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Emissions of Greenhouse Gases in the United States 2000

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Energy Information Administration
Office of Integrated Analysis and Forecasting
U.S. Department of Energy
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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 ninth 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.

The estimates of greenhouse gas emissions contained in this report are based on energy consumption data from the Energy Information Administration's (EIA's) July 2001 *Monthly Energy Review*. Those estimates may differ from other EIA data series prepared after July 2001. Future revisions to the *Monthly Energy Review*, or other EIA data series, will be represented in the next annual report of *Emissions of Greenhouse Gases in the United States*.

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U.S. Anthropogenic Greenhouse Gas Emissions, 1990-2000

	Carbon Equivalent
Estimated 2000 Emissions (Million Metric Tons)	1,906.3
Change Compared to 1999 (Million Metric Tons)	46.1
Change from 1999 *(Percent)*	*2.5%*
Change Compared to 1990 (Million Metric Tons)	228.4
Change from 1990 *(Percent)*	*13.6%*
Average Annual Increase, 1990-2000 *(Percent)*	*1.3%*

U.S. emissions of greenhouse gases in 2000 totaled 1,906 million metric tons carbon equivalent, 2.5 percent more than in 1999 (1,860 million metric tons carbon equivalent). The increase from 1999 to 2000 is nearly double the 1.3-percent average annual growth rate of total U.S. greenhouse gas emissions from 1990 to 2000 and the 1.3-percent increase from 1998 to 1999. The increase from 1999 to 2000 is attributed to strong growth in carbon dioxide emissions due to a return to more normal weather, decreased hydroelectric power generation that was replaced by fossil-fuel power generation, and strong economic growth (a 4.1-percent increase in gross domestic product).

U.S. greenhouse gas emissions in 2000 were about 14 percent higher than 1990 emissions (1,678 million metric tons carbon equivalent). Since 1990, U.S. emissions have increased slightly faster than the average annual growth in population (1.2 percent) but more slowly than the growth in energy consumption (1.6 percent), electric power generation (2.3 percent), or gross domestic product (3.2 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." This concept, developed by the Intergovernmental Panel on Climate Change (IPCC), provides a comparative measure of the impacts of different greenhouse gases on global warming, with the effect of carbon dioxide being equal to one.[1]

In 2001, the IPCC Working Group I released its Third Assessment Report, *Climate Change 2001: The Scientific Basis*.[2] Among other things, the Third Assessment Report updated a number of the GWP estimates that appeared in the IPCC's Second Assessment Report.[3] The GWPs published in the Third Assessment Report

Table ES1. Summary of Estimated U.S. Emissions of Greenhouse Gases, 1990-2000
(Million Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Carbon Dioxide	4,969.4	4,917.7	5,013.0	5,130.4	5,224.4	5,273.5	5,454.8	5,533.0	5,540.0	5,630.7	5,805.5
Methane	31.7	31.9	31.8	31.0	31.0	31.1	29.9	29.6	28.9	28.7	28.2
Nitrous Oxide	1.2	1.2	1.2	1.2	1.3	1.3	1.2	1.2	1.2	1.2	1.2
HFCs, PFCs, and SF_6 ..	*	*	*	*	*	*	*	*	*	*	*

*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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).

Source: Estimates presented in this report.

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[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).

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

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-2000
(Million Metric Tons Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Carbon Dioxide	1,355	1,341	1,367	1,399	1,425	1,438	1,488	1,509	1,511	1,536	1,583
Methane	199	200	200	194	194	195	188	186	181	180	177
Nitrous Oxide	94	96	98	98	106	101	101	99	99	100	99
HFCs, PFCs, and SF_6	30	28	29	30	32	35	39	42	46	45	47
Total	**1,678**	**1,665**	**1,694**	**1,722**	**1,757**	**1,770**	**1,815**	**1,836**	**1,836**	**1,860**	**1,906**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 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.

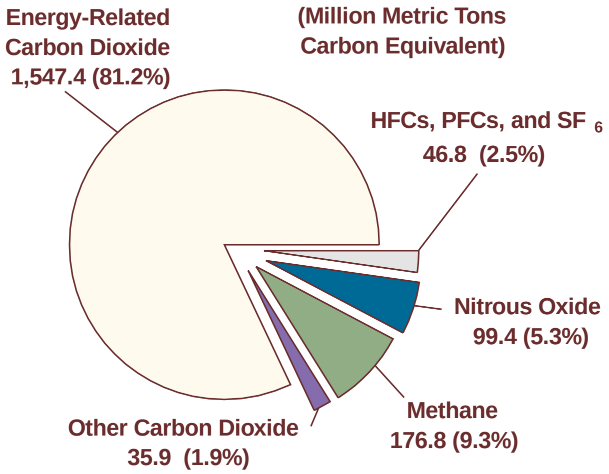
were used for the calculation of carbon-equivalent emissions for this report. For a discussion of GWPs and a comparison of U.S. carbon-equivalent emissions calculated using the GWPs from the IPCC's Third and Second Assessment Reports, see Chapter 1, page 12. Generally, total U.S. carbon-equivalent emissions are 0.6 percent higher when the GWPs from the Third Assessment Report are used.

During 2000, 81.2 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. 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 2000 U.S. greenhouse gas emissions include carbon dioxide from non-combustion sources (1.9 percent of total U.S. greenhouse gas emissions), methane (9.3 percent), nitrous oxide (5.3 percent), and other gases (2.5 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.

The Kyoto Protocol, drafted in December 1997 under the auspices of the United Nations Framework Convention on Climate Change, raised the public profile of climate change issues in the United States in general, and of emissions estimates in particular. 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.

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 2000



Source: EIA estimates presented in this report.

Carbon Dioxide

The preliminary estimate of U.S. carbon dioxide emissions in 2000 is 1,583 million metric tons carbon equivalent—3.1 percent higher than in 1999 and accounting for 83 percent of total U.S. greenhouse gas emissions. The 3.1-percent growth rate in 2000 is the second highest for the 1990 to 2000 period, with only the 3.4-percent growth rate in 1996 being higher. 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, energy use, and income, as well as the "carbon intensity" of energy use (carbon dioxide emissions per unit of energy consumed).

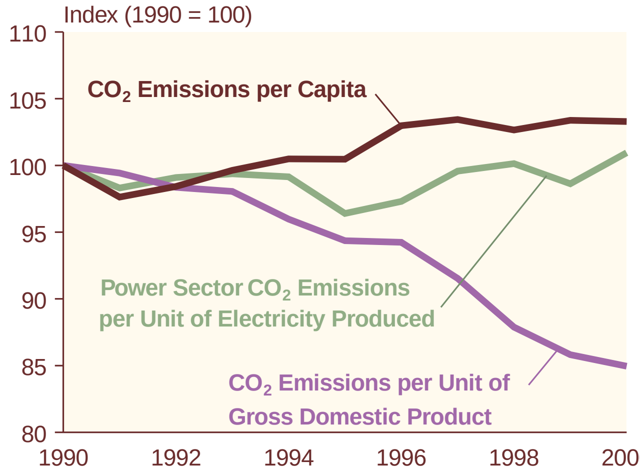
Figure ES2 illustrates some recent U.S. trends in carbon dioxide emissions and energy consumption. Although annual carbon dioxide emissions per dollar of GDP have fallen by 15 percent since 1990, carbon dioxide emissions per capita have risen by 3 percent. The combination of increasing population growth and rising carbon dioxide emissions per capita results in increased aggregate carbon dioxide emissions per year during the 1990 to 2000 time frame. Carbon dioxide emissions per unit of net electricity generation, after initially falling during the early to mid-1990s, have increased to above the 1990 level. The upturn in this measure from 1999 to 2000 helps explain the high 2000 growth rate in carbon dioxide emissions.

Figure ES3 illustrates trends in carbon dioxide emissions by energy consumption sector. In general, emissions have increased in each of the four sectors 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 a 1.0-percent decrease in national carbon dioxide emissions in 1991. Average annual growth rates in carbon dioxide emissions by sector during the 1990-2000 period were 2.4 percent for the commercial sector, 2.0 percent for the residential sector and 1.8 percent for the transportation sector, all higher than the 1.6-percent average for total U.S. carbon dioxide emissions during the 1990-2000 period. For the industrial sector, however, annual growth in carbon dioxide emissions has averaged only 0.3 percent. Industrial sector carbon dioxide emissions, which are relatively sensitive to economic fluctuations, declined by 2.5 percent in 1991 during the economic recession and dipped again in 1998 in the wake of the Asian economic slowdown.

Carbon dioxide emissions from the U.S. electric power sector (which includes cogeneration) in 2000 are estimated at 642 million metric tons carbon equivalent, 4.7 percent higher than the 1999 level. The 2000 increase is almost double the 1990-2000 average increase of 2.4 percent per year. Contributing to the relatively large increase in 2000 was a 4.2-percent increase in fossil fuel use for electricity generation, including a 4.3-percent increase in coal-fired generation and a 7.1-percent increase in natural-gas-fired generation. Electricity generation from renewable fuels was down by 11 percent, including a 14-percent drop in hydroelectric generation. On the demand side, electricity-related emissions in the residential sector were 5.6 percent higher in 2000 than in 1999, and in the commercial sector they were 4.9 percent higher.[4] Although summer cooling degree-days were 4.4 percent above normal in 2000, air conditioning usage was lower than in 1999, when cooling degree-days were 7.3 percent above normal.

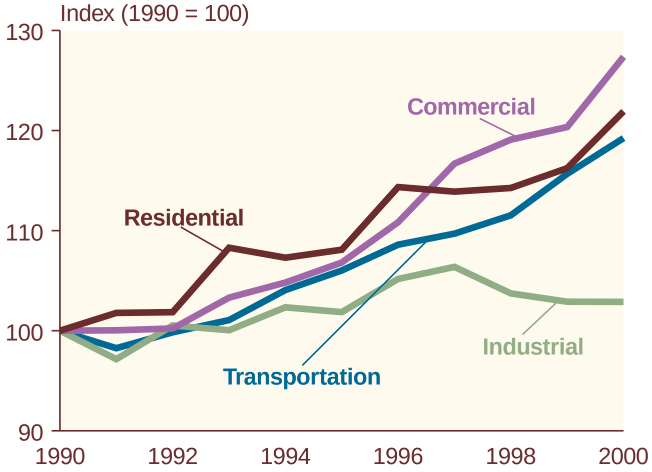
In addition to electricity-related emissions, direct use of energy fuels in the residential, commercial, industrial, and transportation sectors produces carbon dioxide emissions. In the residential and commercial sectors, consumption of winter heating fuels, particularly natural gas, was higher in 2000 than in 1999 as a result of winter weather that was 7.0 percent colder than in 1999.[5]

Figure ES2. Carbon Dioxide Emissions Intensity of U.S. Gross Domestic Product, Population, and Electricity Production, 1990-2000



Sources: Estimates presented in this report.

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1990-2000



Sources: Estimates presented in this report.

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[4] The sectoral shares of electricity-related carbon dioxide emissions are based on the shares of total electric utility power sales purchased in each sector.

[5] Population-weighted heating degree-days in 2000 were 7.0 percent higher than in 1999. See Energy Information Administration, *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, August 2000), Table 1.7.

Carbon dioxide emissions from the direct combustion of fuels (primarily natural gas) increased by 3.5 percent in the residential sector and by 8.8 percent in the commercial sector. Overall, carbon dioxide emissions in the residential and commercial sectors, at a combined 581 million metric tons carbon equivalent and 37.2 percent of total carbon dioxide emissions, grew by 5.3 percent in 2000.

Energy-related carbon dioxide emissions in the industrial sector in 2000 are estimated at 466 million metric tons carbon equivalent—which is equal to the level of emissions in 1999. The lack of growth in industrial emissions is noteworthy because, historically, industrial energy consumption and carbon dioxide emissions have been more sensitive to economic growth than to the weather, and 2000 was a year of solid economic growth (4.1 percent). Industrial energy consumption and emissions are concentrated in a few industries, however, and their performance may have more influence on emissions than does the performance of the industrial sector as a whole. Six industry groups—petroleum refining, chemicals and related products, primary metals, paper, food, and stone, clay and glass—collectively account for 79.6 percent of carbon dioxide emissions from manufacturing and 68.2 percent of carbon dioxide emissions from the industrial sector.

In 2000 the six energy-intensive industry groups appeared to be still recovering from downturns from their 1997 growth rates. Their 2000 annual growth rates were lower than those for the overall economy (4.1 percent), the industrial sector (5.6 percent), and the manufacturing component of industrial production (6.1 percent). For the six energy-intensive industries, 2000 growth rates were 2.5 percent (primary metals), 1.8 percent (chemicals), -0.9 percent (paper), 2.3 percent (stone, clay and glass), 1.6 percent (petroleum products), and 1.9 percent (food). The industries that grew rapidly in 2000 were primarily those with lower energy intensities, including computer equipment, which grew by 43 percent, and semiconductors and related components, which grew by 76 percent.[6]

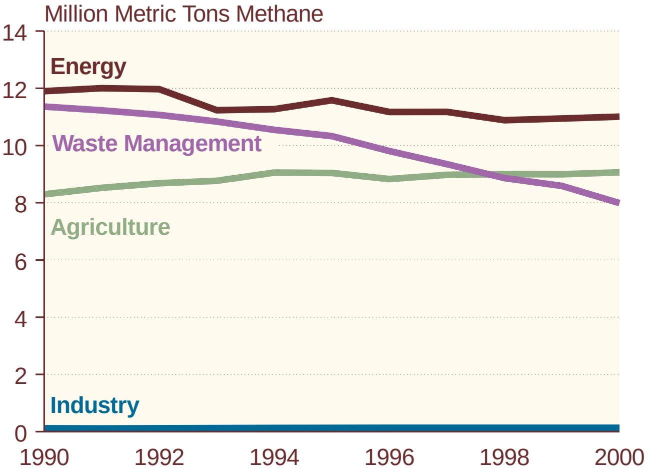
Carbon dioxide emissions in the transportation sector, at 515 million metric tons carbon equivalent, were 3.1 percent higher in 2000 than in 1999. Gasoline consumption, which accounted for 59 percent of transportation sector emissions, grew by 0.6 percent. Emissions from jet fuel use grew by 3.4 percent, and emissions from residual fuel (used mostly by oceangoing ships) grew by 35.9 percent. Emissions from distillate use increased by 4.6 percent, as a healthy U.S. economy led to greater consumption of diesel fuel by freight trucks.

