogram of product) of the emissions range. There is, however, a considerable degree of uncertainty associated with this estimate.

Data Sources

Nitric acid production figures were based on data published by the U.S. Department of Commerce, Bureau of the Census, in its annual and quarterly *Current Industrial Reports* on fertilizer materials. The nitric acid emissions coefficient was taken 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), www.ipcc.ch/pub/guide.htm

HFCs, PFCs, and Sulfur Hexafluoride

Emissions Sources

HFCs, PFCs, and sulfur hexafluoride have hundreds of uses, but the bulk of emissions come from a few broad categories of use:

- As refrigerants or working fluids in air conditioning and refrigeration equipment
- As solvents in various industrial processes
- As blowing agents for making insulating foams
- As fugitive emissions from various industrial processes, including the manufacture of halocarbons.

The emissions profile differs for each emissions source. Refrigerants are used in a closed cycle inside cooling equipment, and they tend to leak out when the equipment is scrapped or serviced. Some portion of the refrigerants is captured and recycled or destroyed, rather than emitted, when equipment is serviced. HFCs solvent applications are often recycled, but net consumption (after recycling) is probably a good indicator of emissions. HFCs used as blowing agents can be characterized by the type of foam manufactured: HFCs s used to make “open cell” foam are released to the atmosphere immediately, while HFCs used to make “closed cell” foam are trapped within the foam for the life of the foam, which can vary (depending on the use) from a few weeks to many years.

Estimation Methods

For the years 1990 through 2000, EIA has relied primarily on estimates of HFC, PFC, and sulfur hexafluoride emissions presented in the U.S. Environmental Protection Agency’s *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, EPA-236-R-01-001 (Washington, DC, April 2002). The preliminary 2001 emissions estimates for HFCs, PFCs, and sulfur hexafluoride are advance estimates developed by the EPA and provided to the EIA, courtesy of the EPA’s Climate Protection Division.

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[50] 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. 2.18,www.ipcc.ch/pub/guide.htm

Data Sources

EPA estimates of emissions of HFCs, PFCs, and sulfur hexafluoride for 1990-2000 are from the U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, EPA-236-R-01-001 (Washington, DC, April 2002), web site www.epa.gov/globalwarming/publications/. Estimate for emissions for 2001 are directly from contacts at EPA's Climate Protection Partnerships Division and Global Programs Division.

Appendix B

Carbon Coefficients Used in This Report

This appendix presents the background and methodology for estimating the carbon coefficients of fossil fuels combusted in the United States. The carbon coefficient of a particular fossil fuel represents the maximum potential emissions to the atmosphere if all carbon in the fuel is oxidized during combustion. Historically, the carbon coefficients used in earlier editions of this report were developed using methods first outlined in the EIA report, *Emissions of Greenhouse Gases in the United States: 1987 – 1992*. The carbon coefficients in that report were developed to replace, in part, the more general coefficients originally developed by Marland and Pippin and subsequently adopted by the Intergovernmental Panel on Climate Change (IPCC).[1] The IPCC coefficients were intended to be suitable for all countries, and to support the division of petroleum consumption into the products defined by the International Energy Agency (IEA). Because U.S. fuels sometimes differ in composition from those used abroad and EIA divides petroleum product consumption into more than 20 different categories, rather than the six described by the IEA, the development of U.S. specific carbon coefficients improved the precision of U.S. carbon emission estimates.

This appendix provides a detailed list of methods and data sources for estimating the carbon coefficients of coal (by consuming sector), natural gas (broken into pipeline-quality and flared gas), and petroleum products. Though the methods for estimating carbon contents for coal, natural gas, and petroleum products differ in their details, they each follow the same basic approach. First, because carbon coefficients are presented in terms of mass/unit-energy (i.e., million metric tons carbon per quadrillion Btu or MMTC/Qbtu), those fuels that are typically described in volumetric units (petroleum products and natural gas) are converted to units of mass using an estimated density. Next, carbon contents are derived from fuel sample data, using descriptive statistics to estimate the carbon share of the fuel by weight. Finally, the heat content of the fuel is then estimated based on the sample data, or where sample data is unavailable or unrepresentative, by default values that reflect the characteristics of the fuel as defined by market requirements. A summary of carbon coefficients used in this report appears in Table B1.

Table B1. Carbon Coefficients Used in this Report
(Million Metric Tons Carbon per Quadrillion Btu)

Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Coal												
Coal (Residential)	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04[p]
Coal (Commercial)	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04[p]
Coal (Industrial Coking)	25.55	25.56	25.55	25.53	25.57	25.57	25.56	25.60	25.62	25.60	25.63	25.63[p]
Coal (Industrial Other)	25.82	25.89	25.87	25.77	25.77	25.80	25.75	25.76	25.79	25.80	25.74	25.74[p]
Coal (Electric Utility)	25.95	25.97	25.99	25.87	25.88	25.92	25.92	25.91	25.93	25.97	25.98	25.98[p]
Natural Gas												
Natural Gas (Pipeline)	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Natural Gas (Flared)	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92
Petroleum												
Asphalt and Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Aviation Gasoline	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Crude Oil	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24	20.24	20.19	20.23	20.29
Distillate Fuel	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33	19.33	19.33	19.33	19.33
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
LPG	16.99	16.98	16.99	16.97	17.01	17.00	16.99	16.99	16.99	16.99	16.99	16.99
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Motor Gasoline	19.41	19.41	19.42	19.43	19.45	19.38	19.36	19.35	19.33	19.33	19.34	19.34
Petrochemical Feed.	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Residual Fuel	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Waxes	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81

Note: All coefficients based on Heating (Gross Calorific) Value and assume 100% combustion
[p]=Preliminary
Source: Estimates described in this Appendix

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[1] G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol.14 (1990), pp. 319-336, and Intergovernmental Panel on Climate Change, Estimation of Greenhouse Gases and Sinks (1991), p. 2.18.

This appendix also supplies a detailed discussion of each fuel and its derived carbon coefficient below. The discussion begins with the carbon contents of coal because about one third of all U.S. carbon emissions from fossil fuel combustion are associated with coal consumption. The estimated carbon coefficients of coal have been revised this year to reflect the composition of a new set of coal samples from the U.S. Geological Survey, Coal Quality Database Version 2.0. This appendix then discusses the methods and sources for estimating the carbon content of natural gas. About one fifth of U.S. greenhouse gas emissions from fossil fuel combustion are attributable to natural gas consumption. Finally, this appendix examines carbon contents of petroleum products. There are more than 20 different petroleum products accounted for in U.S. energy consumption statistics.

Coal

Approximately one-third of all U.S. carbon dioxide emissions from fossil fuel combustion are associated with coal consumption. Because the EIA collects coal consumption data by consuming sector, EIA adopted carbon coefficients by consuming sector. Because the carbon content of coal varies by the state in which it was mined and by coal rank, and the sources of coal for each consuming sector vary by year, the weighted average carbon coefficient for coal combusted in each consuming sector also varies over time. A time-series of carbon coefficients by coal rank and consuming sector appears in Table A1-2. Since the IPCC guidelines provide carbon coefficients by rank, EIA also adopted carbon coefficients by rank for comparison with other nations carbon coefficients.

Table B2. Carbon Coefficients for Coal by Consuming Sector and Coal Rank, 1990 - 2001
(Million Metric Tons Per Quadrillion Btu)

Consuming Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Electric Power	25.95	25.97	25.99	25.87	25.88	25.92	25.92	25.91	25.93	25.97	25.98	25.98^{p}
Industrial Coking	25.55	25.56	25.55	25.53	25.57	25.57	25.56	25.60	25.62	25.60	25.63	25.63^{p}
Other Industrial	25.82	25.89	25.87	25.77	25.77	25.80	25.75	25.76	25.79	25.80	25.74	25.74^{p}
	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04^{p}
Residential/Commercial												
Coal Rank												
Anthracite	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26^{p}
Bituminous	25.43	25.45	25.44	25.45	25.46	25.47	25.47	25.48	25.47	25.48	25.49	25.49^{p}
Sub-bituminous	26.50	26.49	26.49	26.48	26.49	26.49	26.49	26.49	26.49	26.49	26.48	26.48^{p}
Lignite	26.19	26.21	26.22	26.21	26.24	26.22	26.17	26.20	26.23	26.26	26.30	26.30^{p}

^{p}=Preliminary

Sources: U.S. Geological Survey, US Coal Quality Database Version 2.0 (1998) and analysis prepared by Science Applications International Corporation (SAIC) for the U.S. Environmental Protection Agency, Office of Air and Radiation, Market Policies Branch, October 2002.

Estimation Methods

Carbon coefficients are estimated on the basis of 6,588 coal samples collected by the US Geological Survey between 1973 and 1989. These coal samples are classified according to rank and state of origin. For each rank in each state, the average heat content and carbon content of the coal samples are calculated. Dividing the carbon content (reported in pounds carbon dioxide) by the heat content (reported in million Btu) yields an average carbon coefficient. This coefficient is then converted into units of million metric tons per quadrillion Btu.

U.S. energy statistics provide data on the origin of coal used in four areas: 1) the electric power industry 2) industrial coking, 3) all other industrial uses, and 4) the residential and commercial end-use sectors. Because U.S. energy statistics do not provide the distribution of coal rank consumed by each consuming sector, it is assumed that each sector consumes a representative mixture of coal ranks from a particular state that matches the mixture of all coal produced in that state during the year. Sectoral carbon coefficients are then calculated by multiplying the share of coal purchased from each state by rank by the carbon coefficient estimated above. The resulting partial carbon coefficients are then totaled across all states and ranks to generate a national sectoral carbon coefficient.

Although not used to calculate emissions, national-level carbon contents by rank are more easily compared to carbon contents of other countries than are sectoral carbon contents. State-level carbon coefficients by rank developed above are weighted by overall coal production by state and rank (consumption by rank is unavailable in U.S. energy statistics) to support this comparison. Each state-level carbon coefficient by rank is multiplied by the share of national production of that rank that each state represents. The resulting partial carbon coefficients are then summed across all states to generate an overall carbon coefficient for each rank.

The estimates of carbon coefficients for coal were updated and revised in 2002. The methodology employed for these estimates was unchanged from previous years, however, the underlying coal data sample set was updated. Previously, a set of 5,426 coal samples from the EIA coal analysis file were used to develop carbon content estimates. The results from that sample set appear below in Table B3. The EIA Coal Analysis File was originally developed by the U.S. Bureau of Mines and contained over 60,000 coal samples obtained at numerous coal seams throughout the United States. Many of the samples were collected as early as the 1940s and 1950s, with sample collection continuing until the 1980s. The updated sample set included 6,588 coal samples collected by the U.S. Geological Survey between 1973 and 1989.

Table B3. 1990–2000 Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank
(Million Metric Tons Per Quadrillion Btu)

Consuming Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Electric Power	25.68	25.69	25.69	26.71	25.72	25.74	25.74	25.76	25.76	25.76	25.76
Industrial Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56	25.56
Other Industrial	25.58	25.59	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63	25.63
Residential/ Commercial	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00	26.00	26.00
Coal Rank											
Anthracite	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13
Bituminous	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37
Sub-bituminous	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24
Lignite	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62

Sources: Emission factors by consuming sector from B.D. Hong and E.R. Slatick, “Carbon Dioxide Emission Factors for Coal,” U.S. Energy Information Administration, *Quarterly Coal Report*, *January-March 1994.* (Washington, DC, 1994) and emission factors by rank from Science Applications International Corporation, “Analysis of the Relationship Between Heat and Carbon Content of U.S. Fuels: Final Task Report,” prepared for the U.S. Energy Information Administration, Office of Coal, Nuclear, Electric and Alternative Fuels (Washington, DC 1992).

Data Sources

Ultimate analyses of 6,588 coal samples were obtained from the U.S. Geological Survey, CoalQual Database Version 2.0 (1998). Data contained in the CoalQual Database are largely derived from samples taken between 1973 and 1989, and were largely reported on in State Geological Surveys.

Coal distribution by state and consumption by sector from, Energy Information Administration, *Coal Industry Annual*, (Washington, DC, various years) Table 10 and Table 63. Web site at www.eia.doe.gov/cneaf/coal/cia/cia_sum.html.

Coal production by state and rank from, Energy Information Administration, *Coal Industry Annual*, (Washington, DC, various years) Table 9. Web site at www.eia.doe.gov/cneaf/coal/cia/cia_sum.html.

Natural Gas

Natural gas is predominantly composed of methane, which is 75 percent carbon by weight and contains 14.2 million metric tons carbon per quadrillion Btu (Higher Heating Value), but it may also contain many other compounds that can lower or raise its overall carbon content. These other compounds may be divided into two classes: 1) natural gas liquids (NGLs) and 2) non-hydrocarbon gases. The most common NGLs are ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and, to a lesser extent, pentane (C_5H_{12}) and hexane (C_6H_{14}). Because the NGLs have more carbon atoms than methane (which has only one) their presence increases the overall carbon content of natural gas. NGLs have a commercial value greater than that of methane, and therefore are usually separated from raw natural gas at gas processing plants and sold as separate products. Ethane is typically used as a petrochemical feedstock, propane and butane have diverse uses, and natural gasoline[2] contributes to the gasoline/naphtha "octane pool" used primarily to make motor gasoline.

Raw natural gas can also contain varying amounts of non-hydrocarbon gases, such as carbon dioxide, nitrogen, helium and other noble gases, and hydrogen sulfide. The share of non-hydrocarbon gases is usually less than 5 percent of the total, but there are individual natural gas reservoirs where the share can be much larger. The treatment of non-hydrocarbon gases in raw gas varies. Hydrogen sulfide is always removed. Inert gases are removed if their presence is substantial enough to reduce the energy content of the gas below pipeline

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[2] A term used in the gas processing industry to refer to a mixture of liquid hydrocarbons (mostly pentanes and heavier hydrocarbons) extracted from natural gas.

specifications. Otherwise, inert gases will usually be left in the natural gas. Because the raw gas that is usually flared contains NGLs and carbon dioxide, it will typically have a higher overall carbon content than gas that has been processed and moved to end-use customers via transmission and distribution pipeline.

Estimation Methods

In the United States, pipeline-quality natural gas is expected to have an energy content greater than 970 Btu per cubic foot but less than 1,100 Btu per cubic foot. Hydrogen sulfide content must be negligible. Typical pipeline-quality natural gas is about 95 percent methane, 3 percent NGLs, and 2 percent non-hydrocarbon gases, of which perhaps 1 percent is carbon dioxide.

However, there is a range of gas compositions that are consistent with pipeline specifications. The minimum carbon coefficient for natural gas would match that for pure methane, which equals1,005 Btu per standard cubic foot. Gas compositions with higher or lower Btu content tend to have higher carbon emissions factors, because the "low" Btu gas has a higher content of inert gases (including carbon dioxide offset with more NGLs), while "high" Btu gas tends to have more NGLs.

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

- There may be no market for some batches of natural gas, the amount may be too small or too variable, or the quality might too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of carbon dioxide). All natural gas flared for these reasons is probably "rich" associated gas, with relatively high energy content, high NGL content, and a high carbon content.

- Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

Data on the energy content of flare gas, as reported by states to EIA, indicates an energy content of 1,130 Btu per standard cubic foot. Flare gas may have a higher energy content than reported by EIA since rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot.

A relationship between carbon content and heat content may be used to develop a carbon coefficient for natural gas consumed in the United States. In 1994, EIA examined the composition (and therefore carbon contents) of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 States. To demonstrate that these samples were representative of actual natural gas "as consumed" in the US, their heat content was compared to that of the national average. For the most recent year, the average heat content of natural gas consumed in the U.S. was 1,025 Btu per cubic foot, varying by less than 1 percent (1,025 to 1,031 Btu per cubic foot) over the past 5 years. Meanwhile the average heat content of the 6,743 samples was 1,027 Btu per cubic foot and the median heat content was 1,031 Btu per cubic foot. Thus, the average heat content of the sample set falls well within the typical range of natural gas consumed in the United States, suggesting that these samples continue to be representative of natural gas “as consumed” in the U.S. The average and median composition of these samples appears in Table B4.

Table B4. Composition of Natural Gas
(Percent)

Compound	Average	Median
Methane	93.07	95.00
Ethane	3.21	2.79
Propane	0.59	0.48
Higher Hydrocarbons	0.32	0.30
Non-hydrocarbons	2.81	1.43
Higher Heating Value (Btu per cubic foot)	1,027	1,032

Source: Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States.*

Carbon coefficients were then calculated for eight separate sub-samples based on heat content and shown in Table B5.

Table B5. Carbon Content of Pipeline-Quality Natural Gas by Energy Content

Sample	Average Carbon Coefficient (Million Metric Tons per Quadrillion Btu)
GRI Full Sample	14.51
Greater than 1,000 Btu	14.47
1,025 to 1,035 Btu	14.45
975 to 1,000 Btu	14.73
1,000 to 1,025 Btu	14.43
1,025 to 1,050 Btu	14.47
1,050 to 1,075 Btu	14.58
1,075 to 1,100 Btu	14.65
Greater than 1,100 Btu	14.92
Weighted National Average	14.47

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573 (Washington, DC, November, 1994,) Appendix A.

Because there is some regional variation in the energy content of natural gas consumed, a weighted national average carbon content was calculated using the average carbon contents for each sub-sample of gas that conformed with each individual state's typical cubic foot of natural gas. The result was a weighted national average of 14.47 million metric tons per quadrillion Btu. This was identical to the average carbon coefficient for all samples with more than 1,000 Btu per cubic foot and the average carbon coefficient for all samples with a heat content between 1,025 and 1,050 Btu per cubic foot. Because those samples with a heat content below 1,000 Btu had an unusually high carbon coefficient attributable to large portions of carbon dioxide (not seen in the median sample), they were excluded from the final sample so as not to bias the carbon coefficient upwards.

Selecting a carbon coefficient for flare gas was much more difficult than for pipeline natural gas because of the uncertainty of its composition. Because EIA estimates the heat content of flare gas at 1,130 Btu per cubic foot, the average carbon coefficient for samples with more than 1,100 Btu per cubic foot, 14.92 million metric tons per quadrillion Btu, was adopted as the coefficient for flare gas. It should be noted that the sample data set did not include any samples with more than 1,130 Btu per cubic foot.

Data Sources

Natural gas samples were obtained from a Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States.*

Average heat content of natural gas consumed in the U.S. from the Energy Information Administration, *Monthly Energy Review*, (Washington, DC), Table A4. Web site at www.eia.doe.gov/mer/txt/mer-a4.

Average heat content consumed on a state by state basis from the Energy Information Administration, *State Energy Data Report*, (Washington, DC), Table 1 and 2. Web site at www.eia.doe.gov/emeu/sedr/contents.html#PDF%20Files.

Petroleum

There are four critical determinants of the carbon coefficient for a petroleum-based fuel:

1. The density of the fuel (e.g., the weight in kilograms of one barrel of fuel);
2. The fraction by mass of the product that consists of hydrocarbons, and the fraction of non-hydrocarbon impurities;
3. The specific types of 'families' of hydrocarbons that make up the hydrocarbon portion of the fuel; and
4. The heat content of the fuel.

Petroleum products vary between 5.6 degrees API gravity (dense products such as asphalt and road oil) and 247 degrees (ethane).[3] This is a range in density of 60 to 150 kilograms per barrel, or ±50 percent. The variation in carbon content, however, is much smaller (±5 to 7 percent): ethane is 80 percent carbon by weight, while petroleum coke is 90 to 92 percent carbon. The tightly bound range of carbon contents can be explained by basic petroleum chemistry.

Petroleum Chemistry

Crude oil and petroleum products are typically mixtures of several hundred distinct compounds, predominantly hydrocarbons. All hydrocarbons contain hydrogen and carbon in various proportions. When crude oil is distilled into petroleum products, it is sorted into fractions by the boiling temperature of these hundreds of organic compounds. Boiling temperature is strongly correlated with the number of carbon atoms in each molecule. Petroleum products consisting of relatively simple molecules and few carbon atoms have low boiling temperatures and, larger molecules with more carbon atoms have higher boiling temperatures.

Products that boil off at higher temperatures are usually more dense, which implies greater carbon content as well. Petroleum products with higher carbon contents, in general, have lower energy content per unit mass and higher energy content per unit volume than products with a lower carbon content. Empirical research led to the establishment of a set of quantitative relationships between density, energy content per unit weight and volume, and carbon and hydrogen content. Figure B1 compares carbon coefficients calculated on the basis of the derived formula with actual carbon coefficients for a range of crude oils, fuel oils, petroleum products, and pure hydrocarbons. The actual fuel samples were drawn from the sources described below in the discussions of individual petroleum products.

The derived empirical relationship between carbon content per unit heat and density is based on the types of hydrocarbons most frequently encountered. Actual petroleum fuels can vary from this relationship due to non-hydrocarbon impurities and variations in molecular structure among classes of hydrocarbons. In the absence of more exact information, this empirical relationship offers a good indication of carbon content.