Methane

U.S. emissions of methane in 2000 were 1.6 percent lower than in 1999, at 28.2 million metric tons of methane or 177 million metric tons carbon equivalent. The decline resulted primarily from an increase in methane recovery for energy use at landfills and, to a lesser extent, from reductions in emissions from coal mining and petroleum systems.

Methane emissions come from four categories of sources, three major and one minor. The major sources are energy, waste management, and agriculture, and the minor source is industrial processes. The three major sources accounted for 39, 28, and 32 percent, respectively, of total 2000 U.S. emissions of methane, or approximately 9 percent of the Nation's total carbon-equivalent greenhouse gas emissions. The major sources of anthropogenic methane emissions are illustrated in Figure ES4. Methane emissions from the anaerobic decomposition of municipal solid waste in landfills, part of the waste management source category, had been declining slowly before 2000 as a consequence of a reduction in the volume of waste landfilled and a gradual increase in the volumes of landfill gas captured. Emissions of methane resulting from waste management decreased by 7.0 percent in 2000.

Figure ES4. U.S. Methane Emissions by Source, 1990-2000



Sources: Estimates presented in this report.

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[6] All industrial and manufacturing growth rates are taken from U.S. Federal Reserve Board, "G17 Historical Data: Industrial Production and Capacity Utilization." Although the Federal Reserve Board, in calculating indexes, bases its estimates on two main types of source data, output measured in physical units and data on inputs to the production process, it also adjusts its indexes on the basis of technological improvements in factor productivity and outputs. This could be particularly important for indexes related to computers and semiconductors, for which productivity and quality of outputs have improved dramatically over time.

Methane recovery for energy at U.S. landfills rose from 2.2 million metric tons in 1999 to 2.5 million metric tons in 2000 due to the lingering effects of Section 29 of the Windfall Profits Tax Act of 1980. To be eligible for the tax credit, methane recovery systems at landfills must have been operational by June 30, 1998. The last recovery projects installed by the tax credit deadline continued to ramp up in 2000. Additionally, for the first time in 40 years, U.S. coal production fell for a second consecutive year as coal imports increased by 37 percent and electric utilities drew down stocks to meet increasing demand,[7] lowering methane emissions from coal mining and post-mining activities by about 0.1 million metric tons. Domestic oil production also declined in 2000, and methane emissions from petroleum systems decreased accordingly.

Methane is also emitted as a byproduct of fossil energy production and transport. Methane can leak from natural gas production and distribution systems and is also emitted during coal production. Energy-related methane emissions were essentially unchanged in 2000 at 11.0 million metric tons. Agricultural emissions have several sources but are dominated by emissions from domestic livestock, including the animals themselves and the anaerobic decomposition of their waste. Agricultural emissions increased by about 0.8 percent in 2000.

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 livestock and municipal waste emissions are influenced by husbandry and waste management practices.

Nitrous Oxide

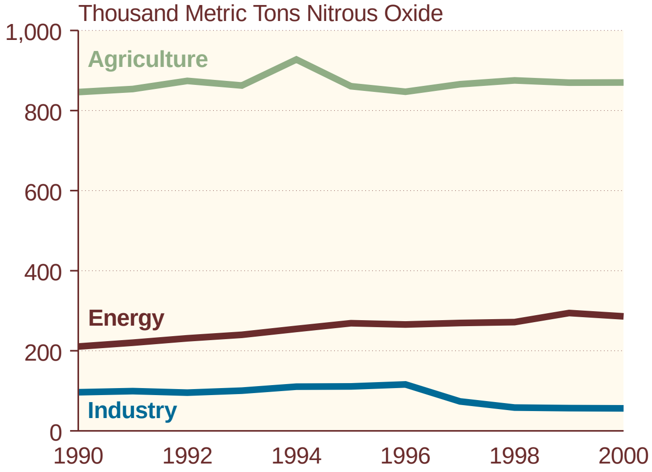
U.S. nitrous oxide emissions decreased by 0.6 percent from 1999 to 2000, to 99 million metric tons carbon equivalent. Nitrous oxide accounts for 5 percent of U.S. GWP-weighted greenhouse gas emissions. Emissions estimates for nitrous oxide are more uncertain than those for either carbon dioxide or methane, because nitrous oxide is not systematically measured and many sources of nitrous oxide emissions, including nitrogen fertilization of soils and motor vehicles, require a significant number of assumptions to arrive at estimated emissions.

U.S. nitrous oxide emissions include one large class of sources and two small classes (Figure ES5). Agricultural sources account for about 70 percent of nitrous oxide emissions, and emissions associated with nitrogen fertilization of soils account for 73 percent of agricultural emissions. In 2000, estimated nitrous oxide emissions from nitrogen fertilization of soils increased by 0.2 percent from 1999. Emissions associated with fossil fuel use account for another 23 percent of nitrous oxide emissions, of which about 83 percent comes from mobile sources, principally motor vehicles equipped with catalytic converters. The balance of nitrous oxide emissions are caused by certain chemical manufacturing and wastewater treatment processes. The most striking trend in U.S. nitrous oxide emissions has been a 52-percent decline from 1996 levels of industrial emissions of nitrous oxide after the implementation of emissions controls at an adipic acid plant operated by the DuPont Corporation.

Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

HFCs, PFCs, and SF_6 are three classes of engineered gases that account for 2.5 percent of U.S. GWP-weighted emissions of greenhouse gases. At 46.8 million metric tons carbon equivalent in 2000, their emissions were 4.5 percent higher than in 1999. The 2000 increase in emissions of the engineered gases was caused almost entirely

Figure ES5. U.S. Nitrous Oxide Emissions by Source, 1990-2000



Sources: Estimates presented in this report.

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[7] Energy Information Administration, *U.S. Coal Supply and Demand: 2000 Review*, web site http://www.eia.doe.gov/cneaf/coal/page/special/feature.html.

by an increase in emissions of HFCs (8.3 percent) as emissions of PFCs and SF_6 fell by 3.7 percent and 4.3 percent, respectively. The increase in HFC emissions in 2000 may be attributable in part to maturing markets for chlorofluorocarbon substitutes and increasing awareness of the potential for recycling these gases.

At 28.1 million metric tons carbon equivalent, emissions of HFCs make up the majority of this category, followed by PFCs at 8.7 million metric tons carbon equivalent and SF_6 at 5.5 million metric tons carbon equivalent. Another group of engineered gases, consisting of other HFCs, other PFCs, and perfluoropolyethers (PFPEs), includes HFC-152a, HFC-227ea, HFC-4310mee, and a variety of PFCs and PFPEs. They are grouped together in this report to protect confidential data. In 2000, their combined emissions totaled 4.4 million metric tons carbon equivalent. Emissions in this “other” group in 2000 were 10.5 percent higher than in 1999. Since 1990, HFC emissions from U.S. sources have increased by 181.4 percent, PFC emissions have decreased by 14.4 percent, and SF_6 emissions have decreased by 41.4 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 hundreds or thousands of years, and consequently they are potent greenhouse gases with GWPs hundreds or 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 chlorofluorocarbon replacements, have shorter atmospheric lifetimes, ranging from 1 to 36 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 270 million metric tons of carbon annually, equivalent to 17.1 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. At present, the Energy Information Administration does not have sufficient information to permit reliable estimation of national-level emissions or sequestration from this source. As more reliable information becomes available, estimates will be included in future reports.

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 eighth annual update, covering national emissions over the period 1990-1999, with preliminary estimates of emissions for 2000. 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 3). Emissions estimates for carbon dioxide are reported in metric tons carbon equivalent; estimates for other gases are reported in metric tons of gas (see “Units for Measuring Greenhouse Gases,” page 2). Total national emissions estimates measured in carbon equivalents are shown in Table ES2.

Chapter 1 of this report briefly summarizes some background information about global climate change and the greenhouse effect and discusses important recent developments in global climate change activities. Chapters 2 through 4 cover emissions of carbon dioxide, methane, and nitrous oxide, respectively. Chapter 5 focuses on emissions of engineered gases, including hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Chapter 6 describes potential sequestration and emissions of greenhouse gases as a result of land use changes.

The Greenhouse Effect and Global Climate Change

The Earth is warmed by radiant energy from the Sun. Over time, the amount of energy transmitted to the Earth’s surface is equal to the amount of energy re-radiated back into space in the form of infrared radiation, and the temperature of the Earth’s surface stays roughly constant; however, the temperature of the Earth is strongly influenced by the existence, density, and composition of its atmosphere. Many gases in the Earth’s atmosphere absorb infrared radiation re-radiated from the surface, trapping heat in the lower atmosphere. Without the natural greenhouse effect, it is likely that the average temperature of the Earth’s surface would be on the order of -19° Celsius, rather than the +14° 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), p. 89-90. See also web site www.ipcc.ch.

[2] The United Nations Framework Convention on Climate Change, which “entered into force” in 1994, calls 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 has no plans, at this time, 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

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, Recent Years[a]	1.5[b]	0.007[b]	0.0008	0.2	1.0
Atmospheric Lifetime (Years)	50–200[c]	12[d]	114[d]	3,200	>50,000

[a] Rate is calculated over the period 1990 to 1999.

[b] 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 to 1999 period.

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

[d] 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.

human impact on climate from normal temporal and spatial variations in temperature on a global scale. The 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 0.6º ± 0.2ºC since the late 19th century[3] (see box on page 4). 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 Bush Administration, 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. The National Academy of Sciences commissioned the National Research Council to carry out this review. The National Research Council in

What's New in This Report

All Chapters

- The Intergovernmental Panel on Climate Change (IPCC) has updated a number of the 100-year greenhouse gas global warming potential (GWP) coefficients,[a] including methane (increased from 21 to 23), nitrous oxide (decreased from 310 to 296), sulfur hexafluoride (decreased from 23,900 to 22,200), and perfluoromethane (decreased from 6,500 to 5,700) that were reported in an earlier IPCC report.[b] The greenhouse gas emissions estimates in this report are based on the new IPCC-updated GWPs (see box on page 12 for a comparison of U.S. emissions calculated with the earlier and revised GWPs).

Chapter 1

- In keeping with the *1996 Revised IPCC Guidelines for the Preparation of National Inventories* and an IPCC Expert Working Group Meeting on Good Practices in Inventory Preparation held in the United Kingdom in October 1999, a study of the uncertainty in greenhouse gas emissions data was conducted using Monte Carlo simulations. This analysis supplements the results presented in last year's report for a study of uncertainty strictly in energy-related carbon dioxide emissions. A summary of the current results is included in Chapter 1.

Chapter 2

- In this year's report, carbon dioxide emissions attributed to nonutility power producers have been removed from the industrial sector and placed in a combined electric power sector, where they have been shared out to end-use sectors in proportion to the amount of electricity purchased by each sector.
- In 1998, EIA conducted a Manufacturing Energy Consumption Survey. The results of the 1998 survey have been used to calculate emissions from the manufacturing subsector, which makes up 85 percent of the U.S. industrial sector.

Chapter 5

- The data presented in Chapter 5 for HFCs, PFCs, SF_6, and other gases are provided by the U.S. Environmental Protection Agency (EPA). This year, the EPA updated a number of its methodologies in order to improve the accuracy and comprehensiveness of the emissions estimates. The Voluntary SF_6 Emissions Reduction Partnership, launched by the EPA in 1999, provided new information on SF_6 emissions from electric power systems and the magnesium industry. In addition, PFC emissions estimates have been revised on the basis of new data from the EPA's Voluntary Aluminum Industrial Partnership Program and from its Global Programs Division, which have resulted in revised emission factors for emissions from aluminum production. The EPA revised the methodology for estimating emissions from semiconductor manufacturing to include production data for 1990-1994 and data reported directly by semiconductor manufacturers for other years. For the substitution of ozone-depleting substances, revisions to chemical substitution trends and new information from industry representatives have led to revised assumptions for the EPA Vintaging Model.

[a] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 388-390.

[b] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 121.

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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.

Key Findings from the Third Assessment Report by the Intergovernmental Panel on Climate Change

The IPCC is 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. The Third Assessment Report by the IPCC, published in 2001, includes the following key findings:

- **The global average surface temperature has increased over the 20th century by about 0.6°C.**
  - The global average surface temperature (the average of near-surface air temperature over land and sea surface temperature) has increased since 1861. Over the 20th century the increase has been 0.6 ±0.2°C.
- **Temperatures have risen during the past four decades in the lowest 8 kilometers of the atmosphere.**
  - Since the late 1950s (the period of adequate observations from weather balloons), the overall global temperature increases in the lowest 8 kilometers of the atmosphere and in surface temperature have been similar at 0.1°C per decade.
- **Snow cover and ice extent have decreased.**
  - Satellite data show that there are very likely to have been decreases of about 10 percent in the extent of snow cover since the late 1960s, and ground-based observations show that there is very likely to have been a reduction of about 2 weeks in the annual duration of lake and river ice cover in the mid- and high latitudes of the Northern Hemisphere over the 20th century.
- **Global average sea level has risen and ocean heat content has increased.**
  - Tide gauge data show that global average sea level rose by between 0.1 and 0.2 meters during the 20th century. Global ocean heat content has increased since the late 1950s, the period for which adequate observations of subsurface ocean temperatures have been available.
- **Concentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities.**
  - The atmospheric concentration of carbon dioxide (CO_2) has increased by 31 percent since 1750. The present CO_2 concentration has not been exceeded during the past 420,000 years and probably not during the past 20 million years. The current rate of increase is unprecedented during at least the past 20,000 years.
  - The atmospheric concentration of methane (CH_4) has increased by 1,060 parts per billion (151 percent) since 1750 and continues to increase. The present CH_4 concentration has not been exceeded during the past 420,000 years.
  - The atmospheric concentration of nitrous oxide (N_2O) has increased by 46 parts per billion (17 percent) since 1750 and continues to increase. The present N_2O concentration has not been exceeded during at least the past 1,000 years.
  - Since 1995, the atmospheric concentrations of many of those halocarbon gases that are both ozone-depleting and greenhouse gases (e.g., $CFCl_3$ and CF_2Cl_2) are either increasing more slowly or decreasing, both in response to reduced emissions under the regulations of the Montreal Protocol and its amendments. Their substitute compounds (e.g., CHF_2Cl and CF_3CH_2F) and some other synthetic compounds (e.g., perfluorocarbons [PFCs] and sulfur hexafluoride [SF_6]) are also greenhouse gases, and their concentrations are currently increasing.
  - The radiative forcing due to increases of the well-mixed greenhouse gases from 1750 to 2000 is estimated to be 2.43 watts per square meter: 1.46 watts per square meter from CO_2; 0.48 watts per square meter from CH_4; 0.34 watts per square meter from the halocarbons; and 0.15 watts per square meter from N_2O.
- **Natural factors have made small contributions to radiative forcing over the past century.**
  - The radiative forcing due to changes in solar irradiance for the period since 1750 is estimated to be about +0.3 watts per square meter, most of which occurred during the first half of the 20th century. Since the late 1970s, satellite instruments have observed small oscillations due to the 11-year solar cycle. Mechanisms for the amplification of solar effects on climate have been proposed but currently lack a rigorous theoretical or observational basis.
  - Stratospheric aerosols from explosive volcanic eruptions lead to negative forcing, which lasts a few years. Several major eruptions occurred in the periods 1880 to 1920 and 1960 to 1991. The combined change in radiative forcing of the two major natural factors (solar variation and volcanic aerosols) is estimated to be negative for the past two, and possibly the past four, decades.

(continued on page 5)

Key Findings from the Third Assessment Report by the Intergovernmental Panel on Climate Change (Continued)

- **There is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities.**
  - The warming over the past 50 years due to anthropogenic greenhouse gases can be identified despite uncertainties in forcing due to anthropogenic sulfate aerosol and natural factors (volcanos and solar irradiance).
- **Human influences will continue to change atmospheric composition throughout the 21st century.**
  - For the IPCC Special Report on Emission Scenarios (SRES) illustrative scenarios, relative to the year 2000, the global mean radiative forcing due to greenhouse gases continues to increase through the 21st century, with the fraction due to CO_2 projected to increase from slightly more than one-half to about three-quarters.
- **Global average temperature and sea level are projected to rise under all IPCC SRES scenarios.**
  - The globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100. These results are for the full range of 35 SRES scenarios, based on a number of climate models.
  - Global mean sea level is projected to rise by 0.09 to 0.88 meters between 1990 and 2100, for the full range of SRES scenarios.
- **Anthropogenic climate change will persist for many centuries.**
  - Emissions of long-lived greenhouse gases (i.e., CO_2, N_2O, PFCs, and SF_6) have a lasting effect on atmospheric composition, radiative forcing, and climate. For example, several centuries after CO_2 emissions occur, about one-quarter of the increase in CO_2 concentration caused by these emissions is still present in the atmosphere.
  - After greenhouse gas concentrations have stabilized, global average surface temperatures would rise at a rate of only a few tenths of a degree per century rather than several degrees per century as projected for the 21st century without stabilization.

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

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:[5]

> *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

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[5] National Research Council, *Climate Change Science, An Analysis of Some Key Questions* (Washington, DC: National Academy Press 2001), p. 1.

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 increased atmospheric CO_2 concentrations.[6] Increased atmospheric temperatures increase the water-holding capability of the atmosphere. According to some of the IPCC emission scenarios, increased water vapor content could double the predicted atmospheric warming above what it would be if water vapor concentration stayed constant. These scenarios, however, have an element of uncertainty due to the possible countervailing effect of increased cloud formation, which can act to cool the planet by absorbing and reflecting solar radiation or warm the planet through the emission of long-wave radiation. According to the IPCC, increases in atmospheric temperatures would not necessarily result in increased concentrations of water vapor, because most of the atmosphere today is undersaturated.

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

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).

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

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.[7]

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.[8] 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.[9] 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.[10]

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.[11] 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.[12]

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.[13]

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

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

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

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

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

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

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

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

bromine or chlorine also deplete the Earth's ozone layer. One of the best known groups of halocarbons is the chlorofluorocarbons (CFCs), particularly CFC-12, often known by its trade name, "Freon-12." CFCs have many desirable features: they are relatively simple to manufacture, inert, nontoxic, and nonflammable. Because CFCs are chemically stable, once emitted, they remain in the atmosphere for hundreds or thousands of years. Because they are not found in nature, these molecules absorb reflected infrared radiation at wavelengths that otherwise would be largely unabsorbed, and they are potent greenhouse gases, with a direct radiative forcing effect hundreds or thousands of times greater, gram-per-gram, than that of carbon dioxide.

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

The threat posed by CFCs to the ozone layer has caused the United States and many other countries to commit themselves to phasing out the production of CFCs and their chemical cousins, hydrochlorofluorocarbons (HCFCs), pursuant to an international treaty, the 1987 Montreal Protocol. As use of CFCs has declined, many related chemicals have emerged as alternatives, including HCFCs and hydrofluorocarbons (HFCs). HCFCs are similar to CFCs, but they are more reactive and consequently have shorter atmospheric lives, with less effect on the ozone layer and smaller direct global warming effects. HCFCs are also being phased out, but over a longer time scale. The ozone-depleting substances with the most potential to influence climate, CFC-11, CFC-12 and CFC-113, are beginning to show reduced growth rates in atmospheric concentrations in the aftermath of the Montreal Protocol. The present radiative forcing of CFC-11 is about 0.065 watts per square meter, and that of CFC-12 is around 0.2 watts per square meter.[14]

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.[15] 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.[16] 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.[17]

[14] 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.

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

[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.

There may be other chemicals not yet identified that exhibit radiative properties similar to those of the halocarbons and other gases described above. One recent discovery identified trifluoromethyl sulfur pentafluoride (SF_5CF_3) as a new anthropogenic greenhouse gas in the atmosphere.[18] 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.[19] This gas is not yet specifically addressed by the United Nations Framework Convention on Climate Change.

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 both as ozone depleters and for 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 via 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.[20] 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.[21] 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, a powerful greenhouse gas, 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.[22]

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

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[18] 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.

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

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

[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. 44.

also reduce atmospheric carbon dioxide concentrations by fertilizing the biosphere.[23]

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).[24]

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.[25] Although the indirect climate effects of aerosols are uncertain, some preliminary evidence points to an indirect cooling effect due to cloud formation.[26]

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*,[27] and subsequently updated in *Climate Change 1995*[28] and *Climate Change 2001*.[29]

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.[30] The uncertainty takes several forms:

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[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* (Cambridge, UK: Cambridge University Press, 2001), Table 4.7(a), p. 258.

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

[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 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

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

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

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

- The radiative efficiencies of greenhouse gases do not necessarily stay constant over time (as calculated in GWPs), particularly if the abundance of a gas in the atmosphere increases. Each gas absorbs radiation in a particular set of wavelengths, or "window," in the spectrum. In some cases, where concentrations of the gas are low and no other gases block radiation in the same window, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, a larger and larger portion of the total light passing through the "window" will already have been captured, and the marginal effects of additional emissions will not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or carbon dioxide, tends to be less than that of a rare gas, such as sulfur hexafluoride. This "diminishing return" effect implies that increasing the concentration of a particular gas reduces the impact of additional quantities of that gas. Thus, the relative impacts of various gases will change as their relative concentrations in the atmosphere change.
- The lifetime of a greenhouse gas (used in GWP calculations), particularly carbon dioxide, is also subject to uncertainty. Various natural processes cause many greenhouse gases to decompose into other gases or to be absorbed by the ocean or ground. These processes can be summarized in terms of the "atmospheric lifetime" of a particular gas, or the period of time it would take for natural processes to remove a unit of emissions from the atmosphere. Some gases, such as CFCs, have very long atmospheric lifetimes, in the hundreds of years. Others, such as carbon monoxide, have lives measured in hours or days. Methane, which decays into carbon dioxide over a period of a few years, has a much larger short-run effect on global warming than does an equivalent amount of carbon dioxide; however, over longer and longer periods—from 10 years to 100 years to 500 years, for example—the differences between the GWPs of methane and carbon dioxide become less significant, because carbon dioxide has a longer atmospheric lifetime than methane.

Table 3 summarizes the consensus results of the most recent studies by scientists working on behalf of the IPCC, showing estimates of atmospheric lifetimes and global warming potentials across various time scales. For the purposes of calculating "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

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.

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 probably continue in the short term, until the UNFCCC reporting rules are changed. The U.S. Environmental Protection Agency (EPA), which compiles the official U.S. emissions inventory for submission to the UNFCCC, intends to present estimates based on the GWPs published in the Second Assessment Report in its *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000* for release in April 2002.

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

The table below shows 2000 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 0.7 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 9.5 percent higher, and carbon-equivalent nitrous oxide emissions are 4.5 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.

			Annual GWP-Weighted Emissions								
	IPCC GWP		1990			1999			2000		
Gas	1996	2001	1996 GWP	2001 GWP	Percent Change	1996 GWP	2001 GWP	Percent Change	1996 GWP	2001 GWP	Percent Change
Carbon Dioxide	1	1	1,355	1,355	0.0	1,536	1,536	0.0	1,583	1,583	0.0
Methane	21	23	181	199	9.5	164	180	9.5	161	177	9.5
Nitrous Oxide	310	296	99	94	-4.5	105	100	-4.5	104	99	-4.5
HFCs, PFCs, and SF_6	—	—	31	30	-2.4	44	45	2.9	45	47	3.5
Total	—	—	**1,666**	**1,678**	**0.6**	**1,848**	**1,860**	**0.6**	**1,894**	**1,906**	**0.7**

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.[31]

International Developments in Global Climate Change

Rising concentrations of carbon dioxide in the atmosphere were first detected in the late 1950s, 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.[32]

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.*[33]

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).[34]

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.

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

[32] 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.

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

[34] 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. In June 1999, Kazakhstan applied for Annex I status but subsequently withdrew its application in June 2000.

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.[35] Developing country signatories do not have quantified targets. Some of the key features of the Protocol are summarized below:

- **Differentiated Targets.** Each Annex I signatory has a "quantified emissions reduction limitation commitment," which limits the signatory to some fraction, ranging from 90 to 110 percent, of its 1990 greenhouse gas emissions.[36] 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 September 28, 2001, 84 countries (including 36 Annex I countries) had signed (not ratified) the Protocol. To date, 40 countries, including a number of Central and South American nations, several small island states, and some Central Asia nations, have ratified the Protocol. Only one Annex I country, Romania, has ratified the Protocol.[37]

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.[38] In 2001, President Bush indicated that he does not intend to submit the Protocol to the Senate for ratification and that the United States will 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."[39] The United States, instead, plans to develop a National Climate Change Technology Initiative that would develop innovative, long-term technologies to address the issue of climate change.[40]

Beyond the Kyoto Protocol

Since the signing of the Kyoto Protocol, the signatories have continued to shape the "work in progress." At the

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

[36] 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.

[37] See web site www.unfcc.int/resource/kpstats.pdf.

[38] 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 . . . ."

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

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

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.[41] 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.[42] COP-6 was rescheduled to resume in the Spring / Summer of 2001 in Bonn, Germany.[43]

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 will be forwarded for official adoption at the Seventh Session of the Conference of the Parties (COP-7), which is to be held in Marrakech, Morocco, from October 29 to November 9, 2001. COP-7 is intended to set up the institutions necessary to make the Bonn Agreement and the Kyoto Protocol operational once ratification is achieved.

The Bush Administration has indicated that it has no objection to the participation of other countries in the Kyoto Protocol or the Bonn Agreement, even without U.S. participation. The Administration has indicated that it intends to develop U.S. alternatives to the Kyoto Protocol, including the National Climate Change Technology Initiative.[44]

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[41] See U.N. Framework Convention on Climate Change, web site http: / / cop6.unfccc.int / media / press.html.
[42] “U.N. Conference Fails to Reach Accord on Global Warming,” *New York Times* (November 26, 2000).
[43] “Odd Culprits in Collapse of Climate Talks,” *New York Times* (November 28, 2000).
[44] Remarks by President Bush on Global Climate Change, Office of the Press Secretary, The White House (June 11, 2001).

Analysis of Uncertainty in Greenhouse Gas Emissions

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, 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 United Nations Framework Convention on Climate Change (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 establishing Tier 1 and Tier 2 methods of estimating uncertainty in greenhouse gas inventories as follows:[a]

- **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 for carbon dioxide, methane, nitrous oxide, and other gases. The results of that analysis can be found in Appendix C of this report. The Tier 1 approach, however, as pointed out by the IPCC may be inappropriate when combining nonnormal distributions, as may be the case with some of the distributions for emissions factors and activities.