Non-hydrocarbon Impurities

Most fuels contain a certain share of non-hydrocarbon material. This is also primarily true of crude oils and fuel oils. The most common impurity is sulfur, which typically accounts for between 0.5 and 4 percent of the mass of most crude oils, and can form an even higher percentage of heavy fuel oils. Some crude oils and fuel oils also contain appreciable quantities of oxygen and nitrogen, typically in the form of asphaltenes or various acids. The nitrogen and oxygen content of crude oils can range from near zero to a few percent by weight. Lighter petroleum products have much lower levels of impurities, because the refining process tends to concentrate all of the non-hydrocarbons in the residual oil fraction. Light products usually contain less than 0.5 percent non-hydrocarbons by mass. Thus, the carbon content of heavy fuel oils can often be several percent lower than that of lighter fuels, due entirely to the presence of non-hydrocarbons.

Variations in Hydrocarbon Classes

Hydrocarbons can be divided into five general categories, each with a distinctive relationship between density and carbon content and physical properties. Refiners tend to control the mix of hydrocarbon types in particular products in order to give petroleum products distinct properties. The main classes of hydrocarbons are described below.

Paraffins. Paraffins are the most common constituent of crude oil, usually comprising 60 percent by mass. Paraffins are straight-chain hydrocarbons with the general formula C_nH_{2n+2}. Paraffins include ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and octane (C_8H_{18}). As the chemical formula suggests, the carbon content of the paraffins increases with their carbon number: ethane is 80 percent carbon by weight, octane 84 percent. As the size of paraffin molecules increases, the carbon content approaches the limiting value of 85.7 percent asymptotically (See Figure B2).

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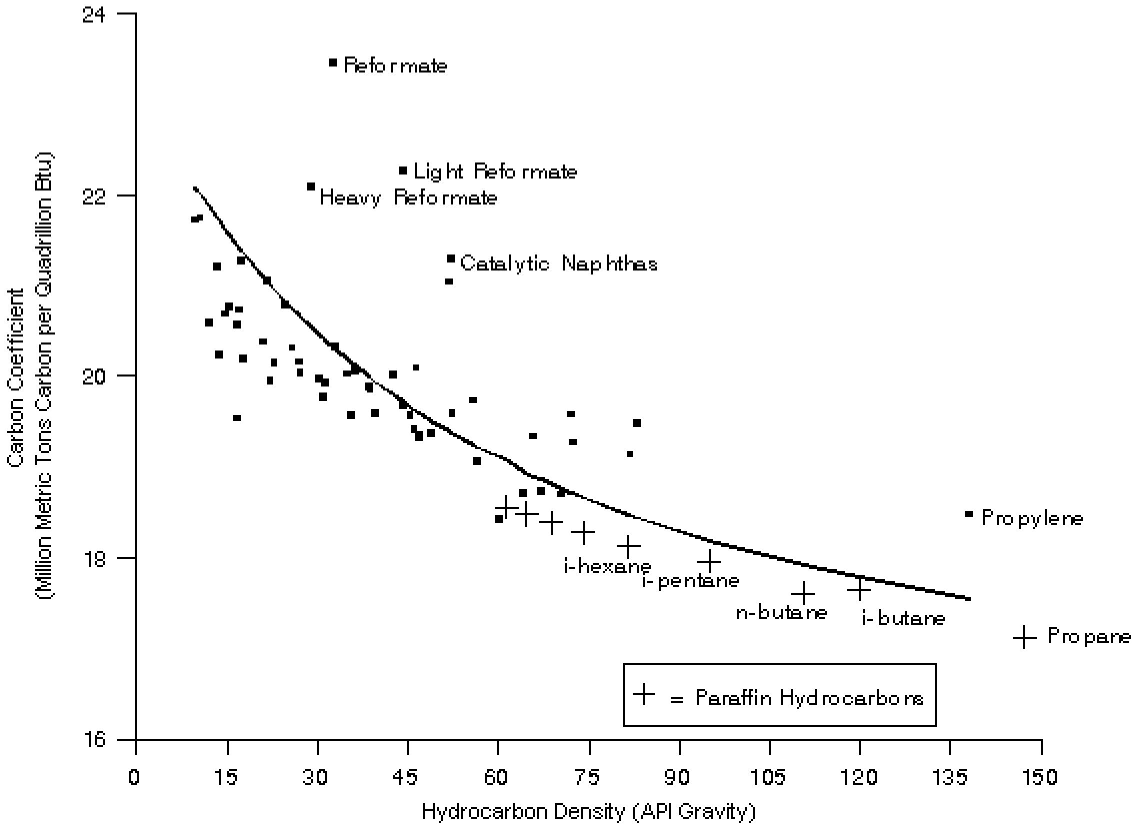
[3] API gravity is an arbitrary scale expressing the gravity or density of liquid petroleum products, as established by the American Petroleum Institute (API). The measuring scale is calibrated in terms of degrees API. The higher the API gravity, the lighter the compound. Light crude oils generally exceed 38 degrees API and heavy crude oils are all crude oils with an API gravity of 22 degrees or below. Intermediate crude oils fall in the range of 22 degrees to 38 degrees API gravity. API gravity can by calculated with the following formula Degrees API =(141.5/Specific Gravity) – 131.5. Specific gravity is the density of a material relative to that of water. At standard temperature and pressure, there are 62.36 pounds of water per cubic foot, or 8.337 pounds water per gallon.

Figure B1. Estimated and Actual Relationships Between Petroleum Carbon Coefficients and Hydrocarbon Density



Source: Carbon content factors for paraffins are calculated based on the properties of hydrocarbons in V. Guthrie (ed.), *Petroleum Products Handbook* (New York: McGraw Hill, 1960) p. 33. Carbon content factors from other petroleum products are drawn from sources described below. Relationship between density and emission factors based on the relationship between density and energy content in U.S. Department of Commerce, National Bureau of Standards, *Thermal Properties of Petroleum Products*, Miscellaneous Publication, No. 97 (Washington, D.C., 1929), pp.16-21, and relationship between energy content and fuel composition in S. Ringen, J. Lanum, and F.P. Miknis, “Calculating Heating Values from the Elemental Composition of Fossil Fuels,’ *Fuel,* Vol. 58 (January 1979), p.69.

Cycloparaffins. Cycloparaffins are similar to paraffins, except that the carbon molecules form ring structures rather than straight chains, and consequently require two fewer hydrogen molecules than paraffins. Cycloparaffins always have the general formula C_nH_{2n} and are 85.7 percent carbon by mass, regardless of molecular size.

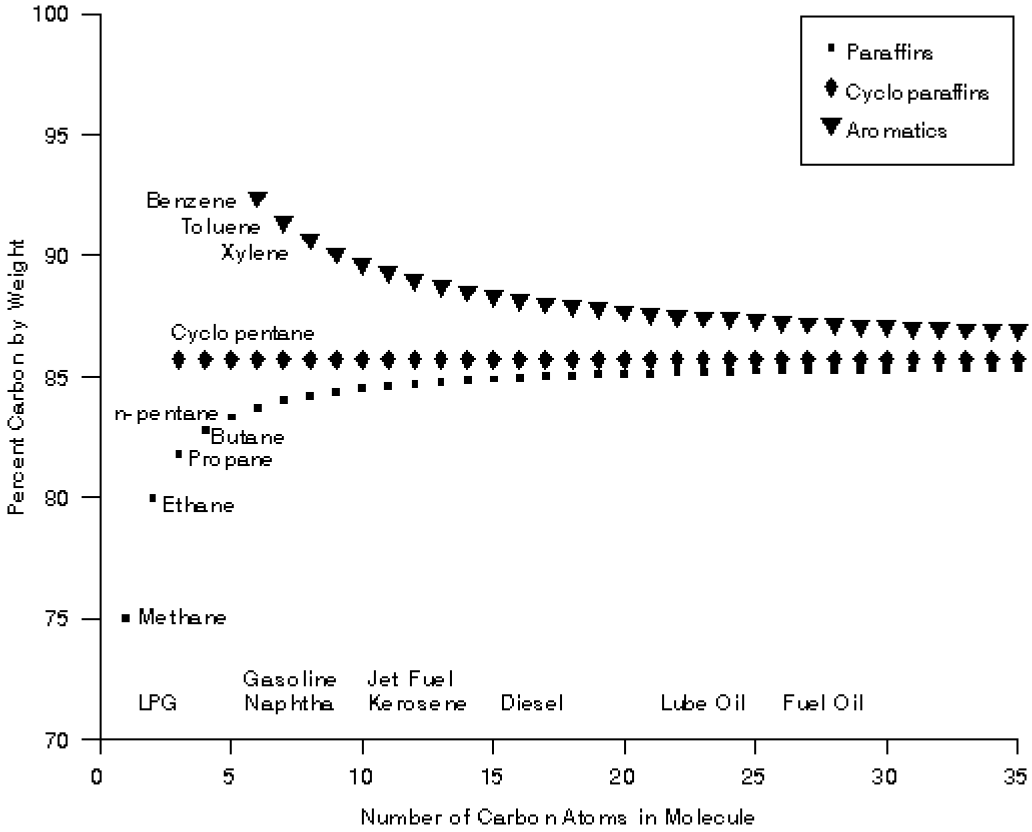
Olefins. Olefins are a reactive and unstable form of paraffin: a straight chain with the two hydrogen atoms at each end of the chain missing. They are never found in crude oil but are created in moderate quantities by the refining process. Thus, gasoline, for example, may contain 2 percent olefins. They also have the general formula C_nH_{2n}, and hence are also always 85.7 percent carbon by weight. Propylene (C_3H_6), a common intermediate petrochemical product, is an olefin.

Aromatics. Aromatics are very reactive hydrocarbons that are relatively uncommon in crude oil (10 percent or less). Light aromatics increase the octane level in gasoline, and consequently are deliberately created by steam reforming of naphtha. Aromatics also take the form of ring structures with some double bonds between carbon atoms. The most common aromatics are benzene (C_6H_6), toluene (C_7H_8), and xylene (C_8H_{10}). The general formula for aromatics is C_nH_{2n-6}. Benzene is 92 percent carbon by mass, while xylene is 90.6 percent carbon by mass. Unlike the other hydrocarbon families, the carbon content of aromatics declines asymptotically toward 85.7 percent with increasing carbon number and density. (See Figure B2)

Polynuclear Aromatics. Polynuclear aromatics are large molecules with a multiple ring structure and few hydrogen atoms, such as naphthalene ($C_{10}H_2$ and 94.4 percent carbon by mass) and anthracene ($C_{14}H_4$ and 97.7 percent carbon). They are relatively rare but do appear in heavier petroleum products.

Figure B2 illustrates the share of carbon by weight for each class of hydrocarbon. Hydrocarbon molecules containing 2 to 4 carbon atoms are all natural gas liquids; hydrocarbons with 5 to 10 carbon atoms are predominantly found in naphtha and gasoline; and hydrocarbon compounds with 12 to 20 carbons comprise "middle distillates," which are used to make diesel fuel, kerosene and jet fuel. Larger molecules are generally used as lubricants, waxes, and residual fuel oil.

Figure B2. Carbon Content of Pure Hydrocarbons as a Function of Carbon Number



Source: J.M. Hunt, *Petroleum Geochemistry and Geology* (San Francisco, CA, W.H. Freeman and Company, 1979), pp. 31-37.

If one knows nothing about the composition of a particular petroleum product, assuming that it is 85.7 percent carbon by mass is not an unreasonable first approximation. Since denser products have higher carbon numbers, this guess would be most likely to be correct for crude oils and fuel oils. The carbon content of lighter products is more affected by the shares of paraffins and aromatics in the blend.

Energy Content of Petroleum Products

The exact energy content (gross heat of combustion) of petroleum products is not generally known. EIA estimates energy consumption in Btu on the basis of a set of industry-standard conversion factors. These conversion factors are generally accurate to within 3 to 5 percent.

Individual Petroleum Products

The U.S. maintains data on the consumption of more than 20 separate petroleum products and product categories. The carbon contents, heat contents, and density for each product are provided below in Table B6. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table B6. Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	2001 Carbon Content (MMTC/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.34	5.253	59.6	86.60
LPG	16.99	*	*	*
Jet Fuel	19.33	5.670	42.0	86.30
Distillate Fuel	19.95	5.825	35.5	86.34
Residual Fuel	21.49	6.287	11.0	85.68
Asphalt and Road Oil	20.62	6.636	5.6	83.47
Lubricants	20.24	6.065	25.6	85.80
Petrochemical Feedstocks	19.37	5.248[a]	67.1 [a]	84.11 [a]
Aviation Gas	18.87	5.048	69.0	85.00
Kerosene	19.72	5.670	41.4	86.01
Petroleum Coke	27.85	6.024	-	92.28
Special Naphtha	19.86	5.248	51.2	84.76
Petroleum Waxes	19.81	5.537	43.3	85.29
Still Gas	17.51	6.000	-	-
Crude Oil	20.29	5.800	30.5	85.49
Unfinished Oils	20.29	5.825	30.5	85.49
Miscellaneous Products	20.29	5.796	30.5	85.49
Pentanes Plus	18.24	4.620	81.7	83.70
Natural Gasoline	18.24	4.620	81.7	83.70

[a] Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Petrochemical feedstocks with higher boiling points are assumed to have the same characteristics as distillate fuel.
* LPG is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and carbon content, see table B9.
-(No sample data available)
Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, Washington, DC, (November, 1994), DOE/EIA 0573

Motor Gasoline and Motor Gasoline Blending Components

Motor gasoline is 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.[4] "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline; but excludes aviation gasoline.

Gasoline is the most widely used petroleum product in the United States, and its combustion accounts for nearly 20 percent of all U.S. carbon dioxide emissions. EIA collects consumption data (i.e., "petroleum products supplied" by wholesalers) for several types of gasoline: leaded regular, unleaded regular, and unleaded high octane. The American Society for Testing and Materials (ASTM) standards permit a broad range of densities for gasoline, ranging from 50 to 70 degrees API gravity, which implies a range of possible carbon and energy contents per barrel. Table B7 reflects changes in the density of gasoline over time and across grades of gasoline through 2001.

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[4] Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 degrees to 158 degrees Fahrenheit at the 10-percent recovery point to 365 degrees to 374 degrees Fahrenheit at the 90-percent recovery point.

Table B7. Motor Gasoline Density, 1990 – 2001
(Degrees API)

Fuel Grade	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Winter Grade												
Low Octane	62.0	61.8	61.4	61.0	60.1	59.8	60.6	61.5	61.8	61.6	61.6	61.7
Mid Octane	60.8	60.4	60.2	59.9	59.4	59.1	59.9	60.7	61.2	61.3	61.2	61.2
High Octane	59.0	59.3	59.0	58.7	58.5	58.0	58.5	59.3	60.0	60.3	59.7	59.1
Summer Grade												
Low Octane	58.2	58.0	57.4	56.1	55.7	56.1	56.9	57.1	57.6	57.7	56.8	57.2
Mid Octane	57.4	57.1	56.4	55.5	54.8	55.6	56.2	56.6	56.7	57.4	58.0	58.0
High Octane	55.5	55.7	55.6	54.4	53.8	55.1	55.3	56.4	55.7	57.4	55.8	55.5

Source: National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* and *Motor Gasoline Winter* (1990-2001).

The density of motor gasoline increased across all grades through 1994, partly as a result of the leaded gasoline phase-out. In order to maintain the “anti-knock” quality and octane ratings of gasoline in the absence of lead, the portion of aromatic hydrocarbons used in gasoline increased. As discussed above, aromatic hydrocarbons have a lower ratio of hydrogen to carbon than other hydrocarbons typically found in gasoline, and therefore increase fuel density.

The trend in gasoline density was reversed beginning in 1996 with the development of fuel additives that raised oxygen content. In 1995, a requirement for reformulated gasoline in non-attainment areas implemented under the Clean Air Act Amendments further changed the composition of gasoline consumed in the United States. In reformulated gasoline, methyl tertiary butyl ether (MTBE) and tertiary amyl methyl ether (TAME) are often added to standard gasoline to boost it oxygen content. The increased oxygen reduces the emissions of carbon monoxide and unburned hydrocarbons. These oxygen-rich blending components are also much lower in carbon than standard gasoline. The average gallon of reformulated gasoline consumed in 2001 contained 8 percent MTBE and 0.5 percent TAME. The characteristics of reformulated fuel additives appear in Table B8.

Table B8. Characteristics of Major Reformulated Fuel Additives

Additive	**Density** (Degrees API)	**Carbon Share** (Percent)	**Carbon Content** (MMTC/Qbtu)
MTBE	59.1	68.2	16.92
ETBE	59.1	70.5	17.07
TAME	52.8	70.5	17.00

Source: American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components, API 4261.

Estimation Methods

U.S. gasoline consumption was divided by product grade and season for both standard gasoline and reformulated gasoline. Carbon coefficients for each grade and type are derived from three parameters: gasoline density, share of the gasoline mixture that is carbon; and the energy content of a gallon of gasoline. Carbon coefficients for reformulated fuels were calculated by applying the carbon coefficient for the fuel additives listed in Table B8 to the increased share of reformulated gasoline represented by these additives (standard gasoline contains small amounts of MTBE and TAME) and weighting the gasoline carbon content accordingly. The carbon content for each grade and type of fuel is multiplied by the share of overall consumption that the grade and fuel type represent. Individual coefficients are then summed to yield an overall carbon content coefficient.

The carbon coefficient for motor gasoline varies annually based on the density of and proportion of additives in a representative sample of motor gasoline examined each year. However, in 1997 EIA began incorporating the effects of the introduction of reformulated gasoline into its estimate of carbon coefficients for motor gasoline. This change resulted in a downward step function in carbon coefficients for gasoline of approximately 0.3 percent beginning in 1995.

Data Sources

The density of motor gasoline is drawn from the National Institute for Petroleum and Energy Research, *Motor Gasolines, Summer* (various years) and the National Institute for Petroleum and Energy Research, *Motor Gasolines, Winter* (various years).

The characteristics of reformulated gasoline additives is taken from American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components, API 4261.

The carbon content of motor gasoline is found in Mark DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity,* Volume 2, ANL/ESD/TM-22, Vol. 2 (Chicago, IL: Argonne National Laboratory, November 1993), Appendix C, pp. C-1 to C-8 and ultimate analyses of one sample of shale-oil derived gasoline from Applied Systems Corp., *Compilation of Oil Shale Test Results* (Submitted to the Office of Naval Research, April 1976), p. 3-2, three varieties of gasoline from C.C. Ward, “Petroleum and Other liquid Fuels,” in *Marks' Standard Handbook for Mechanical Engineers* (New York, NY: McGraw-Hill, 1978), pp. 7-14, and one sample of gasoline from J.W. Rose and J.R. Cooper, *Technical Data on Fuel,* The British National Committee, World Energy Conference, London, England (1977).

Standard heat contents for motor gasoline of 5.253 million Btu per barrel conventional gasoline and 5.150 million Btu per barrel reformulated gasoline were adopted from the Energy Information Administration, *Annual Energy Review 2000* Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Jet Fuel

Jet fuel is a refined petroleum product used in jet aircraft engines. There are two classes of jet fuel used in the U.S.: “naphtha-based” jet fuels and “kerosene-based” jet fuels. In 1989, 13 percent of U.S. consumption was naphtha-based fuel, with the remainder kerosene-based jet fuel. In 1993, the U.S. Department of Defense began a conversion from naphtha-based JP-4 jet fuel to kerosene-based jet fuel, because of the possibility of increased demand for reformulated motor gasoline limiting refinery production of naphtha-based jet fuel. By 1996, naphtha-based jet fuel represented less than one-half of one percent of all jet fuel consumption. The carbon coefficient for jet fuel used in this report represents a consumption-weighted combination of the naphtha-based and kerosene-based coefficients.

Estimation Methods

Because naphtha-based jet fuel is used on a limited basis in the United States, sample data on its characteristics are limited. The density of naphtha-based jet fuel (49 degrees) was estimated as the central point of the acceptable API gravity range published by ASTM. The heat content of the fuel was assumed to be 5.355 million Btu per barrel based on EIA industry standards. The carbon fraction was derived from an estimated hydrogen content of 14.1 percent and an estimated content of sulfur and other non-hydrocarbons of 0.1 percent.[5]

The density and carbon share of kerosene-based jet fuels was based on the average composition of 39 fuel samples taken by Boeing Corporation (the leading U.S. commercial airline manufacturer) in 1989. The EIA’s standard heat content of 5.67 million Btu per barrel was adopted for kerosene-based jet fuel.

The carbon content for each jet fuel type is multiplied by the share of overall consumption of that fuel type. Individual coefficients are then summed to yield an overall carbon coefficient.

Between 1994 and 1995, the carbon coefficient for kerosene-based jet fuel was revised downward from 19.71 million metric tons per quadrillion Btu to 19.33 million metric tons per quadrillion Btu. This downward revision was the result of a shift in the sample set used from one collected between 1959 and 1972 and reported on by Martel and Angello in 1977 to one collected by Boeing in 1989 and published by Hadaller and Momenthy in 1990. The latter set of fuel samples have a decreased density and slightly lower carbon share than the earlier samples. However, the assumed heat content is unchanged because it is based on an EIA standard and thus, probably yields a downward bias in the revised carbon coefficient.

Data Sources

The carbon content of naphtha-based jet fuel is from C.R. Martel and L.C. Angello, “Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels,” in *Current Research in Petroleum Fuels,* Volume I (New York, NY: MSS Information Company, 1977), p. 116.

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[5] Martel, C.R., and Angelo, L.C. Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels. Current Research in Petroleum Fuels. Vol. I. New York, NY: MSS Information Corporation, 1977.

The density of naphtha-based jet fuel is from the American Society for Testing and Materials**,** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985), p. 60.

A standard heat content for naphtha-based jet fuel was adopted from the U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Available online at: www.eia.doe.gov/emeu/aer/contents.html.

Carbon content and density for kerosene-based jet fuels is drawn from O.J. Hadaller and A.M. Momenthy, *The Characteristics of Future Fuels,* Part 1, "Conventional Heat Fuels" (Seattle, WA: Boeing Corp., September 1990), pp. 46-50.

A standard heat content for kerosene-based jet fuel was adopted from the Energy Information Administration, *Annual Energy Review 2000* Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Distillate Fuel

Distillate fuel is a general classification for 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. No. 1, No. 2, and No. 4 fuel oils are also used for space heating and electric power generation.

Estimation Methods

For the purposes of this report, the carbon content of No. 2 fuel oil is assumed to typify the carbon content of distillate fuel generally. The carbon share in No. 2 fuel oil was estimated based on the average of 11 ultimate analyses. This carbon share was combined with EIA's standard heat content of 5.825 million Btu per barrel and the density of distillate assumed to be 35.5 degrees API, in accord with its heat content.

Data Sources

Carbon content and density were derived from the following:

- Four samples of distillate from C. T. Hare and R.L. Bradow, "Characterization of Heavy-Duty Diesel Gaseous and Particulate Emissions, and the Effects of Fuel Composition," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 128;

- Three samples from E.F. Funkenbush, D.G. Leddy, and J.H. Johnson, "The Organization of the Soluble Organic Fraction of Diesel Particulate Matter," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979) p. 128;

- One sample from R.L. Mason, "Developing Prediction Equations for Fuels and Lubricants," SAE Paper 811218, p.34;

- One sample from C.T. Hare, K.J. Springer, and R.L. Bradow, "Fuel and Additive Effects on Diesel Particulate- Development and Demonstration of Methodology," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 179; and

- One Sample from F. Black and L. High, "Methodology for Determining Particulate and Gaseous Diesel Emissions," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 128.

A standard heat content was adopted from the Energy Information Administration *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Residual Fuel

Residual fuel is 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. Residual fuel 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 power plants. 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.

In the United States, electric utilities purchase about a third of the residual oil consumed. A somewhat larger share is used for vessel bunkering, and the balance is used in the commercial and industrial sectors. The residual oil (defined as No.6 fuel oil) consumed by electric utilities has an energy content of 6.287 million Btu per barrel and an average sulfur content of 1 percent.[6] This implies a density of about 17 degrees API.

Estimation Methods

For this report, residual fuel was defined as No.6 fuel oil. The National Institute of Petroleum and Energy Research, Fuel Oil Survey shows an average density for fuel oil of 11.3 API gravity and anecdotal evidence suggests that marine residual fuel is also very dense, with typical gravity of 10.5 to 11.5 degrees API.[7] Because the largest share of fuel oil consumption is for marine vessels, a density of 11 degrees API was adopted when developing the carbon coefficient for this report. An average share of carbon in residual fuel of 85.67 percent by mass was used based on ultimate analyses of a dozen samples.

Data Sources

The carbon content of residual fuel oil is based on the following:

- Three samples of residual fuel from the Middle East and one sample from Texas in F. Mosby, G.B. Hoekstra, T.A. Kleinhenz, and J.M. Sokra, “Pilot Plant Proves Resid Process,” in *Chemistry of Petroleum Processing and Extraction* (MSS Information Corporation, 1976), p.227;

- Three samples of heavy fuel oils from J.P. Longwell, “Interface Between Fuels and Combustion,” in *Fossil Fuel Combustion: A Sourcebook* (New York, NY: John Wiley & Sons, 1991);

- Three samples of heavy fuel oils from C.C. Ward, “Petroleum and Other Liquid Fuels,” in *Marks' Standard Handbook for Mechanical Engineers* (New York, NY: McGraw-Hill, 1978), pp. 7-14;

- Two samples of heavy fuel oils from, D.A. Vorum, “Fuel and Synthesis Gases from Gaseous and Liquid Hydrocarbons,” in American Gas Association, *Gas Engineer's Handbook* (New York, NY: Industrial Press, 1974), p. 3/71; and

- One sample of heavy fuel oil from W. Rose and J.R. Cooper, *Technical Data on Fuel,* The British National Committee, World Energy Conference, London, England (1977).

The density of residual fuel consumed for electric power generation is fromEnergy Information Administration, *Cost and Quality of Fuels*, (Washington, DC). Web site www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html.

Density of residual fuel consumed in marine vessels from Energy Information Administration, Petroleum Supply Division, *Btu Tax on Finished Petroleum Products,* (unpublished manuscript, April 1993) and the National Institute for Petroleum and Energy Research, *Fuel Oil Surveys* (Bartlesville, OK, 1992).

A standard heat content was adopted from Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001).Web site www.eia.doe.gov/emeu/aer/contents.html.

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[6] Energy Information Administration, Cost and Quality of Fuels, DOE/EIA-0191(Washington, DC). Available online at: www.eia.doe.gov/cneaf/ electricity/cq/cq_sum.html.

[7] Energy Information Administration, Petroleum Supply Division, *Btu Tax on Finished Petroleum Products,* (unpublished manuscript, April 1993)

Liquefied Petroleum Gases (LPG)

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and n-butane. Because each of these compounds is a pure paraffinic hydrocarbon, their carbon shares are easily derived by taking into account the atomic weight of carbon (12) and the atomic weight of hydrogen (1). Thus, for example, the carbon share of propane, C_3H_8, is 81.8 percent. The densities and heat content of the compounds are also well known allowing carbon coefficients to be calculated directly. Table B9 summarizes the physical characteristic of LPG.

Table B9. Physical Characteristics of Liquefied Petroleum Gases

Compound	**Chemical Formula**	**Density** (Barrels Per Metric Ton)	**Carbon Content** (Percent)	**Energy Content** (MMBtu/Barrel)	**Carbon Coefficient** (MMTC/Qbtu)
Ethane	C_2H_6	16.88	80.0	2.916	16.25
Propane	C_3H_8	12.44	81.8	3.824	17.20
Isobutane	C_4H_{10}	11.20	82.8	4.162	17.75
n-butane	C_4H_{10}	10.79	82.8	4.328	17.72

Source: V.B. Guthrie (ed.), *Characteristics of Compounds*, Petroleum Products Handbook, (New York, NY: Mcgraw-Hill, 1960), p.3-3.

Estimation Methods

Based on their known physical characteristics, a carbon coefficient is assigned to each compound contained in the U.S. energy statistics category, Liquefied Petroleum Gases. A weighted carbon coefficient for LPG used as fuel is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics. The mix of LPG consumed for non-fuel use differs significantly from the mix of LPG that is combusted. While the preponderance of LPG consumed for fuel use is propane, the largest single LPG used for non-fuel applications is ethane. A carbon coefficient for LPG used for non-fuel applications is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics. The changing shares of LPG fuel use and non-fuel use consumption appear below in Table B10.

Table B10. Consumption and Carbon Content Coefficients of Liquefied Petroleum Gases, 1990-2001
(Million Metric Tons per Quadrillion Btu)

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Consumption (Quads Fuel Use)												
Ethane	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.05	0.05	0.06	0.06	0.05
Propane	0.79	0.79	0.84	0.86	0.86	0.86	0.95	0.92	0.98	0.98	0.98	0.89
Butane	0.08	0.05	0.07	0.06	0.07	0.05	0.04	0.05	0.05	0.06	0.06	0.06
Total	0.90	0.85	0.94	0.94	0.96	0.93	1.02	1.03	0.99	1.10	1.10	1.01
Carbon Coefficient	17.21	7.21	17.21	17.22	17.22	17.20	17.20	17.18	17.18	17.18	17.18	17.18
Consumption (Quads non-Fuel Use)												
Ethane	0.55	0.62	0.62	0.65	0.65	0.68	0.74	0.71	0.68	0.77	0.81	0.73
Propane	0.53	0.59	0.61	0.55	0.65	0.67	0.65	0.71	0.68	0.76	0.76	0.69
Butane	0.13	0.17	0.16	0.15	0.25	0.24	0.26	0.25	0.24	0.28	0.29	0.27
Total	1.20	1.38	1.39	1.35	1.55	1.59	1.65	1.67	1.60	1.81	1.86	1.69
Carbon Coefficient	16.83	16.84	16.84	16.80	16.88	16.87	16.86	16.88	16.87	16.88	16.87	16.88
Weighted Carbon Coefficient	**16.99**	**16.98**	**16.99**	**16.97**	**17.01**	**17.00**	**16.99**	**16.99**	**16.99**	**16.99**	**16.99**	**16.99**

Sources: Consumption of LPG from Energy Information Administration, Petroleum Supply Annual, various years. Non-fuel use of LPG from American Petroleum Institute, Natural Gas Liquids and Liquefied Refinery Gas Survey, various years.

The carbon coefficient of LPG is updated annually to reflect changes in the consumption mix of the underlying compounds: ethane; propane; isobutane; and normal butane. In 1994, EIA included pentanes plus – assumed to have the characteristics of hexane – in the mix of compounds broadly described as LPG. In 1995, EIA removed pentanes plus from this fuel category. Because pentanes plus is relatively rich in carbon per unit of energy, its removal from the consumption mix lowered the carbon coefficient for LPG from 17.26 million metric tons per quadrillion Btu to 17.02 million metric tons per quadrillion Btu. In 1998, EIA began separating LPG consumption into two categories: energy use; and non-fuel use and providing individual coefficients for each. Because LPG for fuel use typically contains higher proportions of propane than LPG for non-fuel use, the carbon coefficient for fuel use is about 2 percent higher than the coefficient for non-fuel use.

Data Sources

Carbon share, density and heat content of liquefied petroleum gases from V.B. Guthrie (ed.), Characteristics of Compounds, *Petroleum Products Handbook*, (New York, NY: Mcgraw-Hill, 1960), p.3-3.

LPG consumtpiton from Energy Information Administration, *Petroleum Supply Annual*, (Washington, DC) various years. Web site www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html.

Non-fuel use of LPG from American Petroleum Institute, Natural Gas Liquids and Liquefied Refinery Gas Survey, various years.

Aviation Gasoline

Aviation gasoline is used in piston-powered airplane engines. It is 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. Aviation gas is a relatively minor contributor to greenhouse gas emissions compared to other petroleum products, representing approximately 0.1 percent of all consumption.

The ASTM standards for boiling and freezing points in aviation gasoline effectively limit the aromatics content to a maximum of 25 percent (ASTM D910). Because weight is critical in the operation of an airplane, aviation gas must have as many Btu per pound (implying a lower density) as possible, given other requirements of piston engines such as high anti-knock quality.

Estimation Methods

A carbon coefficient for aviation gasoline was calculated on the basis of the EIA standard heat content of 5.048 million Btu per barrel. This implies a density of approximately 69 degrees API gravity or 5.884 pounds per gallon. To estimate the share of carbon in the fuel, it was assumed that aviation gasoline is 87.5 percent iso-octane, 9.0 percent toluene, and 3.5 percent xylene. The maximum allowable sulfur content in aviation gasoline is 0.05 percent, and the maximum allowable lead content is 0.1 percent. These amounts were judged negligible and excluded for the purposes of this analysis. This yielded a carbon share of 85 percent and a carbon coefficient of 18.87 million metric tons per quadrillion Btu.

Data Sources

Fuel characteristics were taken from the American Society for Testing and Materials, ASTM and Other Specifications for Petroleum Products and Lubricants (Philadelphia, PA, 1985).

A standard heat content for aviation gas was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Still Gas

Still gas, or refinery gas is composed of light hydrocarbon gases that are released as petroleum is processed in a refinery. The composition of still gas is highly variable, depending primarily on the nature of the refining process and secondarily on the composition of the product being processed. Petroleum refineries produce still gas from many different processes. Still gas can be used as a fuel or feedstock within the refinery, sold as a petrochemical feedstock, or purified and sold as pipeline-quality natural gas. In general, still gas tends to include large amounts of free hydrogen and methane, as well as smaller amounts of heavier hydrocarbons. Because different refinery operations result in different gaseous byproducts, it is difficult to determine what represents typical still gas.

Estimation Methods

The EIA obtained data on four samples of still gas. Table B11 below shows the composition of those samples.

Table B11. Composition, Energy Content, and Carbon Coefficient for Four Samples of Still Gas

Sample	Hydrogen (%)	Methane (%)	Ethane (%)	Propane (%)	Btu Per Cubic Foot	Carbon Coefficient (MMTC/Qbtu)
One	12.7	28.1	17.1	11.9	1,388	17.51
Two	34.7	20.5	20.5	6.7	1,143	14.33
Three	72.0	12.8	10.3	3.8	672	10.23
Four	17.0	31.0	16.2	2.4	1,100	15.99

Because gas streams with a large free hydrogen content are likely to be used as refinery or chemical feedstocks, EIA selected the carbon coefficient from the sample with the lowest hydrogen content as the representative value for still gas.

Data Sources

One still gas sample was drawn from American Gas Association, *Gas Engineer's Handbook,* (New York, NY: Industrial Press, 1974), pp. 3.71, and three still gas samples came from C.R. Guerra, K. Kelton, and D.C. Nielsen, Natural Gas Supplementation with Refinery Gases and Hydrogen," in Institute of Gas Technology, *New Fuels and Advances in Combustion Technologies* (Chicago, IL, June 1979).

Asphalt

Asphalt is used to pave roads. Because most of its carbon is retained in those roads, it is a small source of emissions. It is derived from a class of hydrocarbons called "asphaltenes," abundant in some crude oils but not in others. Asphaltenes have oxygen and nitrogen atoms bound into their molecular structure, so that they tend to have lower carbon contents than other hydrocarbons.

Estimation Methods

Ultimate analyses of twelve samples of asphalts showed an average carbon content of 83.5 percent. The EIA standard heat content for asphalt of 6.636 million Btu per barrel was assumed. The ASTM petroleum measurement tables show a density of 5.6 degrees API or 8.605 pounds per gallon for asphalt. Together, these variables generate a carbon coefficient of 20.62 million metric tons per quadrillion Btu.

Data Sources

A standard heat content for asphalt was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

The density of asphalt is from American Society for Testing and Materials*, ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

Lubricants

Lubricants are substances used to reduce friction between bearing surfaces, or incorporated into processing materials used 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. Lubricant consumption is dominated by motor oil for automobiles, but there is a large range of product compositions and end uses within this category.

Estimation Methods

The ASTM Petroleum Measurement Tables give the density of lubricants at 25.6 degrees API. Ultimate analysis of a single sample of motor oil yielded a carbon content of 85.8 percent. A standard heat content of 6.065 million Btu per barrel was adopted. These factors produce a carbon coefficient of 20.24 million metric tons per quadrillion Btu.

Data Sources

A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000* (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

The density of asphalt was adopted from American Society for Testing and Materials***,*** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

Petrochemical Feedstocks

U.S. energy statistics distinguish between two different kinds of petrochemical feedstocks: those with a boiling temperature below 400 degrees Fahrenheit, generally called "naphtha," and those with a boiling temperature 400 degrees Fahrenheit and above.

Estimation Methods

Because reformed naphtha is used to make motor gasoline (hydrogen is released to raise aromatics content and octane rating), “straight-run” naphtha is assumed to be used as a petrochemical feedstock. Ultimate analyses of five samples of naphtha were examined and showed an average carbon share of 84.11 percent and an average density of 67.1 degrees API gravity. The standard EIA heat content of 5.248 million Btu per barrel is used to estimate a carbon coefficient of 18.14 million metric tons per quadrillion Btu.

Petrochemical feedstocks with a boiling temperature greater than 401 degrees Fahrenheit are part of the “middle distillate” fraction in the refining process, and EIA estimates that these petrochemical feedstocks have the same heat content as distillate fuel. Thus, the carbon coefficient of 19.95 million metric tons per quadrillion Btu used for distillate fuel is also adopted for this portion of petrochemical feedstocks. The weighted average of the two carbon coefficients for petroleum feedstocks equals 19.37 million metric tons per quadrillion Btu.

Data Sources

The carbon content and density of naphthas is estimated based on G.H. Unzelman, “A Sticky Point for Refiners: FCC Gasoline and the Complex Model,” *Fuel Reformulation* (July/August 1992), p. 29.

A standard heat content for petrochemical feedstock was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001).). Web site www.eia.doe.gov/emeu/aer/contents.html.

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 is drawn from the same petroleum fraction as jet fuel. Kerosene is generally comparable to No.1 fuel oil.

Estimation Methods

The average density of 41.4 degrees API and average carbon share of 86.01 percent found in five ultimate analyses of No. 1 fuel oil samples were applied to a standard heat content of 5.67 million Btu per barrel to yield a carbon coefficient of 19.72 million metric tons per quadrillion Btu.

Data Sources

A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000,* Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Petroleum Coke

Petroleum coke is the solid residue of the extensive processing of crude oil. It is a coal-like solid, usually with a carbon content greater than 90 percent, that is used as a boiler fuel and industrial raw material.

Estimation Methods

Ultimate analyses of two samples of petroleum coke showed an average carbon share of 92.3 percent. The ASTM standard density of 9.543 pounds per gallon was adopted and the EIA standard energy content of 6.024 million Btu per barrel assumed. Together, these factors produced an estimated carbon coefficient of 27.85 million metric tons per quadrillion Btu.

Data Sources

Carbon content for petroleum coke was estimated from two samples from S. W. Martin, “Petroleum Coke,” in Virgil Guthrie (ed.), *Petroleum Processing Handbook* (New York, NY: McGraw-Hill, 1960), pp. 14-15. Density of petroleum coke adopted from American Society for Testing and Materials**,** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985). A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site www.eia.doe.gov/emeu/aer/contents.html.

Special Naphtha

Special naphtha is defined as a light petroleum product to be used for solvent applications, including commercial hexane and four classes of solvent: stoddard solvent, used in dry cleaning; high flash point solvent, used as an industrial paint because of its slow evaporative characteristics; odorless solvent, most often used for residential paints; and high solvency mineral spirits, used for architectural finishes. These products differ in both density and carbon percentage, requiring the development of multiple coefficients.

Estimation Methods

Hexane is a pure paraffin containing 6 carbon atoms and 14 hydrogen atoms. Thus, it is 83.7 percent carbon. Its density is 76.6 degrees API or 5.649 pounds per gallon and its derived carbon coefficient is 17.17 million metric tons per quadrillion Btu. The other hydrocarbon compounds in special naphthas are assumed to be either paraffinic or aromatic (see discussion above). The portion of aromatics in odorless solvents is estimated at less than 1 percent, Stoddard and high flash point solvents contain 15 percent aromatics and high solvency mineral spirits contain 30 percent aromatics (Boldt and Hall, 1985). These assumptions, when combined with the relevant densities, yield the carbon coefficients contained in Table B12 below.

Table B12. Characteristics of Non-hexane Special Naphthas

Special Naphtha	**Aromatic Content** (Percent)	**Density** (Degrees API)	**Carbon Content** (Percent)	**Carbon Coeficient** (MMTC/QBtu)
Odorless Solvent	1	55.0	84.51	19.41
Stoddard Solvent	15	47.9	84.44	20.11
High Flash Point	15	47.6	84.70	20.17
Mineral Spirits	30	43.6	85.83	20.99

EIA reports only a single consumption figure for special naphtha. The carbon coefficients of the five special naphthas are weighted according to the following formula: approximately 10 percent of all special naphtha consumed is hexane and the remaining 90 percent is assumed to be distributed evenly among the four other solvents. The resulting emissions coefficient for special naphthas is 19.86 million metric tons carbon per quadrillion Btu.

Data Sources

A standard heat content for special naphtha was adopted from the Energy Information Administration, *Annual Energy Review 2000,* Appendix A (Washington, D.C., July 2001).). Web site www.eia.doe.gov/emeu/aer/contents.html.

Density and aromatic contents for special naphthas are from K. Boldt and B.R. Hall, *Significance of Tests for Petroleum Products* (Philadelphia, PA: American Society for Testing and Materials), p. 30.

Petroleum Waxes

The ASTM standards define petroleum wax as a product separated from petroleum that is solid or semi-solid at 77 degrees Fahrenheit (25 degrees Celsius). The two classes of petroleum wax are paraffin waxes and microcrystalline waxes. They differ in the number of carbon atoms and the type of hydrocarbon compounds. Microcrystalline waxes have longer carbon chains and more variation in their chemical bonds than paraffin waxes.