EIA recently 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. Through repeated iterations, points inside the relevant probability density functions for both the activity data and the emissions factors are sampled.

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. The table on pages 17 and 18 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 nonfuel use. For coal, the division is between electricity and other sectors (industrial combined with residential, commercial, and transportation). For natural gas the division is the same as for coal, plus flared gas. Methane and nitrous oxide are divided by source categories. For each source category, bias and random errors are aggregated 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 the electric power sector 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 electricity generators is well known, but for the other sectors (especially residential and commercial) the data are less reliable.

The table on page 18 outlines preliminary results from the Monte Carlo simulations. Monte Carlo simulations were carried out for each greenhouse gas separately, as well as all greenhouse gases as a group. Each column of the table 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 percent) than for methane (-15.6 to 16.0 percent) or nitrous oxide (-53.5 to 54.2 percent).

When 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, which generally assume that emissions are underestimated. Denominating uncertainty as a percentage of estimated 1999 emissions yields the following uncertainty bands: carbon

(continued on page 17)

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[a] Intergovernmental Panel on Climate Change, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (Oxford, UK: Oxford University Press, May 2000), p. 6.12.

[b] 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) (Washington, DC, October 2000).

Analysis of Uncertainty in Greenhouse Gas Emissions (Continued)

Bias and Random Uncertainties Associated with EIA's Reported Greenhouse Gas Inventory Data, 1999

	Activity Data			Emissions Factors		
	Bias (Uniform)			Bias (Uniform)		
Source Category	Minimum[a]	Maximum[b]	Random	Minimum[a]	Maximum[b]	Random
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)	1.0%	7.0%	0.7%	1.0%	1.0%	0.5%
Electric Utility	0.5%	4.0%	0.6%	1.0%	1.0%	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%
Nonfuel 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%
CO_2 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%
Other 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 and Underground Mines	5.0%	10.0%	20.0%	35.0%	25.0%	5.0%
Surface Mines and Post-Mining Emissions	10.0%	10.0%	10.0%	40.0%	100.0%	10.0%
Oil and Gas Systems						
Natural Gas Systems	3.0%	5.0%	3.0%	40.0%	40.0%	5.0%
Petroleum Systems	3.0%	5.0%	3.0%	50.0%	60.0%	5.0%
Combustion						
Residential and Commercial Wood	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary and 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 and Iron	3.0%	5.0%	3.0%	60.0%	60.0%	10.0%

See notes at end of table.

(continued on page 18)

Analysis of Uncertainty in Greenhouse Gas Emissions (Continued)

Bias and Random Uncertainties Associated with EIA's Reported Greenhouse Gas Inventory Data, 1999

Source Category	Activity Data			Emissions Factors		
	Bias (Uniform)		Random	Bias (Uniform)		Random
	Minimum[a]	Maximum[b]		Minimum[a]	Maximum[b]	
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						
Residential and Commercial 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.

R,C,T,I = residential, commercial, transportation, and industrial. GHG = greenhouse gases.

Source: Energy Information Administration, annual data for 1999.

dioxide, -0.7 to 2.0 percent; methane, -2.8 to 33.7 percent; and nitrous oxide, -35.1 to 115.3 percent. When the uncertainty bands are expressed as a percentage of total estimated 1999 emissions,[c] the following uncertainty bands are derived: carbon dioxide, -0.6 to 1.7 percent; methane, -0.3 to 3.4 percent; and nitrous oxide, -1.9 to 6.3 percent.

The final column in the table below shows the Monte 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.

Preliminary Results of Tier 2 Monte Carlo Uncertainty Analysis of EIA's Reported Greenhouse Gas Inventory Data, 1999
(Million Metric Tons Carbon Equivalent)

Gas	Carbon Dioxide	Methane	Nitrous Oxide	Total[a]
Estimated 1999 Value[b]	1,526.8	180.7	98.8	1,806.3
Monte Carlo Simulated 1999 Mean[c]	1,536.4	208.2	138.0	1,882.2
5th Percentile	1,515.5	175.6	64.2	1,799.5
95th Percentile	1,556.8	241.5	212.8	1,969.6
Total Uncertainty Around Simulated Mean	41.3	65.9	148.6	170.1
Uncertainty as Percent of Simulated Mean	-1.4% - 1.3%	-15.6% - 16.0%	-53.5% - 54.2%	-4.4% - 4.6%
Uncertainty as Percent of Estimated Value	-0.7% - 2.0%	-2.8% - 33.7%	-35.1% - 115.3%	-0.4% - 9.0%
Uncertainty as Percent of Total Estimated Emissions[d]	-0.6% - 1.7%	-0.3% - 3.4%	-1.9% - 6.3%	-0.4% - 9.0%

[a] Note that, with the exception of estimated 1999 values, columns will not sum to total because each individual column denotes a separate simulation. Monte Carlo simulations were carried out for all the gases separately and as a group.

[b] Estimated 1999 emissions from Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).

[c] 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* (Washington, DC, May 2001).

[d] Expressed as a percentage of total carbon dioxide, methane, and nitrous oxide emissions in 1999. Note that this excludes HFC, PFC and SF_6 emissions, which were not included in the uncertainty analysis.

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[c] 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) (Washington, DC, October 2000).

2. Carbon Dioxide Emissions

Overview

U.S. Anthropogenic Carbon Dioxide Emissions, 1990-2000

	Carbon Dioxide	Carbon Equivalent
Estimated 2000 Emissions (Million Metric Tons)	5,806.1	1,583.3
Change Compared to 1999 (Million Metric Tons)	174.8	47.7
Change from 1999 *(Percent)*	*3.1%*	*3.1%*
Change Compared to 1990 (Million Metric Tons)	836.2	228.0
Change from 1990 *(Percent)*	*16.8%*	*16.8%*
Average Annual Increase, 1990-2000 *(Percent)*	*1.6%*	*1.6%*

Total emissions of carbon dioxide in the United States and its territories were 1,583.3 million metric tons carbon equivalent in 2000—47.7 million metric tons carbon equivalent (3.1 percent) more than the 1999 total (Table 4). The increase in emissions from 1999 to 2000 was the highest since 1996, when demand for heating fuels related to abnormally cold weather resulted in a 3.4-percent increase from the 1995 level. The large growth in carbon dioxide emissions in 2000 can be attributed to a return to more normal weather, a reduction in hydroelectric power generation (which was replaced with generation from fossil fuels), and strong economic growth. The average annual growth in emissions since 1990 has been about 1.6 percent (Figure 1).

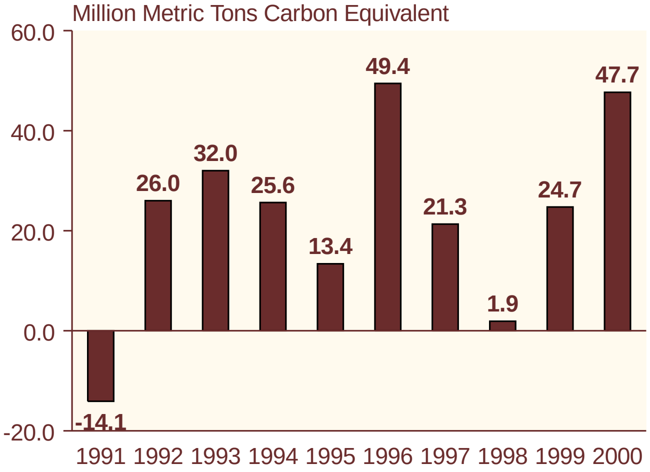
In the United States, most carbon dioxide (98 percent) is emitted as the result of the combustion of fossil fuels; consequently, carbon dioxide emissions and energy use are highly correlated. Historically, economic growth, the weather, the carbon and energy intensity of the economy, and movements in energy prices have caused year-to-year fluctuations in energy consumption and resulting carbon dioxide emissions. After several years of warmer-than-normal winters, the winter weather in 2000 was close to normal, and energy consumption for heating was an important factor in the increase from the 1999 level of carbon dioxide emissions.

The increased use of heating fuels can be seen in the residential and commercial sectors, where energy consumption is dominated by electricity use for air conditioning and fuel use for winter heating. Emissions for these sectors combined increased by 5.3 percent (Table 5). In the residential sector, emissions of carbon dioxide rose by 4.9 percent (from 298.8 million metric tons carbon equivalent in 1999 to 313.4 million metric tons carbon equivalent in 2000), while commercial sector emissions increased by 5.8 percent (from 253.1 million metric tons carbon equivalent in 1999 to 267.8 million metric tons carbon equivalent in 2000).

Industrial energy consumption, particularly in the manufacturing subsector, is much less affected by the weather and more strongly affected by economic fluctuations than are the buildings sectors (i.e., residences and commercial establishments). In 2000, however, energy-related carbon dioxide emissions from the industrial sector were essentially unchanged from 1999, at 465.7 million metric tons carbon equivalent.

In 2000, the six energy-intensive industry groups appeared to be still recovering from downturns in their 1997 growth rates. Their 2000 annual growth rates were lower than those for the overall economy (4.1 percent), the industrial sector (5.6 percent), and the manufacturing component of industrial production (6.1 percent). For the six energy-intensive industries, 2000 growth rates were 2.5 percent (primary metals), 1.8 percent (chemicals), -0.9 percent (paper), 2.3 percent (stone, clay

Figure 1. Annual Change in U.S. Carbon Dioxide Emissions, 1990-2000



Source: Estimates presented in this chapter.

and glass), 1.6 percent (petroleum products), and 1.9 percent (food). The industries that grew rapidly in 2000 were primarily those with lower energy intensities, including computer equipment, which grew by 43 percent, and semiconductors and related components, which grew by 76 percent.[45]

In this year's report, for the first time, energy-related carbon dioxide emissions for the industrial sector do not include emissions from nonutility power producers, including cogenerators. Removing nonutility power production from the industrial sector gives a more clearly defined split between industrial carbon dioxide emissions and those from the electric power sector. When emissions from this rapidly growing source are subtracted from the total for the industrial sector, the reported growth in industrial-sector emissions is lower than it would be if emissions from nonutility power producers were included. See the box below and Appendix A for a discussion of the methodology employed.

Method Used for Reallocation of Nonutility Power Producers' Emissions to Energy End-Use Sectors

For this report a methodology was developed that not only estimates emissions for the electric power sector (as was done last year) but also reallocates the nonutility power producer portion of those emissions to the end-use sectors based on their shares of total electricity sales and removes the appropriate portion from industrial sector emissions (which was not done last year). This means that, going back to 1990, emissions reported for the industrial sector are lower, and emissions reported for the other end-use sectors are higher, than those in previous editions of this report (see Appendix A for further details on the new methodology). There is little change in the emissions reported for the transportation sector, where only a small amount of electricity is used.

The reallocation process has four steps:

Step One: *Estimate and separate the electrical energy component from the thermal energy component of the fuel consumed by nonutility power producers (NUPPs).* For recent years (1999 and 2000), EIA has separated the thermal and electrical components of NUPP energy consumption data. As a result, it is possible to derive a heat rate (the amount of input energy used per kilowatthour of electricity produced) by comparing the amount of energy consumed with the amount of electricity generated. Using this heat rate as a proxy for heat rates previous to 1999, the thermal energy component of NUPP energy use is separated from the energy used to generate electricity by multiplying kilowatthours of NUPP generation (a number that is available for all years from 1989 to the present) by the proxy heat rate.

Step Two: *Subtract the energy value of the fuel used by NUPPs for electricity generation from total fuel use in the industrial sector.* The value calculated for the electrical energy component of industrial energy consumption by fuel is subtracted from industrial sector fuel use, leaving only the energy that is consumed directly in the industrial sector for process heat and other applications not related to electricity generation.

Step Three: *Apply the appropriate emissions factors to the energy values of the fuels reallocated from the industrial sector to the electric power sector.* When the energy value of the fossil fuel used to generate electricity has been reallocated from the industrial sector to the electric power sector, the emissions associated with that energy consumption can be estimated. The reallocated amounts of energy are multiplied times the appropriate emissions factors for the electric power sector. Because fuel-specific emissions factors for the electric power sector may vary from those for the industrial sector, this part of the reallocation can cause small changes in the estimates of total emissions, in the range of 0.1 to 0.2 million metric tons carbon equivalent out of total energy-related emissions of more than 1,500 million metric tons carbon equivalent in recent years.

Step Four: *Combine all the electricity-related emissions and share them out to the end-use sectors for the estimation of total emissions by sector.* To complete the process, the total emissions for the electric power sector—including electric utilities, NUPPs, and the electricity component of industrial cogenerators—are shared out to the four end-use sectors (residential, commercial, industrial, and transportation) according to each sector's share of total electricity sales. It is assumed that all NUPP direct sales to end users are to other large industrial entities, because no data are available to indicate how much of that electricity may be going to large commercial customers.

[45] All industrial and manufacturing growth rates are taken from U.S. Federal Reserve Board, "G17 Historical Data: Industrial Production and Capacity Utilization." Although the Federal Reserve Board, in calculating indexes, bases its estimates on two main types of source data, output measured in physical units and data on inputs to the production process, it also adjusts its indexes on the basis of technological improvements in factor productivity and outputs. This could be particularly important for indexes related to computers and semiconductors, for which productivity and quality of outputs have improved dramatically over time.