Estimation Methods

For the purposes of this analysis, paraffin waxes are assumed to be composed of 100 percent paraffinic compounds with a chain of 25 carbon atoms. The resulting carbon share for paraffinic wax is 85.23 percent and the density is estimated at 45 degrees API or 6.684 pounds per gallon.

Microcrystalline waxes are assumed to consist of 50 percent paraffinic and 50 percent cycloparaffinic compounds with a chain of 40 carbon atoms, yielding a carbon share of 85.56 percent. The density of microcrystalline waxes is estimated at 36.7 degrees API, based on a sample of 10 microcrystalline waxes found in the *Petroleum Products Handbook*.

A weighted average density and carbon coefficient was calculated for petroleum waxes, assuming that wax consumption is 80 percent paraffin wax and 20 percent microcrystalline wax. The weighted average carbon content is 85.29 percent, and the weighted average density is 6.75 pounds per gallon. EIA's standard heat content for waxes is 5.537 million Btu per barrel. These inputs yield a carbon coefficient for petroleum waxes of 19.81 million metric tons per quadrillion Btu.

Data Sources

The density of paraffin wax is from American Society for Testing and Materials**,** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985). The density of microcrystalline waxes is based on 10 samples found in V. Guthrie (ed.), *Petroleum Products Handbook* (New York, NY: McGraw-Hill, 1960).

A standard heat content for petroleum waxes was adopted from the Energy Information Administration, *Annual Energy Review 2000,* Appendix A (Washington, D.C., July 2001).). Web site www.eia.doe.gov/emeu/aer/contents.html.

Crude Oil, Unfinished Oils, and Miscellaneous

U.S. energy statistics include several categories of petroleum products designed to ensure that reported refinery accounts "balance" and cover any "loopholes" in the taxonomy of petroleum products. These categories include crude oil, unfinished oils, and miscellaneous products. Crude oil is rarely consumed directly, miscellaneous products account for less than one percent of oil consumption and unfinished oils are a balancing item that may show negative consumption. For carbon accounting purposes, it was assumed that all these products have the same carbon content as crude oil.

Estimation Methods

EIA reports on the average density and sulfur content of U.S. crude oil purchased by refineries. To develop a method of estimating carbon content based on this information, ultimate analyses of 182 crude oil samples were collected. Within the sample set, carbon content ranged from 82 to 88 percent carbon, but almost all samples fell between 84 percent and 86 percent carbon. The density and sulfur content of the crude oil data were regressed on the carbon content, producing the following equation:

$$\textit{Percent Carbon} = 76.99 + (10.19 * \textit{Specific Gravity}) + (-0.76 * \textit{Sulfur Content})$$

Absent the term representing sulfur content, the equation had an R-squared of only 0.35.[8] When carbon content was adjusted to exclude sulfur, the R-squared rose to 0.65. While sulfur is the most important nonhydrocarbon impurity, nitrogen and oxygen can also be significant, but they do not seem to be correlated with either density or sulfur

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[8] R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

content. Restating these results, density accounts for about 35 percent of the variation in carbon content, impurities account for about 30 percent of the variation, and the remaining 35 percent is accounted for by other factors, including (presumably) the degree to which aromatics and polynuclear aromatics are present in the crude oil. Applying this equation to the 2001 crude oil quality data (30.49 degrees API and 1.42 percent sulfur) produces an estimated carbon content of 85.81 percent. Applying the density and carbon content to the EIA standard energy content for crude oil of 5.8 million Btu per barrel produces an emissions coefficient of 20.29 million metric tons per quadrillion Btu.

Data Sources

The carbon content for crude oil was developed from an equation based on 182 crude oil samples, including 150 samples from U.S. National Research Council, *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology* (New York, NY: McGraw-Hill, 1927).

A standard heat content for crude oil was adopted from Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001).). Web site.eia.doe.gov/emeu/aer/contents.html.

Appendix C

Uncertainty Analysis of Emissions Estimates

Overview

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*,[1] as established at the UNFCCC 4th Conference of the Parties in Kyoto, Japan in December 1997, recommend that nations carry out analyses to estimate the uncertainty in their national greenhouse gas emissions inventories. According to the guidelines, nations should construct 95 percent confidence intervals for their greenhouse gas emission estimates using classical sampling techniques, Monte Carlo techniques, or assessments by national experts. The UNFCCC subsequently requested that the IPCC complete its work on uncertainty and prepare a report on good practice in inventory management. In 2000, the IPCC issued its report *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*.[2] The report established Tier 1 and Tier 2 methods of estimating uncertainty in greenhouse gas inventories as follows:[3]

Tier 1: Estimation of uncertainties by source category using error propagation equations ... and simple combination of uncertainties by source category to estimate overall uncertainty for one year and the uncertainty in the trend.

Tier 2: Estimation of uncertainties by source category using Monte Carlo analysis, followed by the use of Monte Carlo techniques to estimate overall uncertainty for one year and the uncertainty in the trend.

In response to the IPCC's good practices guidelines, EIA in 1998 carried out a Tier 1 uncertainty analysis of U.S. greenhouse gas emissions. This was done for carbon dioxide, methane, nitrous oxide, and other gases. The results of this analysis can be found in Table C1 below. The Tier 1 analysis provides a "weighted uncertainty" for each source calculated as the squared root of the sum of the squared activity factor and emission factor errors multiplied by the point estimate of the share of total emissions for the source. The Tier 1 approach, however, as pointed out by the IPCC may be inappropriate when combining non-normal distributions, as may be the case with some of the distributions for emissions factors and activity data.

In the 2000 to 2001 timeframe, EIA undertook a "Tier 2" uncertainty analysis of U.S. carbon dioxide, methane and nitrous oxide emission estimates to augment its previous "Tier 1" uncertainty analysis. The Tier 2 uncertainty analysis involves Monte Carlo simulations that facilitate the combination of various types of probability density functions. This analysis involved 1999 data, but the uncertainty would be consistent with the uncertainty associated with emissions estimates for the near to medium term.

Both Tier 1 and Tier 2 methods are discussed in detail below. However, they share some attributes in common. For either "Tier I" or "Tier II" analysis the sources of uncertainty fall into the following categories:

- Uncertainty associated with underlying activity data and uncertainty associated with emissions factors
- Random errors and bias errors
- Potential for upward and downward bias errors
- Reliability of emissions estimates by source.

The Tier 1 uncertainty analysis found in Table C1 excludes estimates for emissions and sequestration from land use changes and forestry. The Tier 1 analysis concluded that U.S. national greenhouse gas emissions, taken as a group, may differ by as much as 13 percent from the estimates published in the earlier edition of this report. Much of the uncertainty in national emissions was attributable to estimates of nitrous oxide emissions. If nitrous oxide emissions were excluded, the uncertainty of the total estimate was calculated to be on the order of 10 percent. As a point of comparison, the Tier 2 analysis, estimated total uncertainty about a simulated mean of total carbon dioxide,

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[1] Intergovernmental Panel on Climate Change, Revised 1996 !PCC Guidelines for National Greenhouse Gas Inventories, 1997.

[2] Intergovernmental Panel on Climate Change, Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, May 2000.

[3] Intergovernmental Panel on Climate Change, Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, May 2000, p. 6.12.

methane and nitrous oxide emissions to be -4.4% to 4.6%. When expressed as a percentage of total estimated 1999 emissions[4], the uncertainty becomes -0.4 to 9.0%.

The bulk of the potential uncertainty in the overall national estimate takes the form of bias errors, which are likely to persist from one year to the next and, thus, have relatively little influence on trends, rather than random errors, which would increase the difficulty of determining whether or not a trend exists. This is because estimates of energy-related carbon dioxide are probably accurate to well within 10 percent of estimated emissions, and energy-related carbon dioxide accounts for 81 percent of national emissions of greenhouse gases. There are much larger uncertainties for methane and, particularly, for nitrous oxide emissions, but the present evidence suggests that emissions from these sources account for only a small portion of total emissions.

The uncertainties in the estimates presented in this report come from the following sources:

- **Evolving Definitions.** In general, this report attempts to measure "anthropogenic" (human-caused) emissions of greenhouse gases in the United States, excluding carbon emissions of biological origin. Although in most cases it is obvious whether emissions from a particular source fall within this definition, there are a number of ambiguous cases, and the range of accepted definitions has shifted over time. Since the first edition of this report, sulfur hexafluoride has been added to the generally accepted definition of "greenhouse gases." Emissions from bunker fuels are now excluded from the definition of "U.S. emissions." Definitional changes tend to raise or lower emission estimates systematically.

- **Emissions Sources Excluded From the Report.** An estimate that excludes some sources will be biased downward by the amount of the excluded source. Of course, if the existence or magnitude of the excluded emissions were known, they would be included. But it is probable that there are still sources that have not yet been identified and escape inclusion in both the estimates and the list of sources excluded.

- **Incorrect Models of Emissions Processes.** An estimate based on a belief that emissions are caused by (or can be estimated from) a particular activity or process can produce large, systematically biased errors if the emissions are actually caused by some other process. The incorrect method can produce estimates that are considerably higher or lower than actual emissions and have different time-series properties.

- **Errors in Emissions Factors.** Errors in emissions factors can have diverse causes, the most common of which are definitional errors, sampling errors, and measurement errors. These errors can be either random or systematic. (See discussion of carbon coefficients below).

- **Errors in Activity Data.** Activity data are also subject to definitional errors, frame errors, sampling errors, and measurement errors, which can be either random or systematic.

- **Computational Errors.** Computational errors can exist in the estimation of emissions factors by EIA, in the calculation of emissions by EIA, or in the computation of the underlying activity data by the source organization.

Although any single computational error will usually produce a systematic error, computational errors as a group tend to produce very small (about 0.1 percent) random errors in the estimate.

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[4] Total 1999 emissions of carbon dioxide, methane and nitrous oxide as estimated in *EIA, Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99), October 2000.

Table C1. Estimate of the Reliability of 1999 U.S. Emissions Estimates (Tier 1 Method)

Greenhouse Gas Source	Share of Total Emissions	Activity Data			Emissions Factor			Weighted by Total Emissions	
		Bias		Random	Bias		Random		
		Min	Max		Min	Max		Min	Max
	Percent of Source							Percent of Total	
Carbon Dioxide									
Petroleum	35.2%	2.1%	2.4%	0.5%	1.7%	1.7%	0.5%	1.0%	1.1%
Coal	29.9%	0.6%	4.3%	0.6%	1.0%	1.0%	0.5%	0.4%	1.4%
Natural Gas	17.2%	0.5%	2.8%	0.5%	0.0%	0.0%	0.4%	0.1%	0.5%
Other	0.6%	-9.3%	7.8%	11.1%	23.3%	23.3%	4.4%	0.2%	0.2%
Missing Sources	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%
Total	82.9%	1.1%	3.7%	0.6%	1.2%	1.2%	0.5%	1.7%	3.5%
Methane									
Energy-Related	3.2%	13.2%	14.0%	4.9%	20.8%	25.0%	4.5%	0.8%	0.9%
Agricultural	2.8%	3.1%	5.0%	3.0%	36.4%	36.4%	10.6%	1.1%	1.1%
Industrial & Waste	3.2%	9.7%	29.4%	5.0%	50.5%	13.8%	10.1%	1.6%	1.1%
Missing Sources	0.0%	0.0%	4.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	9.2%	8.9%	20.6%	4.3%	35.9%	24.6%	8.3%	3.5%	3.1%
Nitrous Oxide									
Energy-Related	1.3%	0.5%	2.8%	0.5%	55.0%	200.0%	10.0%	0.7%	2.5%
Agricultural	4.1%	4.0%	5.0%	4.5%	90.0%	100.0%	10.0%	3.7%	4.1%
Industrial & Waste	0.4%	2.8%	5.0%	3.5%	55.0%	200.0%	10.0%	0.1%	0.5%
Missing Sources	0.0%	0.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.5%
Total	5.7%	3.1%	19.5%	3.5%	80.0%	128.5%	10.0%	6.5%	7.5%
HFCs, PFCs, SF6									
HFCs, PFCs, SF6	2.2%	4.5%	2.4%	0.9%	13.8%	15.5%	2.5%	0.5%	0.6%
Missing Sources	0%	0.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Total	2.2%	4.5%	12.4%	0.9%	13.8%	15.5%	2.5%	0.5%	0.6%
Total-All Sources	**100.0%**	**2.0%**	**6.4%**	**1.1%**	**9.2%**	**11.0%**	**1.8%**	**13.2%**	**12.9%**

Notes: The “low” and “high” bias errors provide a subjective estimate of the largest bias error lower or higher than the current point estimate that would be consistent with current understanding of the nature of the activity or emissions mechanism. Each value is calculated as the weighted average of the uncertainties associated with a group of sources in each category. It is calculated as a percentage of the point estimate of emissions from that source. "Random error" is a subjective estimate of the largest random error that is consistent with current understanding of the nature of the activity or emissions estimate. "Weighted uncertainty" is calculated as the square root of the sum of the squared activity factor and emissions factor errors and then multiplied by the point estimate of the share of total emissions for the source. It is calculated as a percentage of the point estimate of total 1997 U.S. emissions.
Source: Estimates prepared for *Emissions of Greenhouse Gases In the United States 1997.*

The different sources of error, as noted above, can produce random or systematic (“bias”) errors. Random errors have the appearance of “noise” in the estimate, causing random year-to-year changes in the estimate as compared with (unobservable) actual emissions. Random errors might be caused by data collection and computation errors, the inherent imprecision of metering and measurement, and timing problems. Thus, it should be difficult to distinguish the “signal” of growing or declining emissions until the magnitude of the trend exceeds the “noise” from the random fluctuations. Since, in the case of U.S. energy data, rather small trends in the underlying data can be detected, it is likely that the aggregate magnitude of random errors in U.S. energy data is small, and, in particular, smaller than bias errors.

Bias errors will produce an error of approximately the same magnitude every year. If bias errors are small, they are not likely to affect the estimates of trends. Excluded sources and changes in definition produce bias errors. “Double counting” in activity data surveys will produce upwardly biased estimates of the activity; frame errors or other forms of undercounting will produce estimates that are biased downward. Because EIA, like other statistical agencies, produces data by approximately the same methods every year, double counting and undercounting errors are likely to persist over time.

There is no reason to believe that the distribution of bias errors is symmetrical around the point estimate of the value. In fact, *a priori* or independently gathered information may indicate that the potential size and probability of the existence of bias errors may be skewed: for example, in EIA data it is likely that essentially all the transactions reported to EIA actually occurred; however, it is possible that some transactions were never reported. Thus, EIA energy data are more likely to underestimate than to overestimate actual energy consumption. Further, because there are multiple surveys of energy production and consumption, undertaken for multiple purposes, the results of the surveys can help put bounds on the extent of possible bias errors.

Bias errors can be hard to detect, and it is hard to prove either the presence or absence of bias errors. The best ways of detecting them are to use multiple methods of estimating the source series and compare the results, or to determine the range of possible values from *a priori* information. Comparison methods usually can establish “ceilings” and “floors” for bias errors: that is, it is possible to demonstrate that if the bias error exceeded a certain percent, then a separate, independently collected series must also have a bias error of the same sign. An investigation of how the data are collected may also uncover information about the magnitude or scale of potential bias errors.

The reliability of emissions data varies by category and by source. In general, estimates of carbon dioxide emissions are more reliable than estimates for other gases. It is likely that the estimate of carbon dioxide emissions is accurate to within 5 percent. Estimates of methane emissions are much more uncertain. The level of uncertainty may exceed 30 percent. Estimates of methane emissions are also likely to understate actual emissions, as a result of the exclusion of sources that are unknown or difficult to quantify such as abandoned coal mines or industrial wastewater. Nitrous oxide emissions estimates are much more unreliable than carbon dioxide or methane emissions estimates, in part because nitrous oxide emissions have been studied far less than emissions from other sources and in part because the largest apparent sources of nitrous oxide emissions are area sources that result from biological activity, which makes for emissions that are highly variable and hard to measure or characterize. The uncertainty for nitrous oxide emissions may exceed 100 percent.

Tier 2 Analysis of Uncertainty in Greenhouse Gas Emissions

In order to carry out a Monte Carlo analysis, estimates of minimum, maximum and random bias in emission factors and activity data must be established. Table C2 shows the estimated bias and random uncertainties in activity data and emissions factors for carbon dioxide, methane and nitrous oxide delineated by fuel type and activity that was used in the Monte Carlo analysis. For petroleum, the activity data are divided into the following sectors: residential, commercial, and transportation (R,C,T); industrial; electric utility; and non-fuel use. For coal emissions, the division is between electric utility and other sectors (industrial combined with residential, commercial, and transportation). For natural gas emissions the division is the same as those for coal with the addition of flared gas. Methane and nitrous oxide emissions are divided by source categories. For each source category, bias and random errors are combined by assuming an aggregate emission factor and a single scaling factor for activity data.

Because the underlying data are obtained from various EIA surveys, they have different levels of associated uncertainty. For example, the maximum bias error for coal activity associated with electric utilities is estimated to be 4 percent, whereas the maximum bias error for coal activity associated with the other sectors is estimated to be 7 percent. This is because fuel use among the reporting electric power generators is relatively well known, but for the other sectors (especially residential and commercial) the data are less reliable.

Monte Carlo simulations were carried out for each greenhouse gas separately, as well as all greenhouse gases as a group. As such, each column of the Table C3 denotes a separate simulation. Uncertainty about the simulated mean varies by type of gas. There is less uncertainty around the carbon dioxide simulated mean (-1.4% to 1.3%) than methane (-15.6% to 16%) or nitrous oxide (-53.5% to 54.2%). If uncertainty is expressed as a percentage of estimated 1999 emissions, the uncertainty becomes more skewed in the positive direction. This follows from the bias error assumptions above that generally assume that emissions are underestimated. Denominating uncertainty as a percentage of estimated 1999 emissions yields the following uncertainty bands: carbon dioxide (-0.7% to 2.0%), methane (-2.8% to 33.7%) and nitrous oxide (-35.1% to 115.3%). If these uncertainty bands are expressed as a percentage of total estimated 1999 emissions[5], the following uncertainty bands are derived: carbon dioxide (-0.6% to 1.7%), methane (-0.3% to 3.4%) and nitrous oxide (-1.9% to 6.3%). The final column in the table shows the Monte

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[5] Total 1999 emissions of carbon dioxide, methane and nitrous oxide as estimated in *EIA, Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99), October 2000.

Carlo results when all the gases are simulated together. This simulations shows that total uncertainty about the simulated mean is -4.4% to 4.6 percent. Expressed as a percentage of total emissions, the uncertainty is –0.4 to 9.0 percent.

Table C2. Random and Bias Uncertainties Associated with 1999 Inventory Data

Source Category	Activity Data Uncertainty			Emission Factor Uncertainty		
	BIAS (Uniform)		Random	BIAS (Uniform)		Random
	Min[a]	Max[b]	Mean	Min[a]	Max[b]	Mean
Carbon Dioxide						
NATURAL GAS						
Other Sectors (R,C,I,T)	0.5%	3.0%	0.5%	0.0%	0.0%	0.4%
Electric Utility	0.5%	2.0%	0.5%	0.0%	0.0%	0.4%
Flared	10.0%	25.0%	2.0%	10.0%	10.0%	5.0%
COAL						
Other Sectors (R,C,I,T)	1.00%	7%	0.70%	1%	1%	0.5%
Electric Utility	0.50%	4%	0.60%	1%	1%	0.5%
PETROLEUM						
R,C,T Sectors	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
Industrial	2.0%	3.0%	0.6%	4.0%	4.0%	0.6%
Electric Utility [Heavy Oil,Light Oil,Petroleum Coke]	0.5%	2.0%	0.5%	3.0%	3.0%	0.6%
Non-Fuel Use	1.0%	4.0%	0.6%	3.0%	3.0%	0.6%
U.S. TERRITORIES	5.0%	10.0%	5.0%	1.0%	1.0%	0.5%
CO2 IN NATURAL GAS	5.0%	5.0%	5.0%	30.0%	30.0%	5.0%
BUNKERS	10.0%	10.0%	0.2%	1.0%	1.0%	2.0%
CEMENT	2.0%	4.0%	1.0%	3.0%	3.0%	1.0%
OTHERS INDUSTRIAL SOURCES	5.0%	10.0%	3.0%	5.0%	5.0%	5.0%
Methane						
COAL						
Underground Coal Mines-Very “Gassy”	5.0%	10.0%	20.0%	0.0%	0.0%	0.0%
Degasification & Underground Mines	5.0%	10.0%	20.0%	35.0%	25.0%	5.0%
Surface Mines & Post-mining Emissions	10.0%	10.0%	10.0%	40.0%	100.0%	10.0%
OIL AND GAS SYSTEMS						
Natural Gas Systems	3%	5%	3%	40%	40%	5%
Petroleum Systems	3%	5%	3%	50.0%	60.0%	5.0%
COMBUSTION						
R&C Wood	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary & Mobile Combustion	0.5%	2.8%	0.5%	30.0%	30.0%	15.0%
WASTE HANDLING						
Landfills - Recovery Systems. (Modeled)	5.0%	20.0%	10.0%	25.0%	25.0%	10.0%
Landfills - Recovery Systems in Place (1992)	10.0%	10.0%	7.0%	0.0%	0.0%	0.0%
Landfills no Recovery Systems	10.0%	30.0%	5.0%	50.0%	10.0%	10.0%
Wastewater Systems	0.0%	3.0%	5.0%	55.0%	200.0%	10.0%
AGRICULTURAL SOURCES						
Livestock - Enteric Fermentation	3.0%	5.0%	3.0%	10.0%	10.0%	10.0%
Livestock Waste	3.0%	5.0%	3.0%	30.0%	40.0%	10.0%
Rice	5.0%	5.0%	3.0%	60.0%	60.0%	20.0%
Crop Residues	5.0%	5.0%	3.0%	60.0%	60.0%	20.0%
INDUSTRIAL PROCESSES						
Chemicals and Steel & Iron	3.00%	5%	3.00%	60%	60%	10.0%
Nitrous Oxide						
AGRICULTURAL SOURCES						
Nitrogen Fertilization	5.0%	10.0%	5.0%	90.0%	200.0%	10.0%
Animal Waste	3.0%	5.0%	3.0%	90.0%	100.0%	10.0%
Crop Residues	5.0%	10.0%	3.0%	60.0%	60.0%	20.0%
ENERGY COMBUSTION						
R&C Wood	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary Combustion	0.5%	2.8%	0.5%	55.0%	200.0%	10.0%
Waste Combustion	30.0%	30.0%	10.0%	90.0%	200.0%	15.0%
Mobile Sources	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
WASTE MANAGEMENT	2.0%	5.0%	5.0%	55.0%	200.0%	10.0%
INDUSTRIAL PROCESSES	10.0%	10.0%	3.0%	55.0%	200.0%	10.0%

a: The minimum bias is the relative change below the mean value.
b: The maximum bias is the relative change above the mean value.
Key: R,C,T, I: Residential, Commercial, Transportation, and Industrial; GHG: Greenhouse Gases.
Source: EIA-DOE annual data for 1999. Inventory Database.

Table C3. Preliminary Results of the Tier 2 Monte Carlo Uncertainty Analysis of EIA's Reported Greenhouse Gas Inventory Data, 1999

Based on 1999 Data (Million Metric Tons of Carbon Equivalent, MMTCe)

	Carbon Dioxide	Methane	Nitrous Oxide	Total
Estimated 1999 Value	1526.8	180.7	98.8	1806.3
Monte Carlo Simulated 1999 Mean	1536.4	208.2	138.0	1882.2
5th Percentile	1515.5	175.6	64.2	1799.5
95th Percentile	1556.8	241.5	212.8	1969.6
Total Uncertainty Around Simulated Mean	41.3	65.9	148.6	170.1
Uncertainty as Percent of Simulated Mean	-1.4% to 1.3%	-15.6% to 16.0%	-53.5% to 54.2%	-4.4% to 4.6%
Uncertainty as Percent of Estimated Value	-0.7% to 2.0%	-2.6% to 33.7%	-35.1% to 115.3%	-0.4% to 9.0%
Uncertainty as Percent of Total Estimated Emissions	-0.6% to 1.7%	-0.3% to 3.4%	-1.9% to 6.3%	-0.4% to 9.0%

[a] Estimated 1999 emissions from EIA, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99), October 2000.

[b] Monte Carlo simulations using 1999 EIA data from Science Applications International Corporation, prepared for the Energy Information Administration, Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emissions and Related Support Work, May 2001.

[c] Expressed as a percentage of total carbon dioxide, methane and nitrous oxide emissions in 1999. Note, that this excludes HFC, PFC and SF6 emissions as these were not included in the uncertainty analysis.

[d] Note that, with the exception of estimated 1999 values, rows will not sum to total because each individual row denotes a separate simulation. Monte Carlo simulations were carried out for each pollutant separately, as well as a group.

Uncertainty of Carbon Coefficients Used in This Report

Because carbon dioxide emissions are such a large component of total greenhouse gas emissions, EIA has undertaken a review and update of the carbon coefficients for fossil fuels that when combined with combustion factors produce the emission factor for that fuel. A discussion of the uncertainty inherent in those factors is presented below.

Coal

Carbon coefficients for coal vary considerably by rank and state. Bituminous coal production and sub-bituminous coal production represented 53.4 percent and 38.1 percent of total U.S. supply in 2000, respectively. Carbon coefficients for bituminous coal vary from a low of 200.5 pounds carbon dioxide per million Btu in Kansas to a high of 232.0 pounds carbon dioxide per million Btu in Montana. In 2000, however, just 200 tons of bituminous coal were produced in Kansas and none were produced in Montana. In 2000, more than 60 percent of bituminous coal was produced in three states: West Virginia, Kentucky and Pennsylvania, and this share has remained fairly constant since 1990. These three states show a variation in carbon content for bituminous coals of ±0.7% that is based on more than 2,000 samples (See Table C4).

Similarly, the carbon coefficients for sub-bituminous coals range from 201.3 pounds carbon dioxide per million Btu in Utah to 217.5 pounds carbon dioxide per million Btu in Washington. Utah showed no sub-bituminous production in 2000 and Washington just 4,000 tons. Wyoming, however, has represented between 75 percent and 82 percent of total sub-bituminous coal production in the United States since 1990. Thus, the carbon content coefficient for Wyoming, based on 435 samples, dominates. The interquartile range of carbon content coefficients among samples of sub-bituminous coal in Wyoming was ±1.5% from the mean. Similarly this range among samples of bituminous coal from West Virginia, Kentucky, and Pennsylvania was ±1.0% or less for each State. The large number of samples and the low variability within the sample set of the states that represent the predominant source of supply for U.S. coals suggest that the uncertainty in this factor is very low, on the order of ±1.0%.

Table C4. Variability in Carbon Content Coefficients by Rank Across States
(Pounds Carbon Dioxide Per Million Btu)

State	Number of Samples	Bituminous	Sub-bituminous	Anthracite	Lignite
Alabama	946	204.7	-	-	218.5
Alaska	90	216.8	216.3	-	217.5
Arizona	11	-	215.0	-	-
Arkansas	70	212.8	-	-	209.4
Colorado	292	208.1	212.7	-	212.7
Georgia	35	209.5	-	-	-
Idaho	1	-	209.2	-	-
Illinois	16	205.8	-	-	-
Indiana	125	204.3	-	-	-
Iowa	89	202.7	-	-	-
Kansas	28	200.5	-	-	-
Kentucky	870	204.1	-	-	-
Louisiana	1	-	-	-	211.7
Maryland	46	208.0	-	-	-
Massachusetts	3	-	-	253.1	-
Michigan	3	204.7	-	-	-
Mississippi	8	-	-	-	216.5
Missouri	91	202.5	-	-	-
Montana	301	232.0	215.5	228.4	219.1
Nevada	2	208.1	-	-	220.1
New Mexico	167	210.0	209.2	229.1	-
North Dakota	186	-	-	-	219.5
Ohio	646	202.5	-	-	-
Oklahoma	46	204.3	-	-	-
Pennsylvania	739	205.9	-	228.5	-
Tennessee	58	204.6	-	-	-
Texas	48	-	-	-	208.9
Utah	152	211.8	201.3	-	-
Virginia	456	206.2	-	217.2	-
Washington	14	210.3	217.5	226.0	234.9
West Virginia	566	207.0	-	-	-
Wyoming	476	208.7	214.3	-	-

- (No Sample Data Available)
Source: U.S. Geological Survey, CoalQual Database Version 2.0 (1998) and analysis prepared by Science Applications International Corporation (SAIC) for the U.S. Environmental Protection Agency, Office of Air and Radiation, Market Policies Branch, October 2002.

Natural Gas

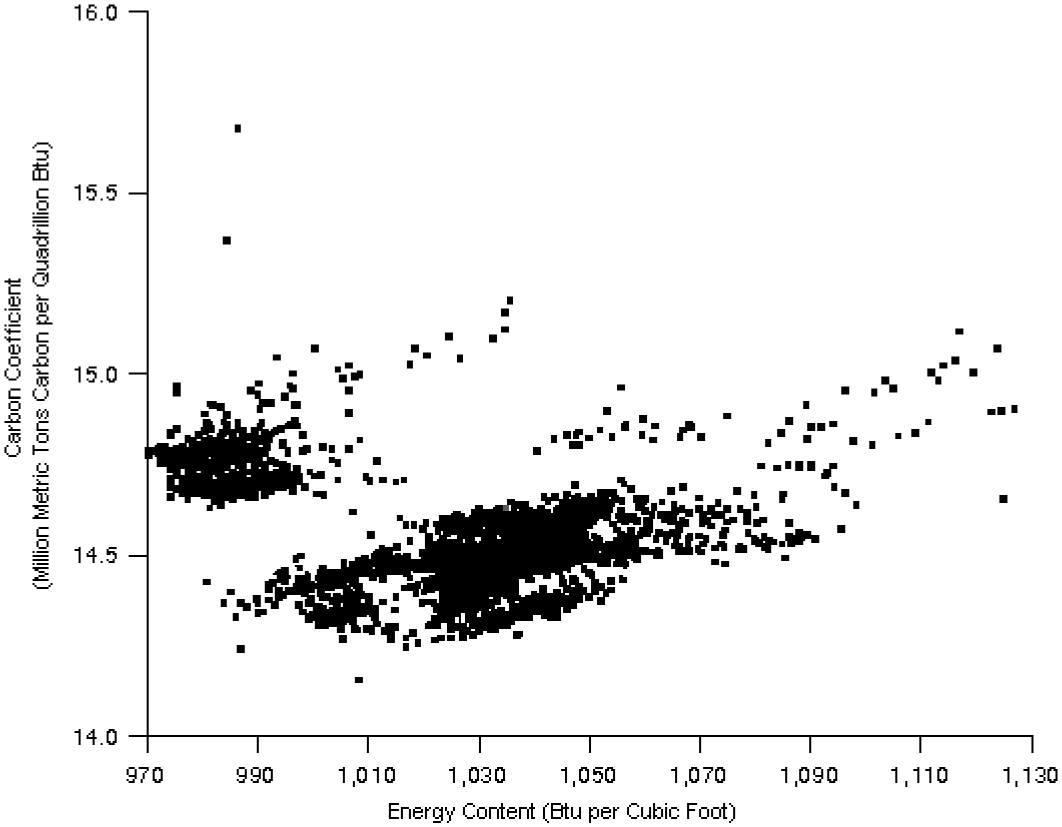
Pipeline-Quality

The EIA examined the composition of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 States. Figure C1 shows the relationship between the calculated carbon coefficient for each natural gas sample and its energy content. This figure illustrates the relatively restricted range of variation in both the energy content (which varies by about 6 percent from average) and the carbon coefficient of natural gas (which varies by about 5 percent). Thus, the knowledge that gas has been sold via pipeline to an end use consumer allows us to predict its carbon coefficient with an accuracy of ±5.0%.

Natural gas suppliers may achieve the same energy contents with a wide variety of methane, higher hydrocarbon, and non-hydrocarbon gas combinations. Thus, the plot reveals large variations in carbon content for a single Btu value. In fact, the variation in carbon content for a single Btu value may be nearly as great as the variation for the whole sample. As a result, while energy content has some predictive value, the specific energy content does not substantially improve the accuracy of an estimated carbon content coefficient beyond the ±5.0% offered with the knowledge that it is of pipeline-quality.

The plot of carbon content also reveals other interesting anomalies. The samples with the lowest emissions coefficients tend to have energy contents of about 1,000 Btu per cubic foot. They are composed of almost pure methane. Samples with a greater proportion of natural gas liquids (NGLs) (e.g., ethane, propane, and butane) tend to have energy contents greater than 1,000 Btu per cubic foot, along with higher emissions coefficients. Samples with a greater proportion of inert gases tend to have lower energy content, but they usually contain carbon dioxide as one of the inert gases and, consequently, also tend to have higher emissions coefficients (see left side of Figure C1).

Figure C1. Carbon Content for Samples of Pipeline-Quality Natural Gas Included in the Gas Technology Institute (Formerly Gas Research Institute) Database



Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992,*) DOE/EIA 0573, Appendix A (Washington, DC, November, 1994)

For the full sample (N=6,743), the average carbon content of a cubic foot of gas was 14.51 million metric tons per quadrillion Btu. However, this average was raised by both the samples with less than 1,000 Btu per cubic foot that contained large amounts of inert carbon dioxide and those samples with more than 1,050 Btu per cubic foot that contain an unusually large amount of NGLs. Because typical gas consumed in the U.S. does not contain such a large amount of carbon dioxide or natural gas liquids, a weighted national average of 14.47 million metric tons per quadrillion Btu that represents fuels more typically consumed is used.[6]

Flare Gas

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

- There may be no market for some natural gas associated with oil wells, as the amount may be too small or too variable, or the quality might be too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of carbon dioxide). All natural gas flared for these reasons is probably "rich" associated gas, with relatively high energy content, high NGL content, and a high carbon content.

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[6] The national average was weighted by applying the carbon content associated with the average heat content of natural gas consumed in each state by the portion of national natural gas consumption represented by that state.

- Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

Data on the energy content of flare gas, as reported by states to EIA, indicates an energy content of 1,130 Btu per standard cubic foot. Flare gas may have a higher energy content than reported by EIA because rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot. Rich associated gas will have a much higher proportion of natural gas liquids than pipeline natural gas. The most common NGLs are ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and, to a lesser extent, pentane (C_5H_{12}) and hexane (C_6H_{14}). Because the NGLs have more carbon atoms than methane (which has only one) their presence increases the overall carbon content of natural gas. Hexane is 83.7 percent carbon compared to the 75 percent carbon share found in methane.

Another important source of uncertainty associated with the carbon coefficient for flare gas is the definition of flare gas as reported to EIA by the States. EIA collects data on natural gas vented and flared without a clear distinction between gas flared and gas vented. For the purposes of this report all gas reported to EIA as vented or flared is assumed to be flared. Further, States may report a broad array of gases under the vented and flared category, some of which, such as hydrogen sulfide, are quite different in composition from the natural gas samples used for deriving the carbon coefficient adopted for this report. In some States, carbon dioxide that is vented is reported as vented and flared and its contribution to overall national emissions is not accurately reflected by treating it as combusted natural gas. Thus, there is a wide band of uncertainty associated with the carbon coefficient for flared natural gas.

Petroleum

Motor Gasoline and Motor gasoline Blending Components

There are two primary contributors to the uncertainty of carbon coefficients for motor gasoline. The first is the small number of motor gasoline samples and ultimate analyses from the work by Mark Deluchi.[7] However, the amount of variation in carbon content of gasoline is restricted by the compounds in the fuel to ± 4%. The second primary contributor to uncertainty is the assumed heat content. The heat contents are industry standards established many years ago. The heat contents are standard conversion factors used by EIA to convert volumetric energy data to energy units. Because the heat contents of fuels change over time, without necessarily and directly altering their volume, the conversion of known volumetric data to energy units may introduce bias. Thus, a more precise approach to estimating emissions factors would be to calculate carbon content per unit of volume, rather than per unit of energy. Adopting this approach, however, makes it difficult to compare U.S. carbon coefficients with those of other nations. The changes in density of motor gasoline over the last decade suggest that the heat content of the fuels is also changing. However, that change within any season grade has been less than 1% over the decade. Of greater concern is the use of a standardized heat content across grades which show a variation in density of ± 1.5%.

Jet Fuel

Variability in jet fuel is relatively small with the average carbon share of kerosene-based jet fuel varying by less than ± 1% and the density varying by ± 1%. This is because jet fuel is used to transport passengers long distances on commercial airliners. The ratio of fuel mass to useful energy must be tightly bounded to maximize safety and range. There is more uncertainty associated with the density and carbon share of naphtha-based jet fuel because sample data were unavailable and default values were used. This uncertainty has only a small impact on the overall uncertainty of the carbon coefficient for jet fuels, however, because naphtha-based jet fuel represents a small and declining share of total jet fuel consumption in the United States.

Distillate Fuel

The primary source of uncertainty for the estimated carbon coefficient of distillate fuel is the selection of No.2 fuel oil as the typical distillate fuel. No.2 fuel oil is generally consumed for home heating. No.1 fuel oil is generally less dense and if it is consumed in large portions for mobile sources, the carbon content estimated for this report is likely to be too high. The five No.1 fuel oil samples obtained by EIA contained an average of 86.01 percent carbon

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[7] DeLuchi, Mark, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity,* Volume 2, ANL/ESD/TM-22, Vol. 2 (Chicago, IL: Argonne National Laboratory, November 1993).

compared to the 86.34 percent contained in samples of No.2 fuel oil. A carbon coefficient based on No.1 fuel oil would equal 19.72 million metric tons per quadrillion Btu rather than the 19.95 million metric tons per quadrillion Btu for No.2 fuel oil. There is also small uncertainty in the share of carbon based on the limited sample size of ± 1 percent.

Residual Fuel

The largest source of uncertainty for estimating the carbon coefficient of residual fuel centers on the estimates of density, which differ from power generation to marine vessel fuels. The difference between the density implied by the energy content of electric power sector fuels and the density observed in the NIPER surveys is probably due to nonsulfur impurities, which reduce the energy content without greatly affecting the density of the product. Impurities of several percent are commonly observed in residual oil. The presence of these impurities also affects the share of the fuel that is carbon. Overall, the uncertainty associated with the carbon coefficient of residual fuel is probably ± 1%.

Liquefied Petroleum Gases

Because LPG consists of pure paraffinic compounds whose density, heat content and carbon share are physical constants, there is limited uncertainty associated with the carbon coefficient for this petroleum product. Overall uncertainty is derived mainly from the collection of consumption data and non-fuel data in U.S. energy statistics. This uncertainty is probably less than ± 3%.

Aviation Gasoline

The uncertainty associated with the carbon content coefficient for aviation gasoline is larger than that for other liquid petroleum products examined because no ultimate analyses of samples were conducted. However, given the requirements for safe operation of piston-powered aircraft the composition of aviation gas is well bounded and the uncertainty of the carbon coefficient is likely to be ± 5%.

Still Gas

Because the composition of still gas is highly heterogeneous, the carbon coefficient for this product is highly uncertain, with an accuracy of ± 33%. The carbon coefficient used for this report is probably at the high end of the plausible range.

Asphalt

The share of carbon in asphalts ranges somewhat broadly from 79 percent to 88 percent by weight with the remainder of the mixture also being variable; hydrogen shares vary by weight from seven to 13 percent and sulfur shares vary from trace levels to eight percent. Because carbon share and total heat content in asphalts do vary systematically, the overall carbon coefficient is likely to be accurate to ± 5%.

Lubricants

Uncertainty in the estimated carbon coefficient for lubricants is driven by the large range of product compositions and end uses in this category combined with an inability to establish the shares of the various products captured under this category in U.S. energy statistics. Because lubricants may be produced from either the distillate or residual fractions during refining, the possible carbon content coefficients range from just under 20.0 million metric tons per quadrillion Btu to about 21.5 million metric tons per quadrillion Btu, or an uncertainty band from – 1% to + 6% of the estimated value.

Petrochemical Feedstocks

Petrochemical feedstocks are not so much distinguished on the basis of chemical composition as on the identity of the purchaser, who may be presumed to be a chemical company or petrochemical unit co-located on the refinery grounds. This produces a considerable degree of uncertainty about the exact composition of petrochemical feedstocks. Since the carbon coefficient for petrochemical feedstocks is a weighted average of the coefficients for naphtha and some class of middle distillates, the accurate coefficient is likely bounded by the two individual coefficients suggesting an uncertainty of ±6%.

Kerosene

Uncertainty in the estimated carbon coefficient for kerosene is driven by the selection of No. 1 fuel oil as a proxy for kerosene. If kerosene is more like kerosene-based jet fuel, the true carbon coefficient is likely to be some 2 percent lower. If kerosene is more aptly compared to No. 2 fuel oil, then the true carbon content coefficient is likely to be about 1 percent higher.

Petroleum Coke

The uncertainty associated with the estimated carbon coefficient of petroleum coke can be traced to two factors: the use of only two samples to establish carbon contents and a standard heat content which may be too low. Together, these uncertainties are likely to bias the carbon coefficient upwards by as much as 6 percent.

Special Naphtha

The principal uncertainty associated with the estimated carbon coefficient for special naphtha is the allocation of overall consumption across individual solvents. The overall uncertainty is bounded on the low end by the carbon content of hexane and on the upper end by the carbon content of high solvency mineral spirits. This implies an uncertainty band of –15 percent to + 6 percent.