Energy End-Use Sector Sources of U.S. Carbon Dioxide Emissions, 1990-2000

	Million Metric Tons Carbon Equivalent		Percent Change	
Sector	1990	2000	1990-2000	1999-2000
Transportation	431.8	514.8	19.2%	3.1%
Industrial	452.7	465.7	2.9%	0.0%
Commercial	210.3	267.8	27.4%	5.8%
Residential	257.0	313.4	21.9%	4.9%

Note: Electric utility emissions are distributed across sectors.

Industrial sector emissions grew by only 2.9 percent from 1990 to 2000, and were essentially unchanged from 1999 to 2000 (465.8 and and 465.7 million metric tons carbon equivalent, respectively). It is difficult to discern at this point whether industrial emissions are being suppressed by increases in energy efficiency, by changes in industrial processes (such as less coal use in the metals industry), or by the changing mix of production activity in the industrial sector.[46]

Transportation sector energy demand is driven largely by income growth, fuel prices, and fuel economy trends. Propelled by gross domestic product (GDP) growth of 4.1 percent in 2000 and real disposable income growth of 3.3 percent, transportation energy-related carbon dioxide emissions increased by 3.1 percent, from 499.4 million metric tons carbon equivalent in 1999 to 514.8 million metric tons carbon equivalent in 2000.

Net generation of electricity increased by 3.4 percent in 2000, and total carbon dioxide emissions from the electric power sector increased by 4.7 percent (from 612.6 million metric tons carbon equivalent in 1999 to 641.6 million metric tons carbon equivalent in 2000). In this report, the electric power sector includes all generators and cogenerators.

Nonfuel uses of fossil fuels, principally petroleum, sequestered 87.9 million metric tons carbon equivalent in 2000, down by 2.0 million metric tons carbon equivalent (2.3 percent) from 1999. The major fossil fuel products that sequester carbon include liquefied propane 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 7.1 million metric tons carbon equivalent was emitted as carbon dioxide from the burning of the plastic components of municipal solid waste as well as other waste burning.

Emissions of carbon dioxide from non-energy-consuming industrial processes contributed 1.1 million metric tons carbon equivalent to the increase in emissions from 1999 to 2000 (Table 4). Emissions from cement production processes (excluding the energy portion) rose from 10.9 to 11.3 million metric tons carbon equivalent, while emissions from natural gas flaring rose from 4.0 to 4.5 million metric tons carbon equivalent.

Energy Consumption

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 2000 U.S. carbon dioxide emissions (adjusting for U.S. Territories and bunker fuels), 98 percent, or 1,547.4 million metric tons carbon equivalent, resulted from the combustion of fossil fuels. This figure represents a 3.1-percent increase over 1999 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 is retired only as it begins to break down or becomes obsolete.

The Energy Information Administration (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 from independent power producers and industrial cogenerators are included in the electric power sector estimates along with emissions from integrated electric utilities. EIA is in the process of reclassifying the data in the integrated data reports on fuel consumed for electricity generation in the industrial sector into total fuel consumption for

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[46] Because assumptions made in the reallocation of industrial emissions to electric power generators may change, industrial sector emissions may be adjusted in future estimates.

electricity generation. In the interim, this report provides, below, a preliminary estimate of the entire electric power sector for the 1990 to 2000 time period.[47]

In last year's report, emissions for nonutility power producers were not reallocated from the industrial sector. In this year's report a method was applied to the underlying data that removed the emissions attributable to nonutility power producers from the industrial sector and shared them out to the end-use sectors in proportion to the electricity consumed by those sectors. Although there is a small amount of electricity production in the commercial sector, this adjustment was made only for the industrial sector.

Residential Sector

At 313.4 million metric tons carbon equivalent, residential carbon dioxide emissions represented 20 percent of U.S. energy-related carbon dioxide emissions in 2000. The residential sector's pro-rated share of electric power sector emissions accounts for about two-thirds of that amount (211.5 million metric tons carbon equivalent).[48] Since 1990, residential electricity-related emissions have grown by 2.4 percent annually. In contrast, emissions from the direct combustion of fuels in the residential sector have grown by 1.3 percent annually since 1990.

Total carbon dioxide emissions from the residential sector increased by 4.9 percent in 2000 (Table 6). Year-to-year, residential sector emissions are heavily influenced by weather. For example, in 1996, a relatively cold year, carbon dioxide emissions from the residential sector grew by 5.8 percent over 1995. In 1997, they declined by 0.4 percent due to warmer winter weather.

Since 1990, the growth in carbon dioxide emissions attributable to the residential sector has averaged 2.0 percent per year. As a result, residential sector emissions in 2000 were 56.3 million metric tons carbon equivalent higher than in 1990, representing 27 percent of the total increase in U.S. energy-related carbon dioxide emissions since 1990. Long-term trends in residential carbon dioxide emissions are heavily 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. 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 267.8 million metric tons carbon equivalent, account for about 17 percent of total energy-related carbon dioxide emissions, of which almost three-quarters (202.5 million metric tons carbon equivalent) is the sector's pro-rated share of electricity-related emissions. Although 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 electric consumption increased by 3.1 percent in 2000, while emissions from the direct combustion of fuels (dominated by natural gas, as in the residential sector) increased by 8.8 percent. Overall, carbon dioxide emissions related to commercial sector activity increased by 5.8 percent—from 253.1 to 267.8 million metric tons carbon equivalent—between 1999 and 2000 (Table 7). Since 1990, commercial emissions growth has averaged 2.4 percent per year—the largest growth of any energy-use sector. Commercial sector carbon dioxide emissions have risen by 57.6 million metric tons carbon equivalent since 1990, accounting for 27 percent of the total increase in U.S. energy-related carbon dioxide emissions.

Transportation Sector

Transportation sector emissions, at 514.8 million metric tons carbon equivalent, accounted for one-third of total energy-related carbon dioxide emissions in 2000. Almost all (98 percent) of transportation sector emissions result from the consumption of petroleum products, particularly motor gasoline at 59 percent of total transportation sector emissions; middle distillates (diesel fuel) at 21 percent; jet fuel at 13 percent of the total;

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[47] Note that Table 12.6 of the *Annual Energy Review 2000* includes thermal energy in the data for 1996 and earlier, and some thermal energy for Other Power Producers is included in all years, whereas the numbers in this report do not include thermal energy.

[48] Sectoral (residential, commercial, and industrial) energy-related carbon dioxide emissions are based on 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 nonutility power production that is not sold into the grid are allocated to the industrial sector as either direct use or sales to end users. It is assumed for this estimate that all direct sales of nonutility power production to end users are from one industrial entity to another.

and residual oil (i.e., heavy fuel oil, largely for maritime use) at 4 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 grew by 3.1 percent in 2000, from 499.4 to 514.8 million metric tons carbon equivalent (Table 8). The fuel-use patterns and related emissions sources in the transportation sector are different from those in the other energy-use sectors. By far the largest single source of emissions, motor gasoline, at 301.5 million metric tons carbon equivalent, grew by 0.6 percent. The highest rates of growth were for residual fuel emissions (which grew by 35.9 percent, from 17.0 to 23.1 million metric tons carbon equivalent) and distillate fuel emissions (which grew by 4.6 percent, from 101.9 to 106.6 million metric tons carbon equivalent). Since 1990, carbon dioxide emissions related to the transportation sector have grown at an average annual rate of 1.8 percent. The growth since 1990 has meant that transportation emissions have increased by a total of 83.1 million metric tons carbon equivalent, representing 39.5 percent of the growth in energy-related carbon dioxide emissions from all sectors. Transportation sector emissions have grown almost as rapidly as commercial sector emissions, but from a larger base. Transportation is the largest contributing sector to total emissions.

Industrial Sector

Industrial sector emissions, at 465.7 million metric tons carbon equivalent, accounted for about 30 percent of total U.S. energy-related carbon dioxide emissions in 2000. In terms of fuel shares, electricity consumption was responsible for 48.7 percent of total industrial sector emissions (226.7 million metric tons carbon equivalent), natural gas for 22.3 percent (104.0 million metric tons carbon equivalent), petroleum for 18.8 percent (87.6 million metric tons carbon equivalent), and coal for 9.8 percent (45.7 million metric tons carbon equivalent).

Estimated carbon dioxide emissions related to energy consumption in the industrial sector were 465.7 million metric tons carbon equivalent (Table 9) in 2000, compared with 465.8 million metric tons carbon equivalent in 1999. For this year's calculation, the energy allocated to nonutility power producers has been reallocated from the industrial sector total to the end-use sectors for which the electricity is generated.[49] When these emissions are reallocated, growth in carbon dioxide emissions attributable to industrial sector energy consumption has averaged 0.3 percent per year since 1990. Because of this low growth rate, total energy-related industrial emissions in 2000 were only 2.9 percent (13.1 million metric tons carbon equivalent) higher than in 1990, despite a much larger economy. The increase in industrial sector emissions from 1990 to 2000 represents 6.2 percent of the total growth in U.S. energy-related carbon dioxide emissions over the same period.

A contributing factor to the low growth 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 28.9 million short tons in 2000. Additionally, other industrial coal consumption has declined from 76.3 million short tons in 1990 to 65.1 million short tons in 2000. When the increase in coal for electricity generation in the industrial sector is accounted for, the remaining industrial coal consumption for thermal energy production is reduced even further. Nonutility power producers consumed 131.6 million short tons of coal in 2000, compared with 32.3 million short tons in 1990.

Electric Power Sector

Electric Power Sector Carbon Dioxide Emissions by Fuel Input, 1990-2000

	Million Metric Tons Carbon Equivalent		*Percent Change*	
Fuel	1990	2000	1990-2000	1999-2000
Petroleum	28.2	26.0	*-7.9%*	*-11.6%*
Natural Gas	58.3	93.2	*59.9%*	*10.2%*
Coal	420.4	522.4	*24.3%*	*4.8%*
Total	507.0	641.6	*26.5%*	*4.7%*

In last year's report, *Emissions of Greenhouse Gases in the United States 1999*, Table 10 (U.S. Carbon Dioxide Emissions from Electricity Generation, 1990-1999) showed estimates of carbon dioxide emissions for both electric utilities and nonutility power producers (NUPPs), including cogenerators. This was a "standalone" table, in that the emissions estimates shown were not integrated with the rest of the report, where all fuel inputs to NUPPs were counted in the industrial sector—with

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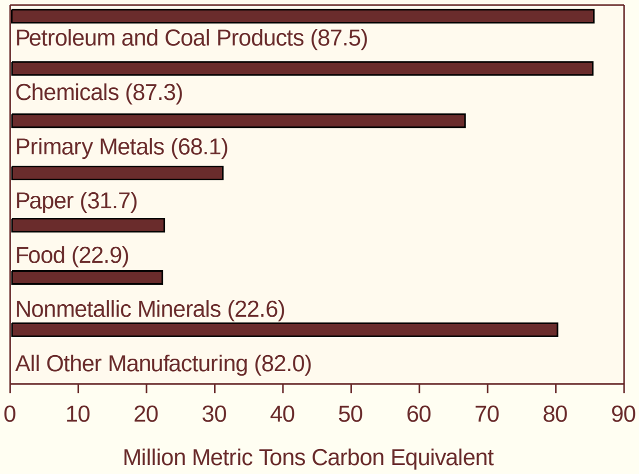
[49] Because this report is the first time that energy consumption (and related emissions) from nonutility power producers and cogenerators has been subtracted from the industrial sector total, the estimates should be viewed as preliminary. It is possible that some of the assumptions made in order to perform the calculation may be reconsidered for future reports, and that the results may be revised accordingly.

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 figure below shows the latest estimate of energy-related carbon dioxide emissions from the manufacturing subsector, based on energy consumption statistics from EIA's 1998 Manufacturing Energy Consumption Survey (MECS).

Total Energy-Related Carbon Dioxide Emissions for Selected Manufacturing Industries, 1998



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

The carbon intensity of energy use is the amount of carbon emitted per unit of energy used. Both the mix of energy sources and the uses of energy affect carbon intensity. Overall, manufacturing industries had carbon intensities of 17.16 and 16.90 million metric tons per quadrillion Btu in 1994 and 1998, respectively; however, the carbon intensities of the various industries differed markedly.

The petroleum industry and the chemical industry both transform energy sources into products such as petrochemical feedstocks, asphalt, and plastics. Only a part of the carbon content of the energy inputs for such products is emitted into the atmosphere; the remainder is sequestered in the products (see Table A2 in Appendix A). Because both industries use energy for nonfuel purposes, the petroleum and chemical industries have lower carbon intensities than the manufacturing average: 12.91 and 11.95 million metric tons per quadrillion Btu for the petroleum industry in 1994 and 1998, respectively, and 14.69 and 14.40 million metric tons per quadrillion Btu for the chemicals industry.

The paper industry uses wood byproducts extensively, yielding carbon intensities of 11.87 and 11.54 million metric tons per quadrillion Btu in 1994 and 1998, respectively. The 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 relatively high carbon content, such as coal. As a result, the overall carbon intensities for the primary metals industry were 26.19 and 26.62 million metric tons per quadrillion Btu in 1994 and 1998, respectively.

The 1994 MECS estimated carbon dioxide emissions from the manufacturing subsector as a whole at 371.7 million metric tons carbon equivalent. The corresponding estimate for 1998 is 402.1 million metric tons carbon equivalent—an increase of 30.4 million metric tons carbon equivalent, or 8.2 percent. Over the same interval, real manufacturing output increased by 20.1 percent.

From 1994 to 1998, carbon dioxide emissions associated with electricity use by manufacturing industries increased by 19.4 million metric tons carbon equivalent (15 percent), and emissions associated with natural gas use increased by 8.5 million metric tons carbon equivalent (9 percent). Electricity use continues to account for the largest share of manufacturers' carbon dioxide emissions—36 percent (131.1 million metric tons carbon equivalent) and 38 percent (150.4 million metric tons carbon equivalent) in 1994 and 1998, respectively. 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).