Petroleum Waxes

Although there is considerable qualitative uncertainty associated with the allocation of petroleum waxes and microcrystalline waxes, the quantitative variation in the carbon contents for all waxes is limited to ± 1% because of the nearly uniform relationship between carbon and other elements in petroleum waxes broadly defined.

Crude Oil, Unfinished Oils and Miscellaneous

The uncertainty of the estimated carbon content for crude oil centers on the 35 percent of variation that cannot be explained by density and sulfur content. However, as crude is not currently directly consumed in the United States this does not add to the overall uncertainty of the U.S. emissions estimate. Because unfinished oils and miscellaneous products are difficult to define, the uncertainty of applying a crude oil carbon content is likely to be bounded by the range of petroleum products described in this chapter at ± 10%. This has a larger implication for the overall uncertainty of the emissions estimate than does crude oil directly. Miscellaneous products have been relatively stable in recent years with consumption in the range of 100 to 120 trillion Btu. However, in 2001, the volume of unfinished oils was estimated to contain an energy value of 69 trillion Btu, a value that is subtracted from the total supply disposition in order to avoid double counting with finished products. In 2000 this value was about 401 trillion Btu. Because this is a negative number in the energy consumption total, this fluctuation effectively added about one-third a quad of energy to the balance – or 6 million metric tons of carbon equivalent from 2000 to 2001. Therefore, the uncertainty associated with emission coefficients for unfinished oils could contribute to the overall uncertainty of the emissions estimate to a measurable degree.

Appendix D
Emissions Sources Excluded

Overview

Certain sources of emissions of greenhouse and related gasses are not included in the estimates presented in this report. The omissions have been made on the basis of lack of essential data, highly speculative estimation methods, ambiguity of overall climate effect, or classification as "natural" sources.

Carbon Dioxide

Biofuel Combustion

The carbon found in biofuels is the result of atmospheric uptake. During the combustion of biofuels, and the biogenic component of municipal solid waste, there is an immediate release of the carbon in the form of carbon dioxide. Thus, as part of the natural carbon cycle, carbon is reabsorbed over time. Because they produce no net change in the overall carbon budget, such emissions are not included in this report. If the initial flux had been counted, carbon dioxide emissions in 2001 would have been approximately 65 million metric tons of carbon higher than reported in Chapter 2. Table D1, below, delineates biofuel sources excluded.

Table D1. Carbon Dioxide Emissions from Biofuels Combustion, 1990-2001
(Million Metric Tons Carbon)

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**P2001**
Municipal Solid Waste (biogenic only)	6.4	5.1	6.3	5.8	6.3	6.5	6.4	5.5	4.6	5.0	5.4	5.4
Alcohol Fuel	1.6	1.3	1.5	1.7	1.9	2.1	1.5	1.9	2.1	2.2	2.2	2.2
Wood and Wood Waste	58.0	58.1	60.7	58.9	61.1	63.9	65.1	61.7	57.1	58.1	59.3	57.1
Total Biofuels	66.1	64.5	68.6	66.5	69.3	72.4	73.0	69.2	63.9	65.3	67.0	64.7

P=Preliminary data.

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

Sources: Underlying energy data from Energy Information Administration, Annual Energy Review 2001, DOE/EIA-0384(2001) (Washington, DC, November 2002), pp. 299-300. Emissions coefficients for municipal solid waste combustion and wood and wood waste from Energy Information Administration, Electric Power Annual 1999, Vol. 2, DOE//EIA-0348(99/2) (Washington, DC, October, 2000), Table A-3, p. 123.

Emissions are estimated by multiplying Energy Information Administration (EIA) energy consumption data for biofuels by the applicable emissions factors. Carbon dioxide emissions factors for combustion of wood fuels are taken from the EIA report, *Electric Power Annual 1999*.[1] The emissions coefficient for alcohol fuels, 17.99 million metric tons of carbon per quadrillion Btu, was derived specifically for use in this report.

Enhanced Oil Recovery

Carbon dioxide is injected into petroleum reservoirs for the purpose of retrieving additional oil. Over time, the carbon dioxide seeps into the producing well, creating a mixture of oil, natural gas, and carbon dioxide. If the energy content is sufficiently high, the gaseous portion of this mix will probably be sent to a gas plant. If the energy content is low, the gas is likely to be vented or flared. At this time, there is no basis for EIA to estimate the quantity of added carbon dioxide that is vented or flared. EIA believes that most of the carbon dioxide recovered with the oil is re-injected, so that annual emissions are a fraction of the carbon dioxide recovered. The annual amount of carbon dioxide used for enhanced oil recovery is probably on the order of 8 million metric tons,[2] and emissions would be some fraction of that figure. Emissions from this source may be included in future reports if more data become available.

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[1] Energy Information Administration, *Electric Power Annual 1999*, Vol. 2, DOE/EIA-0348(99/2) (Washington, DC, October, 2000), Table A3, p. 123.

[2] The U.S. Department of Commerce reports total sales of industrial carbon dioxide in 2000 were approximately 13 million metric tons annually, while past Freedonia Group, Inc. reports have reported that approximately 5 million metric tons are used for purposes other than enhanced oil recovery.

“Off Spec” Gases

Combustion of “off spec” gases and fuels is not covered as a separate line item in this report, but much of the emissions from this source may be included in the “flaring” category, which is covered in this report, or as industrial consumption of “still gas” by refineries.

Forest Fires

Forest fires are known to create greenhouse gas fluxes within the atmosphere over extensive time periods. Specifically, forest fires produce carbon dioxide, methane, and nitrous oxide. Considering that carbon uptake occurs with subsequent regrowth (assumed to balance out the initial carbon flux), and because emissions from natural forest fires cannot be distinguished from those from human-induced fires, estimates from this source are not included in this report.

Unaccounted for Natural Gas

The editions of *Emissions of Greenhouse Gases in the United States* published by EIA before 1997 included an emissions category called “unmetered natural gas.” In those years, U.S. natural gas producers consistently reported selling about 3 percent more natural gas than U.S. consumers reported buying. In EIA natural gas statistics, this “missing” gas is described as “the balancing item” or “unaccounted for gas.” The balancing item can be viewed as the sum of leakage, measurement errors, data collection problems, and undetected over- and underreporting, as well as undetected nonreporting. Only a fraction of this amount can credibly be attributed to leakage from transmission systems.

Estimates of carbon dioxide emissions from this source were included in early reports, on the grounds that there was an element of systematic underreporting of consumption in the balancing item. In 1996 and 1997, however, the sign of the balancing item changed to positive, and in 1998, 1999 and 2000 it was an increasing, negative number. These changes in sign reduce the credibility of the undercounting theory, and consequently this report no longer carries “unmetered natural gas” consumption as a source of emissions. The balancing item does serve as a basis for understanding the uncertainty inherent in natural gas combustion emissions estimates (see Appendix C). It should be noted that if this amount were included, U.S. emissions for 2000 would be about 12 MMTCE higher.

Fermentation

During the fermentation process, complex organic compounds are decomposed through a variety of chemical reactions. The most common is the anaerobic conversion of sugar into carbon dioxide and alcohol. Fermentation does not create a net flux of emissions, however, because the carbon dioxide produced is of biological origin.

Lead Smelting

Smelting of lead includes a stage in which limestone undergoes calcination. As described in Chapter 2, carbon dioxide is released as a byproduct of the calcination reaction. Emissions estimates cannot be calculated for this report because there are no known statistics regarding the amount of limestone used in lead smelting. EIA is currently researching alternative data sources in an effort to include estimates of these emissions in future reports.

Methane

Industrial Wastewater Treatment

Methane emissions from industrial wastewater treatment are believed to be a function of the volume of wastewater generated, the organic content of the wastewater, and the method used to treat the wastewater. Methane emissions will be much more greater if the wastewater is treated anaerobically (in the absence of oxygen) than if it is treated aerobically. Because data on volumes of wastewater generated by industry and the methods for treating that wastewater are limited, EIA does not present estimates of methane emissions from industrial wastewater. There is anecdotal evidence that very little industrial wastewater is treated anaerobically. Further, when industrial wastewater is treated anaerobically, the methane generated may be flared or recovered for energy use. Thus, 500,000 metric tons is likely to be at the high end of the emissions estimate range.

Abandoned Coal Mines

The Mine Safety and Health Administration estimate that some 7,500 underground coal mines have been abandoned in the United States since 1970.[3] Measurements taken from 20 abandoned mines showed a total of 25,000 metric tons of emissions.[4] Data gathered from these mines suggest a range in emissions from abandoned mines of 25,000 to 700,000 metric tons.[5] U.S. EPA is currently developing a comprehensive database of abandoned mines in the U.S. This database will include date of abandonment, specific emissions, seam thickness, mine depth, mining method, and ventilation emissions. Upon completion, this data should provide the ability to develop improved estimation methods. Until then, existing estimates are too uncertain to appear in this report.

Emissions from Wetlands

Wetlands are a known source of methane. Environments low in oxygen, combined with abundant organic matter, are conducive to the creation of methane, and wetlands meet both criteria. Wetlands cover approximately 274 million acres of land in the United States and are a potentially important source of atmospheric methane.

The stock of natural wetlands in the United States has diminished considerably over the past two centuries, which should, in principle, have reduced methane emissions from wetlands (EIA is not aware of research proving or disproving this principle). A recent study of wetland losses concluded that the United States had lost approximately 30 percent of its wetlands between colonial times and the mid-1980s. Almost all of the loss has occurred in the lower 48 States, which have lost 53 percent of their original wetlands.[6] Ten States— Arkansas, California, Connecticut, Illinois, Indiana, Iowa, Kentucky, Maryland, Missouri, and Ohio—have lost 70 percent or more of their original wetland acreage. By the mid-1980s, a total of approximately 119 million acres had been lost from the original U.S. total.

An update of the wetlands study indicates that 654,000 acres were converted from wetlands to other uses between 1982 and 1987, and that an additional 431,000 acres were converted between 1987 and 1991.[7] Extrapolating from these data, it is estimated that wetlands in the United States are currently destroyed at a rate of approximately 86,000 acres per year. Wetlands, also known as swamps and marshes, have historically been drained or filled in for agriculture, land development, and mosquito control, although it is currently illegal to drain or fill a wetland without a permit from the U.S. Army Corps of Engineers. It is difficult to find information on the conversion of other land categories *to* wetlands. It is assumed that the number and extent of wetland creations is small enough to leave the above loss estimates essentially unchanged.

Estimates of global methane fluxes from wetlands suggest that methane emissions from temperate-zone wetlands are minimal—typically between 5 and 10 million metric tons of methane per year for worldwide temperate-zone wetlands (which include U.S. wetlands)[8]—when compared with estimated global wetlands emissions of 115 to 237 million metric tons.[9] The U.S. share of all temperate-zone wetlands is about 57 percent, and temperate-zone wetlands lost during the 1980s accounted for about 0.5 percent of U.S. wetlands at the beginning of the period. Consequently, the reduction in natural methane emissions from wetlands lost might be on the order of 0.57 × 0.005 × 5 to 10 million metric tons of methane, or from 10,000 to 20,000 metric tons of methane annually over the decade.

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[3] U.S. Environmental Protection Agency, Coalbed Methane Outreach Program, *Draft Analysis of Abandoned Coal Mine Methane Emissions Estimation Methodology* (December 18, 1998)

[4] S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

[5] U.S. Environmental Protection Agency, 1997, *Introductory Analysis of Opportunities to Reduce Methane Emissions from Abandoned Coal Mines*, unpublished internal report.

[6] T. Dahl, U.S. Department of the Interior, Fish and Wildlife Service, *Wetlands Losses in the United States: 1780's to 1980's* (Washington, DC, 1990).

[7] U.S. Department of Agriculture, Soil Conservation Service, *1991 Update of National Resources Inventory Wetlands Data for Non-Federal Rural Lands* (Washington, DC, not dated), p. 4.

[8] See E. Matthews and I. Fung, "Methane Emissions From Natural Wetlands: Global Distribution, Area, and Environmental Characteristics," *Global Biogeochemical Cycles*, Vol. 1, No. 1 (March 1987); and K. Bartlett and R.C. Harriss, "Review and Assessment of Methane Emissions from Wetlands," *Chemosphere*, Vol. 26, Nos. 1-4 (1993), p. 280.

[9] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.2, p. 250. See also web site www.ipcc.ch.

Nitrous Oxide

Emissions from Industrial Wastewater

Just as industrial wastewater may contain large volumes of organic matter, so, under certain circumstances, industrial wastewater may be a source of nitrogen, leading ultimately to nitrous oxide emissions. However, the problems associated with estimating methane emissions from industrial wastewater are even more difficult with respect to nitrous oxide emissions from industrial wastewater. The nitrogen content of industrial wastewater is more problematic, and the extent to which bacterial action converts the nitrogen into nitrous oxide (as opposed to molecular nitrogen or nitrogen oxides) is more uncertain.

Land Use Changes Affecting Methane and Nitrous Oxide

The scientific literature suggests that both grasslands and forest lands are weak natural sinks for methane and weak natural sources for nitrous oxide. Natural soils apparently serve as methane sinks: well-aerated soils contain a class of bacteria called “methanotrophs” that use methane as food and oxidize it into carbon dioxide. Experiments indicate that cultivation reduces methane uptake by soils and increases nitrous oxide emissions.

One report indicates that methane uptake in temperate evergreen and deciduous forests in the United States ranges from 0.19 to 3.17 milligrams (measured in carbon units) per square meter per day, equivalent to the uptake of 36.8 to 624.4 metric tons of methane per million acres per year. The range is larger for agricultural lands: 0.2 to 6.3 milligrams per square meter per day. Estimates for methane uptake resulting from the abandonment of farmland range from 0.6 to 6.1 milligrams per square meter per day. While all of these ranges are wide, the total amount of methane in question is less than 1 percent of methane emissions from anthropogenic sources.

Of all the greenhouse gases discussed in this report, the least amount of data is available for nitrous oxide. It is known that conversion of forests and grasslands to cropland accelerates nitrogen cycling and increases nitrous oxide emissions from the soil. It is not known with certainty by how much.[10] Some estimates have been made of the difference between fertilized and unfertilized soils. According to one study, unfertilized soils produce emissions of 0.25 to 0.35 milligrams (measured in nitrogen units) per square meter per day, while emissions from fertilized soils range from 0.6 to 1.65 milligrams per square meter per day.[11] Thus, abandoning fertilization should reduce nitrous oxide emissions by 0.35 to 1.3 milligrams per square meter per day—the equivalent of 86 to 321 metric tons of nitrous oxide per million acres per year.

Applying this figure to the 35 million acres of cropland idled between 1982 and 1992 implies a reduction in nitrous oxide emissions ranging from 3,010 to 11,235 metric tons annually. In principle, however, about three-quarters of the reduction in emissions from this source should be captured by reduced application of nitrogen fertilizers; thus, reporting emissions reductions using this method would result in significant double counting of units already included in the agriculture statistics in Chapter 4.

If such estimates are to be applied to emissions inventories, a problem of crediting the uptakes applies. Removing an acre of farmland from production in a particular year creates a *permanent* annual methane sink that will absorb small additional amounts of methane each year thereafter, or at least until the use of the land changes. The method that should be used to credit such permanent reductions to a particular year is not obvious.

Ozone-Depleting Substances and Criteria Pollutants

The impact of ozone-depleting substances on global climate is ambiguous, because they have indirect effects that tend to offset their direct warming effects. Furthermore these manufactured substances are being phased out pursuant to the Montreal Protocol. They are not included among the greenhouse gases to be controlled under the Kyoto Protocol. Emissions estimates for chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), bromofluorocarbons (halons), and other ozone-depleting gases are excluded from the main body of this report. However, emissions estimates for these substances are presented in this appendix, in Table D2.

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[10] See A. Mosier, “Nitrous Oxide Emissions From Agricultural Soils,” paper presented at RIVM International Workshop on Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control (Amersfoort, The Netherlands, February 3-5, 1993).

[11] A. Mosier and D. Schimel, “Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide,” *Chemistry & Industry*, Vol. 2 (December 1991), p. 875.

Table D2. Estimated U.S. Emissions of Ozone-Depleting Substances, 1990-2001

(Thousand Metric Tons)

Item	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
CFCs												
CFC-11	53.5	48.3	45.1	45.4	36.6	36.2	26.6	25.1	24.9	24.0	22.8	22.8
CFC-12	112.6	103.5	80.5	79.3	57.6	51.8	35.5	23.1	21.0	14.0	17.2	21.3
CFC-113	52.7	41.1	34.2	34.2	17.1	17.1	*	*	*	*	*	*
Other CFCs	2.3	1.5	*	*	*	*	*	*	*	*	*	
Halons	2.8	2.9	2.7	2.8	2.4	2.5	2.5	2.4	2.4	2.4	2.4	2.3
HCFCs												
HCFC-22	34.0	35.4	35.2	35.3	37.7	39.3	41.0	42.4	43.8	74.1	79.1	80.5
HCFC-141b	0.8	1.4	1.9	2.6	3.3	3.6	4.0	4.3	4.7	5.0	5.4	5.8
HCFC-142b	1.3	1.7	1.7	2.9	6.2	9.9	9.9	8.8	9.7	10.9	10.9	10.7
Other HCFCs	*	*	*	3.0	5.8	6.3	6.7	7.1	7.4	7.6	7.7	7.7
Other Chemicals												
Carbon Tetrachloride	32.3	27.0	21.7	18.6	15.5	4.7	*	*	*	*	*	*
Methyl Chloroform	316.6	309.4	216.6	185.7	154.7	92.8	*	*	*	*	*	*

*Less than 50 metric tons of gas.

P=Preliminary data.

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/.

Similarly, carbon monoxide, nitrogen oxides, and non-methane volatile organic compounds are excluded from the Kyoto Protocol and from the main body of this report. These gases, termed “criteria pollutants” because they are regulated based on health criteria, have an indirect effect on global climate due to their effect on atmospheric concentrations of greenhouse gases (including carbon dioxide, methane, and ozone). Emission estimates for criteria pollutants are provided in Table D3.

Table D3. U.S. Emissions of Criteria Pollutants, 1990-2001

(Million Metric Tons of Gas)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Carbon Monoxide	89.3	91.7	89.2	89.8	93.4	84.6	94.1	94.9	91.0	91.8	98.1	NA
Nitrogen Oxides	21.8	21.9	22.3	22.6	22.9	22.5	23.1	23.3	23.0	22.4	21.9	NA
Nonmethane VOCS	19.1	19.3	18.9	19.1	19.7	19.0	18.0	18.4	17.5	17.6	18.5	NA

Note: Revised.

Source: U.S. EPA, Office of Air Quality Planning and Standards, National Air Pollutant Emission Trends Summaries (May 2002), Tables A2, A4, and A5.

Appendix E

Emissions of Energy-Related Carbon Dioxide in the United States, 1949-2001

This appendix presents estimates of U.S. carbon dioxide emissions for the period 1949-2001. U.S. energy data have undergone a number of changes over the years. The estimates are divided into three periods as outlined below:

- **1989-2001.** The emissions estimates for this period were developed using the methods and sources described in this report. As this is the first year that the EIA has included Independent Power Producers whose primary business is the generation of electricity in the Electric Power Sector, the *Annual Energy Review* is used for the time period from 1989 to 2001 as this is the first integrated data series to incorporate these changes and the only available at the time of publication.[1] The State Energy Data Report will follow this new data structure in the 2003 report that will include data for 2001 and earlier. When this series is available, it will be used for this report.

- **1960-1988.** Before 1980, EIA did not maintain a detailed accounting of carbon sequestration due to nonfuel use of fossil fuels. Hence, the data for industrial sector petroleum use, particularly in the category "other petroleum," are more accurate in the period 1980 through 1988 than they are in prior years. EIA has also not attempted to develop annual emissions coefficients for fuels in use before 1980, therefore the estimates do not reflect any changes in fuel quality that may have occurred prior to 1980. The energy data for this period are drawn from the database of the *State Energy Data Report.*[2]

- **1949-1959.** EIA has made no attempt to distinguish between residential and commercial energy consumption for historical data earlier than 1960. To provide consistent estimates for this appendix, the combined data for residential and commercial energy consumption have been prorated by fuel according to the ratio of consumption in 1960. Composite sectoral petroleum emissions factors are used for this period, based on 1960-weighted petroleum products emissions. The energy data for this period are also drawn from the *Annual Energy Review.*

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[1] Energy Information Administration, *Annual Energy Review 2001*, DOE/EIA-0384(2001) (Washington, DC, November 2002), Web site www.eia.doe.gov/emeu/aer/contents.html.

[2] Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(97) (Washington, DC, September 1999), pp. 21-26, Web site www.eia.doe.gov/emeu/sep/states.html.

Table E1. Energy-Related Carbon Dioxide Emissions from the Residential and Commercial Sectors, by Fuel Type, 1949-2001

(Million Metric Tons of Carbon)

Year	Residential					Commmercial				
	Natural Gas	Petroleum	Coal	Electricity	Total	Natural Gas	Petroleum	Coal	Electricity	Total
1949	15.1	23.2	30.2	19.0	87.4	5.0	13.2	42.2	15.0	75.3
1950	17.8	27.6	29.9	20.2	95.4	5.9	15.7	41.7	15.9	79.2
1951	21.8	30.1	26.4	22.5	100.8	7.2	17.1	36.8	17.8	78.8
1952	23.9	30.8	24.0	24.0	102.8	7.9	17.5	33.5	19.0	77.9
1953	24.8	31.3	20.6	26.2	103.0	8.2	17.8	28.8	20.7	75.4
1954	27.8	33.5	17.9	27.5	106.7	9.2	19.0	25.0	21.7	74.9
1955	30.9	36.0	17.8	30.0	114.7	10.2	20.4	24.9	23.7	79.2
1956	34.1	37.6	16.6	32.4	120.7	11.2	21.3	23.1	25.6	81.3
1957	36.7	36.5	12.7	34.7	120.7	12.1	20.7	17.7	27.4	78.0
1958	40.2	39.1	12.4	35.3	127.0	13.2	22.2	17.3	27.9	80.6
1959	43.5	39.9	10.6	39.1	133.1	14.3	22.6	14.8	30.9	82.6
1960	46.2	43.8	10.6	42.3	142.9	15.2	24.9	14.5	33.4	88.0
1961	48.4	45.1	9.6	44.4	147.5	16.0	25.3	13.2	34.6	89.2
1962	51.8	47.1	9.2	47.4	155.5	18.0	25.9	13.0	37.0	93.9
1963	53.2	47.4	8.0	51.9	160.5	18.7	25.5	11.1	41.7	97.0
1964	56.1	45.7	7.1	55.9	164.9	20.3	25.2	9.5	44.5	99.6
1965	57.9	47.8	6.6	60.2	172.5	21.4	28.1	9.0	47.9	106.4
1966	61.3	47.5	6.3	66.6	181.7	24.0	29.1	9.1	52.9	115.1
1967	63.9	49.2	5.4	69.8	188.4	29.0	30.1	7.8	55.7	122.6
1968	65.9	51.6	4.9	79.0	201.5	30.7	30.6	7.0	61.7	130.0
1969	70.0	52.5	4.6	87.1	214.2	33.3	30.7	6.6	66.4	137.0
1970	71.3	52.8	4.0	95.9	224.0	35.3	31.4	5.5	72.5	144.7
1971	73.3	53.3	3.7	100.8	231.1	37.0	30.5	5.2	76.3	149.0
1972	75.7	55.5	2.9	109.0	243.1	38.5	30.9	4.0	83.6	156.9
1973	72.0	54.2	2.7	117.5	246.4	38.3	31.6	3.8	90.3	164.0
1974	70.5	49.4	2.7	114.6	237.1	37.6	28.7	3.8	87.2	157.4
1975	72.3	47.9	2.2	113.1	235.5	36.8	26.3	3.1	90.1	156.3
1976	74.1	52.3	2.1	119.4	247.9	39.1	29.4	3.0	96.8	168.4
1977	70.8	51.8	2.2	129.0	253.7	36.7	30.4	3.1	102.8	173.0
1978	71.8	50.4	2.2	130.8	255.2	38.0	29.1	3.3	103.2	173.6
1979	72.7	40.8	1.9	134.1	249.5	40.8	26.9	2.9	106.7	177.3
1980	69.9	33.6	1.6	142.9	247.9	38.4	26.1	2.3	111.3	178.0
1981	67.0	29.6	1.8	141.0	239.4	37.1	22.0	2.5	116.3	177.9
1982	68.4	27.6	1.9	139.9	237.9	38.5	20.3	2.9	116.7	178.4
1983	65.0	25.9	1.9	143.4	236.3	36.1	22.5	3.0	118.6	180.1
1984	67.5	25.6	2.1	146.5	241.6	37.3	23.8	3.2	124.7	189.2
1985	65.7	28.4	1.8	149.5	245.4	36.0	20.6	2.7	129.8	189.3
1986	63.8	27.9	1.8	150.7	244.2	34.3	21.9	2.7	131.6	190.6
1987	63.9	28.8	1.7	157.1	251.5	36.0	21.5	2.6	137.6	197.6
1988	68.5	29.9	1.7	164.4	264.5	39.5	20.7	2.6	144.5	207.3
1989	70.9	29.7	1.5	166.3	268.4	40.3	19.3	3.0	150.6	213.3
1990	65.1	24.0	0.7	167.7	257.5	38.9	18.2	3.3	152.2	212.6
1991	67.6	24.5	0.6	170.3	263.0	40.5	17.1	3.1	152.5	213.2
1992	69.6	24.9	0.6	167.9	263.0	41.6	16.1	3.1	152.6	213.4
1993	73.4	26.3	0.6	179.3	279.6	42.4	14.9	3.1	159.7	220.0
1994	71.8	25.3	0.5	179.6	277.2	42.9	14.8	3.1	162.6	223.4
1995	71.7	25.7	0.4	182.3	280.1	44.8	14.0	3.0	166.6	228.5
1996	77.5	28.1	0.4	191.0	297.0	46.7	14.6	3.1	172.9	237.4
1997	73.7	27.4	0.4	193.5	295.0	47.5	13.8	3.3	184.6	249.3
1998	67.2	24.9	0.3	205.1	297.6	44.6	12.9	2.4	194.1	253.9
1999	69.9	27.2	0.4	204.9	302.5	45.1	12.8	2.7	197.6	258.0
2000	73.7	27.5	0.3	216.5	318.1	47.5	14.0	2.3	210.5	274.4
P2001	71.1	27.2	0.3	216.3	314.9	48.0	14.0	2.3	215.4	279.7

Notes: P = Preliminary.

Sources: **1989-2001:** Estimates documented in this report, based on energy data in the *Annual Energy Review*. **1960-1988:** Calculated from energy data in the *State Energy Data Report*. **1949-1959:** Calculated from energy data in the *Annual Energy Review*.

Table E2. Energy-Related Carbon Dioxide Emissions from the Industrial and Transportation Sectors, by Fuel Type, 1949-2001

(Million Metric Tons of Carbon)

	Residential					Commmercial				
Year	Natural Gas	Petroleum	Coal	Electricity	Total	Natural Gas	Petroleum	Coal	Electricity	Total
1949	45.9	57.7	131.6	33.1	268.4	1.9	119.1	42.9	0.5	164.5
1950	51.1	66.0	140.2	38.4	295.7	2.8	129.7	38.9	0.6	172.0
1951	58.3	70.5	149.9	42.6	321.2	3.1	142.7	34.2	0.6	180.6
1952	60.2	71.6	133.5	43.7	309.0	3.4	149.1	24.5	0.6	177.6
1953	61.9	73.5	143.6	49.1	328.1	3.4	156.1	18.2	0.6	178.4
1954	62.2	75.1	114.5	48.5	300.3	3.7	157.8	11.5	0.6	173.6
1955	67.7	82.9	136.0	60.5	347.0	4.5	169.9	10.5	0.7	185.5
1956	70.1	85.1	137.1	65.3	357.7	4.5	176.4	8.5	0.7	190.0
1957	73.6	84.0	133.8	65.4	356.8	4.6	179.8	6.0	0.7	191.2
1958	75.0	85.8	109.7	61.3	331.8	5.2	183.3	2.9	0.7	192.1
1959	81.3	90.3	106.8	67.4	346.0	5.2	190.6	2.2	0.8	198.7
1960	86.0	89.5	110.2	68.1	353.8	5.2	195.5	1.9	0.7	203.2
1961	86.9	89.1	105.3	69.7	350.9	5.6	199.3	0.5	0.7	206.1
1962	90.8	92.0	106.4	73.2	362.4	5.7	207.9	0.4	0.7	214.7
1963	95.2	93.5	111.3	78.1	378.2	6.3	215.5	0.4	0.6	222.8
1964	100.3	98.6	119.1	83.4	401.4	6.5	221.9	0.4	0.6	229.4
1965	103.5	102.1	124.0	88.8	418.3	7.5	228.9	0.4	0.6	237.3
1966	110.0	105.6	125.9	97.4	438.8	8.0	241.1	0.4	0.6	250.0
1967	113.6	105.5	119.4	99.6	438.0	8.5	253.1	0.3	0.6	262.5
1968	121.4	107.2	117.5	107.9	454.0	8.8	274.2	0.3	0.5	283.7
1969	129.8	111.3	113.4	114.1	468.6	9.3	285.7	0.2	0.5	295.8
1970	133.7	111.1	111.5	117.4	473.6	10.7	295.2	0.2	0.5	306.6
1971	138.7	111.3	94.8	119.0	463.8	11.0	307.0	0.1	0.5	318.6
1972	139.1	121.4	96.0	129.8	486.3	11.3	325.5	0.1	0.5	337.4
1973	147.2	128.4	97.7	139.2	512.5	10.7	343.8	0.1	0.5	355.1
1974	141.1	121.2	94.7	135.7	492.7	9.8	335.5	0.0	0.5	345.9
1975	120.7	114.6	88.9	132.3	456.4	8.6	339.6	0.0	0.6	348.8
1976	124.0	127.0	88.2	148.5	487.6	8.0	356.9	0.0	0.6	365.6
1977	122.3	137.8	83.7	157.2	501.0	7.8	371.3	0.0	0.6	379.7
1978	121.2	135.9	83.1	157.0	497.1	7.8	386.8	0.0	0.5	395.1
1979	120.9	143.6	88.3	165.4	518.1	8.8	383.2	0.0	0.6	392.7
1980	118.4	128.2	76.3	162.3	484.2	9.4	368.1	0.0	0.6	378.1
1981	116.3	110.0	76.2	161.2	463.3	9.5	364.0	0.0	0.6	374.1
1982	100.1	104.0	61.8	142.9	408.2	8.8	356.1	0.0	0.6	365.6
1983	95.2	96.0	60.6	148.2	399.6	7.3	359.0	0.0	0.6	366.9
1984	104.1	105.8	69.6	157.3	436.5	7.8	370.5	0.0	0.7	379.0
1985	98.9	99.9	68.1	157.6	424.1	7.5	376.0	0.0	0.7	384.3
1986	93.1	101.8	65.1	152.8	412.5	7.2	391.0	0.0	0.7	399.0
1987	101.8	101.4	65.9	158.6	427.9	7.7	402.5	0.0	0.7	411.0
1988	106.9	104.8	70.1	165.1	447.9	9.1	417.5	0.0	0.7	427.3
1989	112.6	98.8	68.6	171.8	452.5	9.3	422.0	0.0	0.7	432.1
1990	118.1	100.5	67.8	171.6	458.0	9.8	420.9	0.0	0.7	431.4
1991	119.9	94.9	63.9	168.7	447.6	8.9	414.4	0.0	0.7	424.1
1992	125.4	103.5	61.2	174.5	465.6	8.8	421.3	0.0	0.7	430.8
1993	127.1	97.0	60.8	176.2	461.7	9.3	426.1	0.0	0.7	436.1
1994	126.7	100.4	61.2	179.5	469.2	10.2	437.8	0.0	0.9	448.9
1995	133.8	94.9	60.8	177.1	468.0	10.4	446.1	0.0	0.9	457.4
1996	138.3	102.0	59.3	181.8	482.2	10.6	457.1	0.0	0.9	468.5
1997	138.4	103.0	58.3	185.8	486.9	11.2	461.1	0.0	0.9	473.2
1998	135.0	98.9	54.5	189.1	479.5	9.6	470.8	0.0	0.9	481.3
1999	130.3	99.5	53.3	189.4	474.2	9.7	484.7	0.0	0.9	495.3
2000	133.2	96.0	54.0	193.2	478.4	9.7	496.7	0.0	1.0	507.3
P2001	123.4	97.9	51.0	179.0	452.4	9.2	501.4	0.0	1.0	511.6

Notes: P = Preliminary.

Sources: **1989-2001:** Estimates documented in this report, based on energy data in the *Annual Energy Review*. **1960-1988:** Calculated from energy data in the *State Energy Data Report*. **1949-1959:** Calculated from energy data in the *Annual Energy Review*.

Table E3. Total Energy-Related Carbon Dioxide Emissions by End-Use Sector, and the Electric Power Sector, by Fuel Type, 1949-2001

(Million Metric Tons of Carbon)

	End-Use Sector					Electric Power Sector			
Year	**Residential**	**Commercial**	**Industrial**	**Transportation**	**Total**	**Natural Gas**	**Petroleum**	**Coal**	**Total**
1949	87.4	75.3	268.4	164.5	595.6	8.2	8.7	50.7	67.6
1950	95.4	79.2	295.7	172.0	642.2	9.4	10.0	55.7	75.1
1951	100.8	78.8	321.2	180.6	681.5	11.4	8.5	63.6	83.5
1952	102.8	77.9	309.0	177.6	667.3	13.5	8.9	64.9	87.3
1953	103.0	75.4	328.1	178.4	684.9	15.4	10.8	70.4	96.7
1954	106.7	74.9	300.3	173.6	655.6	17.4	8.9	72.0	98.3
1955	114.7	79.2	347.0	185.5	726.3	17.1	10.0	87.7	114.8
1956	120.7	81.3	357.7	190.0	749.7	18.4	9.5	96.0	124.0
1957	120.7	78.0	356.8	191.2	746.6	19.9	10.6	97.8	128.3
1958	127.0	80.6	331.8	192.1	731.4	20.4	10.4	94.3	125.1
1959	133.1	82.6	346.0	198.7	760.3	24.3	11.7	102.1	138.1
1960	142.9	88.0	353.8	203.2	787.9	25.7	11.7	107.1	144.5
1961	147.5	89.2	350.9	206.1	793.7	27.2	11.8	110.3	149.4
1962	155.5	93.9	362.4	214.7	826.6	29.3	11.9	117.1	158.3
1963	160.5	97.0	378.2	222.8	858.6	32.0	12.4	127.9	172.3
1964	164.9	99.6	401.4	229.4	895.2	34.7	13.4	136.3	184.4
1965	172.5	106.4	418.3	237.3	934.5	34.7	15.3	147.5	197.4
1966	181.7	115.1	438.8	250.0	985.7	39.1	18.7	159.6	217.4
1967	188.4	122.6	438.0	262.5	1011.5	41.1	21.4	163.2	225.7
1968	201.5	130.0	454.0	283.7	1069.2	47.0	25.0	177.1	249.2
1969	214.2	137.0	468.6	295.8	1115.6	52.0	33.3	182.8	268.1
1970	224.0	144.7	473.6	306.6	1149.0	58.3	45.0	183.0	286.3
1971	231.1	149.0	463.8	318.6	1162.5	58.9	52.9	184.8	296.6
1972	243.1	156.9	486.3	337.4	1223.7	58.8	65.5	198.6	322.9
1973	246.4	164.0	512.5	355.1	1277.9	53.8	74.4	219.3	347.5
1974	237.1	157.4	492.7	345.9	1233.1	50.6	71.2	216.2	338.0
1975	235.5	156.3	456.4	348.8	1197.0	46.5	67.0	222.6	336.1
1976	247.9	168.4	487.6	365.6	1269.5	45.4	73.6	246.4	365.4
1977	253.7	173.0	501.0	379.7	1307.4	47.3	82.6	259.8	389.6
1978	255.2	173.6	497.1	395.1	1320.9	47.4	84.5	259.6	391.5
1979	249.5	177.3	518.1	392.7	1337.7	51.9	69.6	285.3	406.9
1980	247.9	178.0	484.2	378.1	1288.2	54.8	55.3	306.9	417.0
1981	239.4	177.9	463.3	374.1	1254.7	54.1	46.3	318.7	419.1
1982	237.9	178.4	408.2	365.6	1190.1	48.0	33.0	319.1	400.1
1983	236.3	180.1	399.6	366.9	1182.9	43.1	32.5	335.3	410.9
1984	241.6	189.2	436.5	379.0	1246.3	46.3	27.0	355.7	429.1
1985	245.4	189.3	424.1	384.3	1243.0	45.5	22.9	369.2	437.6
1986	244.2	190.6	412.5	399.0	1246.2	38.7	30.6	366.5	435.9
1987	251.5	197.6	427.9	411.0	1287.9	42.2	26.4	385.2	454.0
1988	264.5	207.3	447.9	427.3	1347.0	39.0	32.9	402.8	474.8
1989	268.4	210.8	451.1	432.1	1362.4	46.0	35.8	409.4	491.3
1990	257.5	212.6	458.0	431.4	1359.5	47.8	27.0	417.3	492.3
1991	263.0	213.2	447.6	424.1	1347.8	48.9	25.3	417.8	492.2
1992	263.0	213.4	465.6	430.8	1372.8	50.9	21.1	423.7	495.7
1993	279.6	220.0	461.7	436.1	1397.3	51.3	24.1	440.4	515.9
1994	277.2	223.4	469.2	448.9	1418.7	57.6	22.6	442.2	522.5
1995	280.1	228.5	468.0	457.4	1434.1	62.3	16.3	448.2	526.8
1996	297.0	237.4	482.2	468.5	1485.2	55.9	17.6	472.9	546.5
1997	295.0	249.3	486.9	473.2	1504.3	59.7	20.0	484.9	564.8
1998	297.6	253.9	479.5	481.3	1512.3	67.6	28.2	493.3	589.2
1999	302.5	258.0	474.2	495.3	1530.1	70.9	26.1	495.7	592.8
2000	318.1	274.4	478.4	507.3	1578.3	76.5	24.5	520.1	621.2
P2001	314.9	279.7	452.4	511.6	1558.7	77.7	27.5	506.4	611.7

Notes: P = Preliminary. Emissions from the electric power sector are apportioned to each end-use sector according to their share of electricty sales.

Sources: **1989-2001:** Estimates documented in this report, based on energy data in the *Annual Energy Review*. **1960-1988:** Calculated from energy data in the *State Energy Data Report*. **1949-1959:** Calculated from energy data in the *Annual Energy Review*.

Appendix F

Common Conversion Factors

Mass

1 kilogram = 10^3 grams = 2.20462 pounds
1 megagram (metric ton) = 10^6 grams = 2,204.62 pounds
1 gigagram = 10^9 = 1,000 metric tons
1 teragram = 10^{12} = 1 million metric tons
1 short ton = .9072 * 10^6 grams = 2,000 pounds

Energy

1 joule = .2388 calories = .0009478 Btu
1 terajoule = 10^{12} joules = 9.478 * 10^8 Btu
1 exajoule = 10^{18} joules = 0.9478 * 10^{15} Btu
1 Mbtu = 1000 Btu = 1 * 10^3 Btu
1 Mmbtu = 1 million Btu = 1 * 10^6 Btu
1 Bbtu = 1 billion Btu = 1 * 10^9 Btu
1 Tbtu = 1 trillion Btu = 1 * 10^{12} Btu
1 Qbtu = 1 quadrillion Btu = 1 * 10^{15} Btu

Area

1 acre = 0.4047 hectare (ha) = 4,407 m^2
1 hectare = 10,000m^2 = 2.47 acres

Volume

1 cubic centimeter = 3.5318 * 10^{-5} cubic feet
1 cubic foot = 0.02832 cubic meters
1 cubic meter = 35.3147 cubic feet
1 barrel = 42 gallons

Density

1 thousand cubic feet methane = 42.28 pounds methane
1 thousand cubic feet carbon dioxide = 115.97 pounds carbon dioxide

Appendix G
Global Warming Potentials

Overview

Global warming potentials (GWPs) are indices used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative forcing effects[1] (heat-absorbing ability) of each gas relative to that of carbon dioxide (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO_2. The GWP for a gas provides a construct for converting emissions of each GHG into a common measure, which allows analysts to aggregate and compare the radiative impacts of various greenhouse gases into a uniform measure denominated in carbon dioxide equivalents (CO_2e). Thus, applying the appropriate GWP to a greenhouse gas will yield the CO_2e of the greenhouse gas being measured. GWPs can also serve as an important quantitative tool for governments and policymakers seeking consensus in formulating an effective climate policy.

In preparing the estimations of emissions provided in *Emissions of Greenhouse Gases in the United States*, the Energy Information Administration (EIA) seeks to employ the most current data sources. In doing so, EIA has generally relied on the GWPs published in assessment reports by the Intergovernmental Panel on Climate Change (IPCC) prepared every five years. Over the past decade, the IPCC has conducted an extensive research program aimed at determining the sources and effects of various greenhouse gases and their effect on the climate system. The results of that work were originally released in 1995 in an the IPCC first assessment report, *Climate Change 1994*,[2] and subsequently updated in their second assessment report (SAR) *Climate Change 1995*[3] and third assessment report (TAR) *Climate Change 2001*.[4]

There has been some discussion about which GWPs to utilize in preparing estimates of greenhouse gas emissions, largely stemming from the different stages of publication and formal approval of the IPCC's SAR, published in 1996, and the TAR, published in 2001. The United Nations Framework Convention on Climate Change (UNFCCC) requirements for developing national inventories—provided under the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* and the UNFCCC's *Guidelines on Reporting and Review*[5] for national inventories—were developed prior to the publication of the TAR. Both documents continue to require national inventories to be based on the GWPs in the IPCC SAR,[6] and the UNFCCC negotiating body, called the Conference of Parties (COP), has yet to adopt decisions to approve the TAR.[7] As a result, the U.S. Environmental Protection Agency (EPA) and a number of national governmental bodies responsible for publishing and submitting national emissions inventories to the UNFCCC utilize the GWPs published in the SAR.