It should be noted that statistical comparisons of the 1994 and 1998 estimates of carbon dioxide emissions by industry based on MECS data are imperfect, because the 1994 data are categorized by industry under the Standard Industrial Classification (SIC) system, whereas the 1998 data re-categorized under the North American Industry Classification System (NAICS), in accordance with the practice of the U.S. Office of Management and Budget. One relevant example is the reclassification of *Coke Ovens, Not Integrated With Steel Mills*, which was moved from *Primary Metals* (SIC 3312) to *Petroleum and Coal Products* (NAICS 324110). Details on the two classification systems are available on web site www.eia.doe.gov/emeu/mecs/mecs98/naics/naics8.html.

the exception of coal consumed by "Other Power Producers."[50]

The data in Table 10 represent estimates of carbon dioxide emissions for the entire electric power industry. These emissions when taken as a whole account for 41 percent of total U.S. energy-related carbon dioxide emissions. This year's report is the first to show these emissions as an integrated whole, with the estimated emissions from NUPPs reallocated from the industrial sector in Table 9. Appendix A includes a discussion of the method employed for that calculation.

Carbon dioxide emissions from the electric power industry increased by 4.7 percent (29.0 million metric tons carbon equivalent) from 612.6 million metric tons carbon equivalent in 1999 to 641.6 million metric tons carbon equivalent in 2000 (Table 10). Emissions from natural-gas-fired generation increased by 10.2 percent, emissions from coal-fired generation increased by 4.8 percent, and emissions from petroleum-fired generation fell by 11.6 percent. Carbon dioxide emissions from the electric power industry have grown by 26.5 percent since 1990, while total carbon dioxide emissions have grown by 15.5 percent.

Nonfuel Use of Energy Inputs

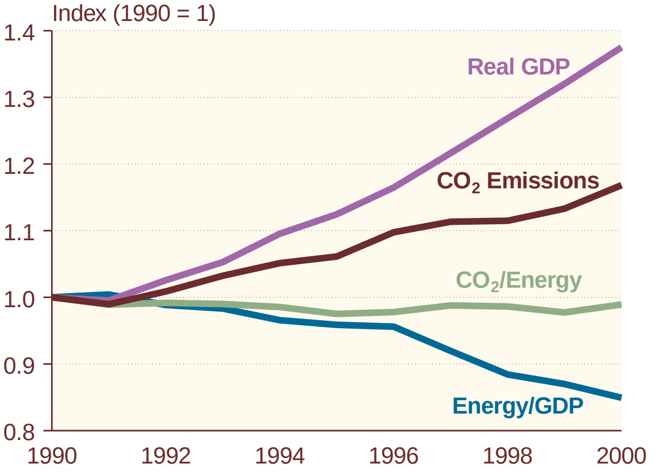
In 2000, 87.9 million metric tons carbon equivalent was sequestered through nonfuel uses of fossil fuels (Table 11). A small amount of this was coal-based (less than 0.5 million metric tons carbon equivalent), about 5.3 million metric tons carbon equivalent was natural-gas-based, and the remainder (82.1 million metric tons carbon equivalent) was petroleum-based. The 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 2000 was 2.3 percent lower than in 1999, when 89.9 million metric tons carbon equivalent was sequestered. Since 1990 sequestration of carbon in this manner has increased by 19.1 million metric tons carbon equivalent or 27.8 percent. This translates to an annual average growth rate of 2.1 percent.

Carbon Dioxide Emissions and Economic Growth

The United States experienced a prosperous period between 1990 and 2000, with economic growth that averaged 3.2 percent per year, despite a recession early in the decade. Energy-related carbon dioxide emissions, however, grew by an average of 1.6 percent annually. As shown in Figure 2, U.S. energy intensity (energy consumed per dollar of GDP) fell by an average of 1.6 percent per year from 1990 to 2000. The carbon dioxide intensity of energy use (carbon-equivalent emissions per unit of energy consumed) has remained slightly below the 1990 level, declining by an average of 0.1 percent per year. Thus, it is primarily 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 at about half the GDP growth rate.

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. For example, economic growth in 2000, while robust, occurred for the most part in industries that are less energy-intensive than the traditional basic industries: for example, computer equipment manufacturing grew by 43 percent, and the manufacture of semiconductors and related components grew by 76 percent in 2000. This growth in the so-called "new economy" means that less energy is used and less carbon dioxide is emitted per dollar of

Figure 2. Growth in U.S. Carbon Dioxide Emissions and GDP, Energy Intensity of GDP, and Carbon Dioxide Intensity of Energy Use, 1990-2000



Sources: Energy Information Administration, *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, July 2001), Tables 1.1 and E1; and estimates presented in this chapter.

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[50] The terms "nonutility generators" (NUGs) and "nonutility power producers" (NUPPs) are synonymous. Independent power producers (IPPs) are NUPPs engaged only in the generation of electricity. Cogenerators, also classified as NUPPs, are further divided into conventional cogenerators, which produce industrial process heat for their own use and produce electricity as a co-product or byproduct, and cogenerators that produce both heat and electricity but sell both to other parties. These are also called "Other Power Producers." Currently the coal inputs for both the heat and electricity generation of Other Power Producers are counted as inputs to the electric power sector in EIA's integrated data.

GDP. The production of computer software takes little additional energy as compared to an industrial process such as steelmaking.

As long as U.S. economic growth continues to be led by industries that use relatively little energy per unit of output, it will have little *direct* effect on energy consumption and related carbon dioxide emissions. Economic growth of this kind does, however, have an *indirect* effect on emissions as 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.

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 emission 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 2000, total carbon dioxide emissions from the U.S. Territories are estimated at 13.6 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 that consume fuel originally purchased in the United States are subtracted from the total, because they are also considered international bunker fuels under this definition.

For 1999, the most recent year for which data are available, the carbon dioxide emissions estimate for bunker fuels is 2.7 million metric tons carbon equivalent.[51] In 2000, approximately 27.8 million metric tons carbon equivalent was emitted in total from international bunker fuels (25.1 million metric tons carbon equivalent) and military bunker fuels (assuming the latter was close to the 1999 estimate). This 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:

- Flared natural gas, 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 is a carbon dioxide emissions rather than a methane emission. In 2000, about 4.5 million metric tons carbon equivalent was emitted in this way (Table 4).

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[51] Military bunker fuels decreased steadily from 1990 (4.9 million metric tons carbon equivalent) to 1994 and appear to have stabilized at the 1994 level of 2.5 ± 0.2 million metric tons carbon equivalent.

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 2000 (Table 4). Appendix D contains 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 (19.38 million metric tons carbon equivalent) of total U.S. carbon dioxide emissions in 2000 (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 2000 were 3.02 million metric tons carbon equivalent (18.5 percent) higher than in 1990 and 0.52 million metric tons carbon equivalent (2.8 percent) higher than in 1999 (Table 12). Fifty-eight 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 2000, the United States manufactured an estimated 90.60 million metric tons of cement, resulting in the direct release of carbon dioxide containing 11.30 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 2.21 million metric tons carbon equivalent (24.3 percent) compared with 1990 and an increase of about 0.37 million metric tons carbon equivalent (3.4 percent) compared with 1999.

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 8.08 million metric tons carbon equivalent was released in emissions from these other industrial process sources in 2000.

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 7.09 million metric tons carbon equivalent, as calculated by the U.S. EPA, with the most recent estimate being for 1999. The 1999 value has been used as an estimate for 2000.

Table 4. U.S. Carbon Dioxide Emissions from Energy and Industry, 1990-2000
(Million Metric Tons Carbon Equivalent)

Fuel Type or Process	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Energy Consumption											
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
Geothermal	0.1	0.1	0.1	0.1	*	*	*	*	*	*	*
Energy Subtotal	**1,351.6**	**1,336.2**	**1,359.0**	**1,385.1**	**1,409.0**	**1,421.1**	**1,471.7**	**1,493.4**	**1,495.4**	**1,517.2**	**1,561.7**
Adjustments to Energy											
U.S. Territories (+)	8.4	9.7	9.7	10.8	10.9	11.4	10.0	10.9	12.3	12.8	13.6
Military Bunker Fuels (-)	4.9	3.6	3.3	3.0	2.6	2.4	2.5	2.6	2.7	2.7	2.7
International Bunker Fuels (-)	27.3	29.1	26.7	24.2	24.1	25.1	25.4	27.3	28.6	26.6	25.1
Total Energy Adjustments	**-23.8**	**-23.0**	**-20.3**	**-16.4**	**-15.8**	**-16.1**	**-17.9**	**-19.0**	**-19.0**	**-16.4**	**-14.3**
Adjusted Energy Total	**1,327.9**	**1,313.1**	**1,338.7**	**1,368.7**	**1,393.2**	**1,405.0**	**1,453.8**	**1,474.4**	**1,476.4**	**1,500.8**	**1,547.4**
Other Sources											
Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.2	3.9	4.0	4.5
CO_2 in Natural Gas	3.8	4.0	4.2	4.4	4.6	4.6	4.8	4.9	4.9	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
Other Industrial	7.3	7.2	7.2	7.1	7.2	7.6	7.9	8.0	8.1	7.9	8.1
Waste Combustion	4.8	5.3	5.4	5.7	6.0	6.3	6.5	7.0	6.9	7.1	7.1
Total Other Sources	**27.4**	**28.0**	**28.5**	**30.5**	**31.7**	**33.2**	**33.8**	**34.6**	**34.5**	**34.9**	**35.9**
Total	**1,355.3**	**1,341.2**	**1,367.2**	**1,399.2**	**1,424.8**	**1,438.2**	**1,487.7**	**1,509.0**	**1,510.9**	**1,535.7**	**1,583.3**

*Less than 50,000 metric tons carbon equivalent.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000
(Million Metric Tons Carbon Equivalent)

End-Use Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
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

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000
(Million Metric Tons Carbon Equivalent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Petroleum											
Liquefied Petroleum Gas	6.3	6.7	6.6	6.8	6.8	6.9	7.5	7.5	7.4	9.1	9.3
Distillate Fuel	16.5	16.4	17.1	18.0	17.4	17.4	18.4	17.8	15.4	16.0	16.2
Kerosene	1.2	1.4	1.3	1.5	1.3	1.5	1.7	1.8	2.1	2.2	2.0
Petroleum Subtotal	**24.0**	**24.5**	**24.9**	**26.3**	**25.4**	**25.8**	**27.6**	**27.1**	**25.0**	**27.3**	**27.5**
Coal	1.6	1.4	1.5	1.5	1.4	1.4	1.4	1.5	1.1	1.2	1.2
Natural Gas	65.1	67.5	69.4	73.4	71.7	71.8	77.6	73.8	67.2	69.9	73.2
Electricity[a]	166.4	168.2	166.0	177.2	177.3	178.9	187.3	190.4	200.4	200.3	211.5
Total	**257.0**	**261.6**	**261.8**	**278.4**	**275.8**	**277.9**	**293.9**	**292.8**	**293.7**	**298.8**	**313.4**

[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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000
(Million Metric Tons Carbon Equivalent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Petroleum											
Motor Gasoline	2.1	1.6	1.5	0.6	0.5	0.4	0.5	0.8	0.8	0.9	0.9
Liquefied Petroleum Gas	1.1	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.6	1.6
Distillate Fuel	9.6	9.5	9.2	9.2	9.2	9.1	9.4	8.8	8.3	8.2	8.6
Residual Fuel	5.0	4.5	4.1	3.7	3.7	3.1	3.0	2.4	1.9	1.9	2.6
Kerosene	0.2	0.2	0.2	0.3	0.4	0.4	0.4	0.5	0.6	0.5	0.5
Petroleum Subtotal	**18.0**	**17.1**	**16.1**	**14.9**	**14.9**	**14.1**	**14.6**	**13.9**	**13.0**	**13.1**	**14.2**
Coal	2.4	2.2	2.2	2.2	2.1	2.1	2.1	2.2	1.7	1.8	1.8
Natural Gas	38.8	40.4	41.5	42.4	42.9	44.9	46.8	47.7	44.6	45.1	49.3
Electricity[a]	151.0	150.7	150.9	157.7	160.5	163.5	169.5	181.6	191.1	193.1	202.5
Total	**210.3**	**210.4**	**210.8**	**217.2**	**220.4**	**224.6**	**233.1**	**245.4**	**250.4**	**253.1**	**267.8**

[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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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 Transportation Sector Energy Consumption, 1990-2000
(Million Metric Tons Carbon Equivalent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
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
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
Jet Fuel	60.1	58.1	57.6	58.1	60.4	60.0	62.7	63.3	64.2	66.3	68.5
Distillate Fuel	75.7	72.6	75.3	77.3	82.5	85.1	89.7	93.5	96.4	101.9	106.6
Residual Fuel	21.9	22.0	23.0	19.4	19.1	19.7	18.4	15.5	15.2	17.0	23.1
Lubricants	1.8	1.6	1.6	1.6	1.7	1.7	1.6	1.7	1.8	1.8	1.8
Aviation Gasoline	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Petroleum Subtotal	**421.2**	**414.6**	**421.6**	**426.4**	**438.2**	**446.5**	**457.4**	**461.5**	**471.2**	**487.6**	**502.5**
Coal	*	*	*	*	*	*	*	*	*	*	*
Natural Gas	**9.8**	**9.0**	**8.8**	**9.3**	**10.2**	**10.4**	**10.6**	**11.3**	**9.5**	**11.0**	**11.4**
Electricity[a]	**0.7**	**0.7**	**0.7**	**0.7**	**0.9**	**0.8**	**0.8**	**0.8**	**0.9**	**0.9**	**0.9**
Total	**431.8**	**424.2**	**431.1**	**436.4**	**449.3**	**457.8**	**468.9**	**473.6**	**481.5**	**499.4**	**514.8**

*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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 9. U.S. Carbon Dioxide Emissions from Industrial Sector Energy Consumption, 1990-2000
(Million Metric Tons Carbon Equivalent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Petroleum											
Motor Gasoline	3.6	3.7	3.7	3.5	3.7	3.9	3.9	4.1	3.8	2.9	2.9
Liquefied Petroleum Gas	12.0	12.1	12.7	12.1	12.9	12.7	13.7	14.0	13.0	13.7	13.7
Distillate Fuel	23.0	22.2	22.2	21.2	21.3	20.6	21.7	21.8	21.9	20.0	20.8
Residual Fuel	7.5	5.5	6.4	7.4	6.7	4.9	4.9	3.8	2.5	0.1	0.5
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
Kerosene	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.2
Other Petroleum	50.8	47.7	54.3	48.3	50.8	48.1	53.9	54.9	52.6	53.0	47.6
Petroleum Subtotal	**98.9**	**93.1**	**101.2**	**94.4**	**97.5**	**92.3**	**100.1**	**100.8**	**96.2**	**91.8**	**87.6**
Coal	**63.4**	**59.3**	**56.1**	**55.6**	**55.8**	**55.9**	**54.2**	**54.5**	**50.4**	**49.6**	**45.7**
Coal Coke Net Imports	**0.1**	**0.2**	**0.9**	**0.7**	**1.5**	**1.5**	**0.6**	**1.2**	**1.7**	**1.5**	**1.7**
Natural Gas	**101.2**	**101.0**	**102.7**	**105.5**	**106.6**	**111.9**	**116.5**	**115.0**	**106.5**	**104.7**	**104.0**
Electricity[a]	**189.0**	**186.2**	**194.2**	**196.6**	**201.9**	**199.4**	**204.6**	**210.1**	**214.7**	**218.2**	**226.7**
Electricity Sales to Grid (-)	**7.7**	**4.8**	**4.9**	**7.4**	**8.4**	**7.0**	**6.8**	**8.2**	**12.8**	**13.2**	**13.2**
Total	**452.7**	**439.8**	**455.1**	**452.9**	**463.3**	**461.1**	**476.1**	**481.5**	**469.5**	**465.8**	**465.7**

*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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000

(Million Metric Tons Carbon Equivalent)

Generator Type and Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Petroleum											
Heavy Fuel Oil	24.9	23.6	19.3	21.4	19.7	13.3	14.6	16.5	22.9	20.8	17.6
Light Fuel Oil	2.0	1.8	1.7	2.0	2.4	2.3	2.5	2.3	3.1	3.8	3.9
Petroleum Coke	1.3	1.3	1.8	2.2	2.1	2.0	1.9	2.6	3.0	4.8	4.4
Petroleum Subtotal	**28.2**	**26.8**	**22.8**	**25.6**	**24.1**	**17.6**	**18.9**	**21.4**	**29.0**	**29.4**	**26.0**
Coal	420.4	418.8	425.3	441.9	446.3	449.4	474.3	487.9	495.5	498.6	522.4
Natural Gas	58.3	60.3	63.9	64.9	70.2	75.5	68.9	73.7	82.6	84.7	93.2
Geothermal	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**507.0**	**506.0**	**512.0**	**532.4**	**540.7**	**542.5**	**562.1**	**583.1**	**607.2**	**612.6**	**641.6**

P = preliminary data.

Notes: Estimates differ from those contained in Energy Information Administration, *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, July 2001), Table 12.7, because of the removal of the thermal energy component. 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, 1990-2000

(Million Metric Tons Carbon Equivalent)

End Use and Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
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
Distillate Fuel	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	0.5	0.5	0.5	0.5	0.5	0.5
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
Lubricants	1.9	1.7	1.7	1.8	1.8	1.8	1.7	1.8	1.9	2.0	1.9
Other *(Subtotal)*	*19.7*	*19.3*	*20.5*	*22.6*	*23.3*	*23.5*	*24.1*	*25.6*	*27.5*	*28.1*	*26.4*
Pentanes Plus	1.2	0.7	0.9	4.0	3.8	4.4	4.6	4.4	3.9	4.8	4.6
Petrochemical Feed	12.6	12.6	13.4	13.6	14.1	13.6	13.8	15.9	16.1	15.1	15.7
Petroleum Coke	2.6	2.2	3.4	2.3	2.5	2.7	2.9	2.5	4.3	5.2	3.1
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
Coal	0.4	0.4	0.8	0.6	0.5	0.6	0.6	0.5	0.5	0.5	0.5
Natural Gas	4.1	3.9	3.5	3.9	5.0	4.7	4.7	5.0	5.0	5.2	5.3
Transportation											
Lubricants	1.8	1.6	1.6	1.7	1.7	1.7	1.6	1.7	1.8	1.8	1.8
Total	**68.7**	**68.3**	**70.2**	**73.0**	**78.1**	**78.6**	**79.9**	**83.1**	**85.0**	**89.9**	**87.9**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000
(Million Metric Tons Carbon Equivalent)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Cement Manufacture											
Clinker Production	8.90	8.66	8.75	9.25	9.82	9.85	9.91	10.24	10.48	10.69	11.05
Masonry Cement	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	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
Cement Subtotal	**9.09**	**8.85**	**8.94**	**9.46**	**10.04**	**10.07**	**10.13**	**10.47**	**10.72**	**10.93**	**11.30**
Other Industrial											
Limestone Consumption											
Lime Manufacture	3.39	3.36	3.47	3.58	3.73	3.96	4.11	4.22	4.30	4.20	4.30
Iron Smelting	0.47	0.44	0.37	0.31	0.30	0.31	0.30	0.31	0.30	0.29	0.31
Steelmaking	0.08	0.09	0.07	0.13	0.15	0.14	0.11	0.09	0.10	0.07	0.12
Copper Refining	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	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
Flue Gas Desulfurization	0.18	0.19	0.19	0.18	0.19	0.24	0.26	0.28	0.27	0.29	0.29
Dolomite Manufacture	0.13	0.10	0.08	0.07	0.07	0.06	0.09	0.09	0.09	0.04	0.04
Limestone Subtotal	***4.33***	***4.24***	***4.27***	***4.36***	***4.57***	***4.85***	***4.98***	***5.05***	***5.15***	***4.98***	***5.16***
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
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	0.02
Sodium Silicate	0.05	0.05	0.05	0.06	0.06	0.07	0.06	0.07	0.07	0.06	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
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***
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
Aluminum Manufacture	1.62	1.65	1.62	1.48	1.32	1.35	1.43	1.44	1.48	1.51	1.48
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**	**7.93**	**8.08**
Total	**16.36**	**16.02**	**16.14**	**16.58**	**17.23**	**17.72**	**17.99**	**18.49**	**18.84**	**18.86**	**19.38**

*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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000

	Methane	Carbon Equivalent
Estimated 2000 Emissions (Million Metric Tons)	28.2	176.8
Change Compared to 1999 (Million Metric Tons)	*-0.5*	*-3.0*
Change from 1999 *(Percent)*	*-1.6%*	*-1.6%*
Change Compared to 1990 (Million Metric Tons)	-3.5	-21.8
Change from 1990 *(Percent)*	*-11.0%*	*-11.0%*

U.S. anthropogenic methane emissions totaled 28.2 million metric tons in 2000, a decline of about 0.5 million metric tons from 1999 levels (Table 13). The decline is primarily the result of increased methane recovery at U.S. landfills, and to a lesser extent reductions in emissions from coal mining. Methane recovery for energy at U.S. landfills rose from 2.2 to 2.5 million metric tons due to the lingering effects of the expiration of Section 29 of the Windfall Profits Tax Act of 1980. To be eligible for the tax credit included in that section, methane recovery systems at landfills must have been operational by June 30, 1998. The last recovery projects installed by the tax credit deadline continued to ramp up in 2000. Meanwhile, methane recovered and flared at landfills rose from 2.0 million metric tons to 2.4 million metric tons. This increase is likely the result of attempts by landfill owners and operators to comply with the New Source Performance Standards and Emissions Guidelines issued by the U.S. Environmental Protection Agency (EPA). In addition, for the first time in 40 years, U.S. coal production fell for a second consecutive year, as coal imports increased by 37 percent and electric utilities drew down stocks to meet increasing demand.[52]

Estimated U.S. emissions of methane in 2000 were 3.5 million metric tons below the 1990 level, a decrease equivalent to almost 22 million metric tons of carbon, or roughly 1.1 percent of total U.S. anthropogenic greenhouse gas emissions.[53] In addition to a 3.4 million metric ton decrease in methane emissions from landfills since 1990, there has also been a 1.3 million metric ton decrease in methane emissions from coal mines during the same period (Table 13). The 32-percent decline in emissions from coal mining is the result of a threefold increase in methane recovery from coal mines and a shift in production away from gassy mines. Overall, methane emissions account for about 8.5 percent of total U.S. greenhouse gas emissions weighted by global warming potential.

Methane emissions estimates are much more uncertain than carbon dioxide emissions estimates. Methane emissions usually are accidental or incidental to biological processes and may not be metered in any systematic way.[54] Thus, methane emission estimates must often rely on proxy measurements. Considerable effort has been devoted to improving estimation methods. However, with very little additional sample or activity data being gathered, the marginal improvements associated with revised methods are severely limited.

Estimated U.S. anthropogenic methane emissions for 2000 also include preliminary data for several key sources; thus, the overall estimate is preliminary. Emissions from three of these sources—coal mining, natural gas systems, and landfills—represent more than three-fifths of all U.S. methane emissions. Thus, comparisons between 1999 and 2000 numbers are more likely to be valid in the context of directional change rather than magnitude of change. For example, because 2000 data on

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[52] Energy Information Administration, *U.S. Coal Supply and Demand: 2000 Review*, web site www.eia.doe.gov/cneaf/coal/page/special/feature.html.

[53] Using the new estimated global warming potential of 23 for methane. For an expanded discussion of global warming potentials, see Chapter 1.

[54] 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 calculated by multiplying some known activity data, such as coal production or natural gas throughput, 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").

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 coal mines and natural gas systems, such as emissions from coal mine degasification systems and miles of gas transmission and distribution pipeline.

Energy Sources

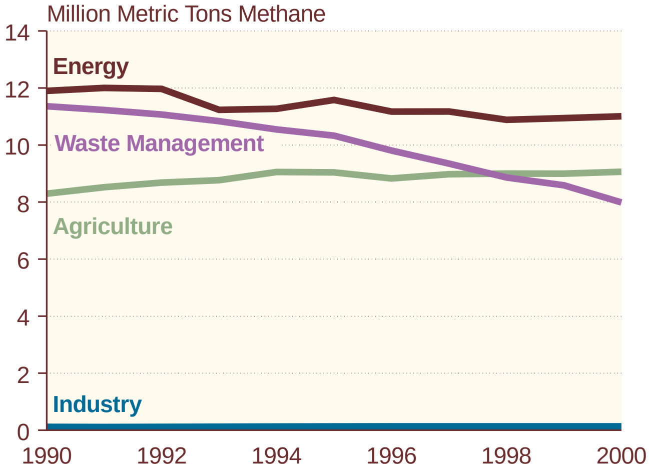
Principal Sources of U.S. Anthropogenic Methane Emissions, 1990-2000

	Million Metric Tons Methane		*Percent Change*	
Source	1990	2000	1990-2000	1999-2000
Energy	11.9	11.0	*-7.5%*	*0.6%*
Waste Management	11.4	8.0	*-29.7%*	*-7.0%*
Agriculture	8.3	9.1	*9.3%*	*0.8%*
Industrial Processes	0.1	0.1	*15.2%*	*1.2%*

U.S. methane emissions from energy sources were estimated at 11.0 million metric tons in 2000, nearly unchanged from 1999 levels and 0.9 million metric tons below 1990 levels (Figure 3). In 2000, an estimated decline of 0.14 million metric tons in emissions from coal mines was offset by a increase of 0.2 million metric tons in emissions from natural gas systems. The drop in methane emissions from energy sources since 1990 can be traced primarily to decreased emissions from coal mines and, to a lesser extent, to lower emissions from petroleum systems and stationary combustion.

Methane emissions from coal mines dropped by 32 percent (1.3 million metric tons) between 1990 and 2000. 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. Between 1990 and 2000, the share of coal production represented by underground mines declined from 41 percent to 35 percent. Methane emissions from petroleum systems dropped from 1.29 million metric tons in 1990 to 1.03 million metric tons in 2000. A decrease of 0.12 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 2000. Together, the declines in emissions from coal mining, petroleum systems and stationary combustion more than compensated for the increase of 0.82 million metric tons in emissions from the natural gas system, attributed to increasing U.S. consumption of natural gas between 1990 and 2000.

Figure 3. U.S. Emissions of Methane by Source, 1990-2000



Source: Estimates presented in this chapter.