In contrast, EIA's *Emissions of Greenhouse Gases* has relied on the high likelihood that the TAR, as published, will be adopted and approved by the COP in the near future, and that there is little reason not to utilize the TAR GWP values but for the fact that the COP has yet to formally adopt the TAR. For this year's *Emissions* report, EIA has added this new appendix to address the differences between the GWPs presented in the SAR and TAR, and to explain the rationale for applying the GWPs from the TAR.

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[1] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in Watts per square meter (W/m^2).

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

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

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

[5] Conference of Parties, Fifth Session, United Nations Framework Convention on Climate Change (UNFCCC) Guidelines on Reporting and Review, FCCC/CP/1999/7 (16 February 2000).

[6] See *Revised Guidelines for the Preparation of National Communications by Parties included in Annex I to the Convention*, FCCC/CP/1996/15/Add.1 (1996).

[7] See decision 2/CP.3 of the UNFCCC.

Understanding Global Warming Potentials

A global warming potential (GWP) is defined as the cumulative radiative forcing—both in terms of direct effects and indirect effects (such as resulting from chemical transformations)—over a period of time, relative to a reference gas.[8] GWP values are derived from laboratory experiments on molecular attributes of greenhouse gases and data modeling of the gases' radiative transfer properties.[9] While any time period can be selected, the IPCC recommends using 100-year GWPs. According to the IPCC, the direct GWPs for gases with distinguished lifetimes have an estimated uncertainty within ±35%, but the indirect GWPs are less certain, particularly those for which lifetimes are not yet understood.[10] Table G1 illustrates the differences in estimated GWP values as a factor of time horizons.

Table G1. 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
Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride				
HFC-23	260	9,400	12,000	10,000
HFC-125	29	5,900	3,400	1,100
HFC-134a	13.8	3,300	1,300	400
HFC-152a	1.4	410	120	37
HFC-227ea	33	5,600	3,500	1,100
Perfluoromethane (CF_4)	50,000	3,900	5,700	8,900
Perfluoroethane (C_2F_6)	10,000	8,000	11,900	18,000
Sulfur Hexafluoride (SF_6)	3,200	15,100	22,200	32,400

[a] No single lifetime can be defined for carbon dioxide due to different rates of uptake by different removal processes.
Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), pp. 38 and 388-389.

Greenhouse gases with relatively long atmospheric lifetimes (e.g., carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. Short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, and other ambient air pollutants (e.g., nitrogen oxide, and non methane volatile organic compounds), and tropospheric aerosols (e.g., sulfur dioxide products and black carbon), however, are present in very different quantities spatially around the world, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially heterogeneous in the atmosphere.[11]

Changes between the Second and Third Assessment Reports

More than two decades of research have provided a progressively improved understanding of the interaction between anthropogenic emissions of greenhouse gases and their potential to alter the Earth’s atmosphere. In the five years between the publication of the SAR in 1996 and the TAR in 2001, considerable progress was achieved in reducing the scientific uncertainty associated with the direct and indirect relationship of atmospheric responses to various external influences.

The IPCC’s TAR includes GWP estimates for several gases that have been modified from the SAR, as well as new GWPs for a more complete set of gases. In keeping with IPCC protocol, the use of all GWPs continues to be based

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[8] U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002. See also Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

[9] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001) Section 6.12.

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

[11] U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002.

on the effect of that greenhouse gas over a 100-year time period. Included among the new gases are certain ozone depleting substances (ODSs), originally considered only to be harmful to stratospheric ozone but now recognized as potent greenhouse gases. In addition, the TAR includes new categories for ethers and halogenated ethers.

In general, the TAR served to confirm and reinforce the conclusions put forth in the SAR. Table G2 provides a comparison of 100-year GWP estimates from the SAR and TAR. The bulk of changes to the GWPs, as described below, have also shown to have little overall impact on the quantification of total greenhouse gases emitted at the U.S. national level. Table G3 presents a comparison of GWPs and lifetimes in the SAR and TAR, while Table G4 illustrates the effect SAR and TAR 100-year GWPs have on U.S. emissions estimates.

Table G2. Comparison of 100-Year GWP Estimates from the IPCC's Second (SAR) and Third (TAR) Assessment Reports

Gas	GWP		Absolute Change	Percentage Change
	SAR	TAR		
Carbon Dioxide	1	1	No Change	No Change
Methane	21	23	2	10%
Nitrous Oxide	310	296	-14	-5%
Hydrofluorocarbons				
HFC-23	11,700	12,000	300	3%
HFC-32	650	550	-100	-15%
HFC-41	150	97	-53	-35%
HFC-125	2,800	3,400	600	21%
HFC-134	1,100	1,100	100	10%
HFC-134a	1,300	1,300	No Change	No Change
HFC-143	300	330	30	10%
HFC-143a	3,800	4,300	500	13%
HFC-152	NA	43	NA	NA
HFC-152a	140	120	-20	-14%
HFC-161	NA	12	NA	NA
HFC-227ea	2,900	3,500	600	21%
HFC-236cb	NA	1,300	NA	NA
HFC-236ea	NA	1,200	NA	NA
HFC-236fa	6,300	9,400	3,100	49%
HFC-245ca	560	640	80	14%
HFC-245fa	NA	950	NA	NA
HFC-365mfc	NA	950	NA	NA
HFC-4310mee	1,300	1,500	200	15%
Iodocarbons				
FIC-1311	<1	1	No Change	No Change
Fully Fluorinated Species				
SF_6	23,900	22,000	-1,900	-8%
CF_4	6,500	5,700	-800	-12%
C_2F_6	9,200	11,900	2,700	29%
C_3F_8	7,000	8,600	1,600	23%
C_4F_{10}	7,000	8,600	1,600	23%
c-C_4F_8	8,700	10,000	1,300	15%
C_5F_{12}	7,500	8,900	1,400	19%
C_6F_{14}	7,400	9,000	1,600	22%

Sources: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

Improvements to GWP Estimates in the Third Assessment Report

Improvements to the IPCC's GWP values in the TAR were a result of an improved calculation of CO_2 radiative forcing, an improved CO_2 response function, and recalculations of some atmospheric lifetimes. GWPs presented in the TAR are drawn from the SAR and the World Meteorological Organization (WMO),[12] and include specific updates drawn from new published cases of laboratory or radiative transfer results.

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[12] World Meteorological Organization, *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project-Report No. 44,* Geneva, Switzerland (1999).

As stated in the TAR:

> *The direct GWPs have been calculated relative to CO_2 using an improved calculation of the CO_2 radiative forcing, the SAR response function for a CO_2 pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.* [TAR 2001]

To determine the direct radiative forcings (per ppbv or parts per billion volume), the IPCC "derived from infrared radiative transfer models based on laboratory measurements of the molecular properties of each substance and considering the molecular weights."[13] The radiative forcing of CO_2 was found to be about 12 percent lower than that reported in the SAR. For example, the improved formula, for fixed changes in gas concentrations, decreased CO_2 and N_2O radiative forcing by 15%, increased CFC-11 and CFC-12 radiative forcing by 10 to 15%, and yielded no change in the case of CH_4. As a consequence of changes in the radiative forcing for CO_2 and CFC-11, the revised GWPs are typically 20% higher than listed in the SAR.[14]

The response function for a CO_2 pulse can be explained in simple terms as the response from adding an additional ton of CO_2 to the atmosphere, and the function specifies the proportion of CO_2 that remains in the atmosphere after a designated amount of time (an average of single exponential decay functions). The GWP of any substance therefore expresses the integrated forcing of a pulse (of given small mass) of that substance relative to the integrated forcing of a pulse (of the same mass) of the reference gas over some time horizon.

Many atmospheric lifetimes were recalculated in the TAR. The lifetimes of non-CO_2 greenhouse gases are dependent largely on atmospheric photochemistry, which controls photo-lysis and related removal processes. When the lifetime of the gas in question differs substantially from the response time of the reference gas (CO_2), the GWP becomes sensitive to the choice of time horizon. For example, for longer time horizons (greater than 100 years), those gases that decay more rapidly than the CO_2 display decreasing GWPs; and conversely those gases with lifetimes much longer than that of the CO_2 display increasing GWPs. Table G3 provides a comparison of the lifetimes and GWPs for the greenhouse gases provided in the SAR and TAR, showing a range of between -15 and + 49 percent in GWP values.

As a result of the adjustments to the radiative forcing of CO_2 and the recalculation of atmospheric lifelines of several gases, the GWPs of the other gases, relative to CO_2, have overall increased. Other variables, such as the radiative efficiency or chemical lifetime, have also altered the GWP values.[15] Because much detailed laboratory data are not yet available, however, some of the GWPs have larger uncertainties than others. As mentioned above, the IPCC estimates that GWPs generally have an uncertainty of ±35 percent.

Because GWP values are based on the concept of radiative forcing, and these forcings do not appear to stay constant over time, the values for GWPs also will continue to fluctuate, particularly if the amounts and composition of the various gases in the atmosphere increase. In some cases, where concentrations of a greenhouse gas are low, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, the marginal effects of additional emissions may not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or CO_2, tends to be less than that of a rare gas, such as sulfur hexafluoride (SF_6). This "diminishing return" effect implies that increasing concentrations 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.

Figure G1 shows the comparative global and annual mean radiative forcing of a range of gases from 1750 to the late 1990s. Note that greenhouse gases are provided in the left-most bar in the graphic. The IPCC notes that, all the forcings shown have distinct spatial and seasonal features such that the global, annual means appearing on this plot do not yield a complete picture of the radiative perturbation. They are only intended to give, in a relative sense, a first-order perspective on a global, annual mean scale, and cannot be readily employed to obtain the climate response to the total natural and/or anthropogenic forcings. As in the SAR, it is emphasized that the positive and negative global mean forcings cannot be added up and viewed a priori as providing offsets in terms of the complete global climate impact.

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[13] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), Section 6.12.1.

[14] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

[15] U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002.

Table G3. Comparison of GWPs and Lifetimes Used in the SAR and the TAR

	Lifetime (years)		GWP (100 year)		Absolute Change	Percent Change
Gas	SAR	TAR	SAR	TAR		
Carbon Dioxide	50-200	5-200[a]	1	1	NC	NC
Methane[b]	12±3	8.4/12[c]	21	23	2	10%
Nitrous Oxide	120	120/114 [c]	310	296	(14)	-5%
Hydrofluorocarbons						
HFC-23	264	260	11,700	12,000	300	3%
HFC-32	5.6	5.0	650	550	(100)	-15%
HFC-41	3.7	2.6	150	97	(53)	-35%
HFC-125	32.6	29	2,800	3,400	600	21%
HFC-134	10.6	9.6	1,000	1,100	100	10%
HFC-134a	14.6	13.8	1,300	1,300	NC	NC
HFC-143	3.8	3.4	300	330	30	10%
HFC-143a	48.3	52	3,800	4,300	500	13%
HFC-152	NA	0.5	NA	43	NA	NA
HFC-152a	1.5	1.4	140	120	(20)	-14%
HFC-161	NA	0.3	NA	12	NA	NA
HFC-227ea	36.5	33.0	2,900	3,500	600	21%
HFC-236cb	NA	13.2	NA	1,300	NA	NA
HFC-236ea	NA	10	NA	1,200	NA	NA
HFC-236fa	209	220	6,300	9,400	3,100	49%
HFC-245ca	6.6	5.9	560	640	80	14%
HFC-245fa	NA	7.2	NA	950	NA	NA
HFC-365mfc	NA	9.9	NA	890	NA	NA
HFC-4310mee	17.1	15	1,300	1,500	200	15%
Iodocarbons						
FIC-1311	<0.005	0.005	<1	1	NC	NC
Fully Fluorinated Species						
SF_6	3,200	3,200	23,900	22,000	(1,900)	-8%
CF_4	50,000	50,000	6,500	5,700	(800)	-12%
C_2F_6	10,000	10,000	9,200	11,900	2,700	29%
C_3F_8	2,600	2,600	7,000	8,600	1,600	23%
C_4F_{10}	2,600	2,600	7,000	8,600	1,600	23%
c-C_4F_8	3,200	3,200	8,700	10,000	1,300	15%
C_5F_{12}	4,100	4,100	7,500	8,900	1,400	19%
C_6F_{14}	3,200	3,200	7,400	9,000	1,600	22%
Ethers & Halogenated Ethers						
CH3OCH3	NA	0.015	NA	1	NA	NA
(CF3)2CFOCH3	NA	3.4	NA	330	NA	NA
(CF3)CH2OH	NA	0.5	NA	57	NA	NA
CF3CF2CH2OH	NA	0.4	NA	40	NA	NA
(CF3)2CHOH	NA	1.8	NA	190	NA	NA
HFE-125	NA	150	NA	14,900	NA	NA
HFE-134	NA	26.2	NA	6,100	NA	NA
HFE-143a	NA	4.4	NA	750	NA	NA
HCFE-235da2	NA	2.6	NA	340	NA	NA
HFE-245cb2	NA	4.3	NA	580	NA	NA
HFE-245fa2	NA	4.4	NA	570	NA	NA
HFE-254cb2	NA	0.22	NA	30	NA	NA
HFE-347mcc3	NA	4.5	NA	480	NA	NA
HFE-356pcf3	NA	3.2	NA	430	NA	NA
HFE-374pcf2	NA	5.0	NA	540	NA	NA
HFE-7100	NA	5.0	NA	390	NA	NA
HFE-7200	NA	0.77	NA	55	NA	NA
H-Galden 1040x	NA	6.3	NA	1,800	NA	NA
HG-10	NA	12.1	NA	2,700	NA	NA
HG-01	NA	6.2	NA	1,500	NA	NA

See notes at end of table.

Table G3. Comparison of GWPs and Lifetimes Used in the SAR and the TAR (Continued)

Gas	Lifetime (years)		GWP (100 year)		Absolute Change	Percent Change
	SAR	TAR	SAR	TAR		
Others[d]						
NF3	NA	740	NA	10,800	NA	NA
SF5CF3	NA	>1,000	NA	>17,500	NA	NA
c-C3F6	NA	>1,000	NA	>16,800	NA	NA
HFE-227ea	NA	11	NA	1,500	NA	NA
HFE-236ea2	NA	5.8	NA	960	NA	NA
HFE-236fa	NA	3.7	NA	470	NA	NA
HFE-245fa1	NA	2.2	NA	280	NA	NA
HFE-263fb2	NA	0.1	NA	11	NA	NA
HFE-329mcc2	NA	6.8	NA	890	NA	NA
HFE-338mcf2	NA	4.3	NA	540	NA	NA
HFE-347-mcf2	NA	2.8	NA	360	NA	NA
HFE-356mec3	NA	0.94	NA	98	NA	NA
HFE-356pcc3	NA	0.93	NA	110	NA	NA
HFE-356pcf2	NA	2.0	NA	260	NA	NA
HFE-365mcf3	NA	0.11	NA	11	NA	NA
(CF3)2CHOCHF2	NA	3.1	NA	370	NA	NA
(CF3)2CHOCH3	NA	0.25	NA	26	NA	NA
(CF2)4CH(OH)-	NA	0.85	NA	70	NA	NA

[a] No single lifetime can be determined for carbon dioxide. (See IPCC 2001)

[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

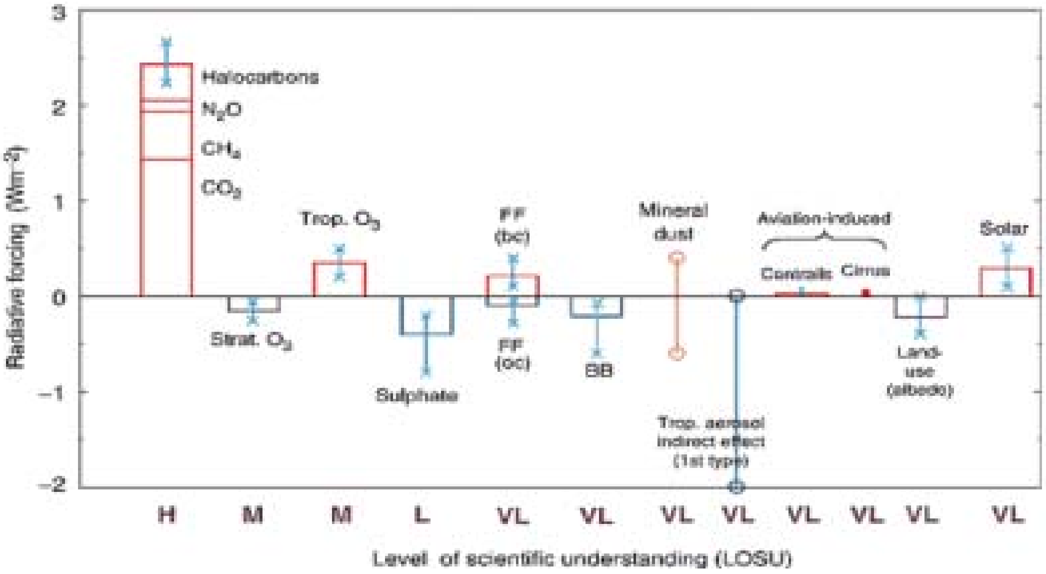
[c] Methane and nitrous oxide have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT).

[d] Gases whose lifetime has been determined only via indirect means of for whom there is uncertainty over the loss process.

Sources: U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the inventory of u.s. Greenhouse Emissions and Sinks: 1990-2000*, April 2002; Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

Notes: NC (No Change); NA (Not Applicable)

Figure G1. Global and Annual Mean Radiative Forcing (1750 to Present)



Notes: This figure illustrates the global, annual mean radiative forcings (Wm^{-2}) due to a number of agents for the period from pre-industrial (1750) to the late 1990s (about 2000). The height of the rectangular bar denotes a central or best estimate value while its absence denotes no best estimate is possible. The vertical line about the rectangular bar with "x" delimiters indicates an estimate of the uncertainty range, guided by the spread in the published values of the forcing and physical understanding. A vertical line without a rectangular bar and with "o" delimiters denotes a forcing for which no central estimate can be given owing to large uncertainties. The uncertainty range specified here has no statistical basis and therefore differs from the use of the term elsewhere in this document. A "level of scientific understanding" (LOSU) index is accorded to each forcing, with H, M, L and VL denoting high, medium, low and very low levels, respectively. This represents our subjective judgment about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of our knowledge of the physical/chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing. The well-mixed greenhouse gases are grouped together into a single rectangular bar with the individual mean contributions due to CO_2, CH_4, N_2O, and halocarbons shown; halocarbons refers to all halogen-containing compounds listed in "FF" denotes fossil fuel burning while "BB" denotes biomass burning aerosol. Fossil fuel burning is separated into the "black carbon" (bc) and "organic carbon" (oc) components with its separate best estimate and range. The sign of the effects due to mineral dust is itself an uncertainty. Only the first type of indirect effect due to aerosols as applicable in the context of liquid clouds is considered here.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

Effect of Using TAR GWPs for Greenhouse Gas Emissions Estimations

As shown in Table G4, when estimating U.S. greenhouse gas emissions for 1990, 2000 and 2001, the values calculated with the TAR GWPs are 0.7 to 0.8 percent higher than the estimate calculated with SAR GWPs. When applying the TAR GWPs, the greatest overall difference to the SAR estimates, in terms of having a significant effect on the atmosphere, can be seen in a 10.0 percent increase in carbon-equivalent methane emissions and a 4.0 percent decrease in carbon-equivalent nitrous oxide emissions. Carbon equivalent emissions of HFCs, PFCs, and SF$_6$ have varied over the years depending on the relative share of the gases. Taken as a whole, however, the differences in GWPs between the SAR and TAR do not prove a significant effect on U.S. emissions trends.

Table G4. GWP Effects on U.S. Greenhouse Gas Emissions

Gas	IPCC GWP		Annual GWP-Weighted Emissions (Million Metric Tons Carbon Equivalent)								
			1990			2000			2001		
	1996	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	1,569	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: U.S. Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2001* (December 2002); Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

Conclusions

In the five years between the publication of the SAR in 1996 and the TAR in 2001, progress has been achieved in reducing the scientific uncertainty associated with the direct and indirect relationship of atmospheric responses to various external influences. Improvements have been made to the GWP values published in the TAR, and these are expected to be adopted and approved by the UNFCCC COP. While participating countries are still required to apply the GWPs published in the SAR according to the most recently adopted requirements for the development of national GHG inventories submitted to the UNFCCC, the TAR has been recognized as providing the most scientifically accurate GWPs to date, and has been adopted by EIA in the completion of this report.