Coal Mining

U.S. Methane Emissions from Coal Mining, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	2.9
Change Compared to 1999 (Million Metric Tons Methane)	-0.1
Change from 1999 *(Percent)*	*-4.5%*
Change Compared to 1990 (Million Metric Tons Methane)	-1.3
Change from 1990 *(Percent)*	*-31.5%*

The preliminary estimate of methane emissions from coal mines for 2000 is 2.89 million metric tons (Table 14), a decrease of 4.5 percent from the 1999 level.[55] This decrease can be traced to coal production levels, which fell for a second consecutive year for the first time in 40 years. U.S. coal production dropped from 1.12 billion short tons in 1998 to 1.07 billion short tons in 2000. The

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

decline was due primarily to a 41 million ton drawdown of coal stocks and the use of 12.5 million tons of imported low-sulfur coal to meet stricter environmental regulations.[56]

Between 1990 and 2000, methane emissions from coal mines dropped by 32 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 0.29 million metric tons in 1990 to about 0.83 million metric tons in 2000; (2) methane drainage from degasification in active mines decreased by more than 0.33 million metric tons between 1990 and 2000; and (3) methane emissions from ventilation systems at gassy mines dropped by about 0.46 million metric tons between 1990 and 2000 (Table 14).[57]

Natural Gas Production, Processing, and Distribution

U.S. Methane Emissions from Natural Gas Systems, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	6.4
Change Compared to 1999 (Million Metric Tons Methane)	0.2
Change from 1999 *(Percent)*	*3.2%*
Change Compared to 1990 (Million Metric Tons Methane)	0.8
Change from 1990 *(Percent)*	*14.7%*

At 6.4 million metric tons, 2000 estimated methane emissions from natural gas production, processing, and distribution were up from the revised estimate of 6.2 million metric tons for 1999 (Table 15). The 3.2-percent increase in emissions levels can be traced to a 3.7-percent rise in gross withdrawals of natural gas and a 24-percent jump in withdrawals from storage; however, the 2000 estimate is preliminary, because gas processing and pipeline data for 2000 had not been finalized as of the publication of this report. The estimated 2000 emissions level is 14.7 percent above 1990 levels, with about two-fifths of the increase attributable to increased mileage of distribution pipelines and one-third attributable to increases in gas withdrawals.[58]

Petroleum Systems

U.S. Methane Emissions from Petroleum Systems, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	1.0
Change Compared to 1999 (Million Metric Tons Methane)	*
Change from 1999 *(Percent)*	*-1.0%*
Change Compared to 1990 (Million Metric Tons Methane)	-0.3
Change from 1990 *(Percent)*	*-20.5%*

*Less than 0.05 million metric tons.

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, 91 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. Overall, methane emissions from petroleum systems are estimated at 1.03 million metric tons in 2000, down slightly from 1.04 million metric tons in 1999 and more significantly from 1.29 million metric tons in 1990. Domestic oil production in 2000 was approximately 79 percent of the 1990 level, accounting for the decline in methane emissions from this source.

Stationary Combustion

U.S. methane emissions from stationary combustion in 2000 were 0.44 million metric tons, up by 4.5 percent from the 1999 level but 22 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

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[56] Energy Information Administration, *U.S. Coal Supply and Demand: 2000 Review*, web site www.eia.doe.gov/cneaf/coal/page/special/feature.html.

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

[58] The EPA estimates that the companies participating in the Natural Gas STAR program together avoided more than 575,000 metric tons in 1999 and 729,000 metric tons in 2000. 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 Institue (formerly the Gas Research Institute).

U.S. Methane Emissions from Stationary Combustion, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	0.44
Change Compared to 1999 (Million Metric Tons Methane)	0.02
Change from 1999 *(Percent)*	*4.5%*
Change Compared to 1990 (Million Metric Tons Methane)	-0.12
Change from 1990 *(Percent)*	*-21.9%*

of residential wood combustion are, however, very uncertain (for further details, see Appendix C). The universe of wood consumers is large and heterogeneous, and wood for residential consumption is typically obtained from sources outside the documented economy. EIA relies on its Residential Energy Consumption Survey (RECS) to estimate residential wood consumption. Residential wood consumption data are derived from the 1990, 1994, and 1997 RECS. Intervening and subsequent years are scaled to heating degree-days. For the first time in 4 years, U.S. winter temperatures were near average rather than warmer than normal. As a result, the estimated level of residential wood consumption in 2000 was higher than in previous years, although it was well below the levels seen between 1990 and 1996.

Mobile Combustion

U.S. Methane Emissions from Mobile Combustion, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	0.25
Change Compared to 1999 (Million Metric Tons Methane)	-0.01
Change from 1999 *(Percent)*	*-3.9%*
Change Compared to 1990 (Million Metric Tons Methane)	*
Change from 1990 *(Percent)*	*1.6%*

*Less than 0.05 million metric tons.

Estimated U.S. methane emissions from mobile combustion in 2000 were 0.25 million metric tons, down by 3.9 percent from 1999 levels but 1.6 percent higher than the 1990 level (Table 18). 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. In 2000, emissions from passenger cars and light-duty trucks declined simultaneously, if only incrementally, as overall vehicle miles traveled dropped in both classes for the first time since 1995.

Waste Management

Methane emissions from waste management account for 28 percent of U.S. anthropogenic methane emissions (Figure 3). This portion has been declining from its 1990 level of 36 percent due to a 3.4 million metric ton drop in emissions from landfills. Landfills represent 98 percent of the 8.0 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 are 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 Appendix D).

Landfills

U.S. Methane Emissions from Landfills, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	7.8
Change Compared to 1999 (Million Metric Tons Methane)	-0.6
Change from 1999 *(Percent)*	*-7.2%*
Change Compared to 1990 (Million Metric Tons Methane)	-3.4
Change from 1990 *(Percent)*	*-30.2%*

Despite a record level of municipal solid waste reaching U.S. landfills in 2000 (Figure 4),[59] estimated methane emissions from landfills dropped to 7.82 million metric tons, 7.2 percent below the 1999 level of 8.42 million metric tons and 3.4 million metric tons or 30 percent below 1990 levels (Table 19). This dramatic decrease 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

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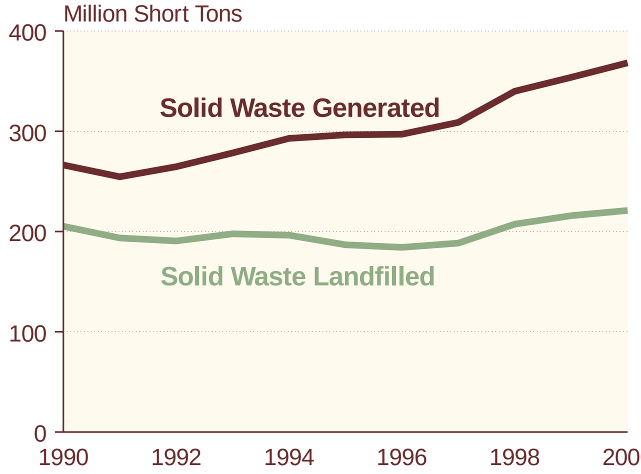
[59] "Nationwide Survey: The State of Garbage in America, 1999," *Biocycle* (April 2000) for years before 2000. Waste generation for 2000 estimated on the basis of annual economic growth.

Figure 4. U.S. Solid Waste Generated and Landfilled, 1990-2000



Source: “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.

estimates of methane recovered and disposed of in both manners are drawn from data collected by the EPA’s Landfill Methane Outreach Program,[60] 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 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 is limited. The energy policy proposed by President George W. Bush and recently passed by the U.S. House of Representatives includes provisions for resurrecting the Section 29 tax credit under Section 45 of the Internal Revenue Code, which currently contains a provision for a tax credit, valued at approximately 1.7 cents per kilowatthour, for electricity generated from wind, closed-loop biomass, or poultry waste. The ultimate outcome of this initiative is uncertain.[61]

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.

Domestic and Commercial Wastewater Treatment

U.S. Methane Emissions from Domestic and Commercial Wastewater Treatment, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	0.17
Change Compared to 1999 (Million Metric Tons Methane)	*
Change from 1999 *(Percent)*	*0.8%*
Change Compared to 1990 (Million Metric Tons Methane)	0.02
Change from 1990 *(Percent)*	*10.2%*

*Less than 0.05 million metric tons.

Methane emissions from domestic and commercial wastewater treatment are a function of the share of organic matter in the wastewater stream and the conditions under which it decomposes. Wastewater may be treated aerobically or anaerobically. 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.

With the U.S. population growing slowly, methane emissions from domestic and commercial wastewater treatment are estimated to have grown by 0.8 percent between 1999 and 2000 to 0.17 million metric tons. This is about 10.2 percent above the 1990 level of 0.15 million metric tons (Table 13). The EPA is conducting research in this area. If additional information becomes available, EIA will review it and revise the estimation method accordingly.

Agricultural Sources

At an estimated 9.1 million metric tons, methane emissions from agricultural activities represent 32 percent of total U.S. anthropogenic methane emissions (Table 13). Ninety-five percent of methane emissions from

[60] See web site www.epa.gov/lmop.
[61] See web site www.swana.org/whypolicy.asp.

agricultural activities result from livestock management. About 65 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. Estimated agricultural methane emissions increased slightly between 1999 and 2000 due mainly to an increase in emissions from enteric fermentation associated with continued growth in average cattle size.

Enteric Fermentation in Domesticated Animals

U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	5.5
Change Compared to 1999 (Million Metric Tons Methane)	0.1
Change from 1999 *(Percent)*	*1.9%*
Change Compared to 1990 (Million Metric Tons Methane)	0.4
Change from 1990 *(Percent)*	*7.3%*

In 2000, estimated methane emissions from enteric fermentation in domesticated animals rose by 1.9 percent to 5.5 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 2000 (with the exception of cattle on feed), average cattle size (excluding calves) reached a 21-year high in 2000. Animal size is a principal determinant of energy intake requirements, which relate directly to methane emissions. Emissions remain 7.3 percent above 1990 levels, principally due to 7.3-percent growth in average cattle size between 1990 and 2000.[62] Meanwhile, cattle populations have fluctuated in a cyclical pattern, settling in 2000 at levels very similar to those seen in 1990.

Solid Waste of Domesticated Animals

U.S. Methane Emissions from Solid Waste of Domesticated Animals, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	3.0
Change Compared to 1999 (Million Metric Tons Methane)	*
Change from 1999 *(Percent)*	*0.7%*
Change Compared to 1990 (Million Metric Tons Methane)	0.4
Change from 1990 *(Percent)*	*13.4%*

*Less than 0.05 million metric tons.

Estimated methane emissions from the solid waste of domesticated animals increased from 3.03 million metric tons in 1999 to 3.05 million metric tons in 2000 (Table 21). This small increase was the result of a small increase in the populations of cattle on feed and dairy cattle in several States, combined with a return of calve sizes to levels not seen since 1997. In the absence of these factors, general decreases in animal populations would have resulted in a small drop in overall methane emissions from the waste of domesticated animals. 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.[63] 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. Estimated 2000 emission levels were approximately 0.36 million metric tons above 1990 levels due to a general increase in the size of cattle over the past decade and a 12-percent increase in the population of market swine.

Rice Cultivation

Estimated methane emissions from U.S. rice cultivation dropped to 0.43 million metric tons in 2000 from 0.49 million metric tons in 1999. This was the first decrease since 1996 and was the result of a 13-percent drop in the number of acres harvested. Arkansas, Mississippi, Louisiana, and Texas all saw substantial drops in acres harvested. Despite these declines, annual emissions remained 6.7 percent above 1990 levels (Table 13).

Burning of Crop Residues

Crop residue burning, being the smallest contributor to agricultural greenhouse gas emissions, represents on the order of 0.2 percent of total U.S. methane emissions. Estimated 2000 methane emissions from the burning of crop residues were 0.05 million metric tons, up by 3.5 percent from 1999 levels and 11 percent above 1990 levels (Table 13). The small increase is attributable mainly

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

[63] 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/globalwarming/publications/emissions/us2001/index.html.

to rising corn, soybean, and potato production. This estimate reflects a small modification to the estimation method. Dry matter content, carbon content, combustion efficiency, and methane conversion rates have been revised, and rice combustion rates have been annualized to reflect new EPA data.[64]

Industrial Sources

U.S. Methane Emissions from Industrial Sources, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Methane)	0.14
Change Compared to 1999 (Million Metric Tons Methane)	*
Change from 1999 *(Percent)*	*1.2%*
Change Compared to 1990 (Million Metric Tons Methane)	0.02
Change from 1990 *(Percent)*	*15.2%*

*Less than 0.05 million metric tons.

Chemical Production

The preliminary estimate of methane emissions from U.S. chemical production in 2000 is 0.080 million metric tons, 0.024 million metric tons higher than in 1990 (Table 22). The 2000 number remains preliminary pending updated production data for five chemicals: methanol, carbon black, ethylene, ethylene dichloride, and styrene. Methane emissions from chemical production grew between 1998 and 1999, and a continued robust economy in 2000 suggests potential additional emissions growth from this source.

Iron and Steel Production

With production of pig iron and coke recovering some of production that was lost in 1999, estimated methane emissions from iron and steel production rose by 3.1 percent to 0.55 million metric tons in 2000, despite continued declines in sinter production. Emissions remained 10.5 percent below the 1990 level of 0.062 million metric tons (Table 22). A general pattern of reduced iron and steel production has resulted in flat or declining methane emissions from this source over the past decade.

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[64] 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. 5-24, web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

Table 13. U.S. Methane Emissions from Anthropogenic Sources, 1990-2000

(Million Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Energy Sources											
Coal Mining	4.22	4.08	3.99	3.41	3.47	3.63	3.24	3.24	3.20	3.03	2.89
Natural Gas Systems	5.58	5.80	5.86	5.85	5.86	5.95	5.97	6.12	5.94	6.20	6.40
Petroleum Systems	1.29	1.30	1.26	1.20	1.17	1.16	1.14	1.14	1.10	1.04	1.03
Stationary Combustion	0.56	0.59	0.62	0.54	0.53	0.58	0.58	0.44	0.40	0.42	0.44
Mobile Sources	0.25	0.23	0.24	0.24	0.24	0.25	0.24	0.24	0.24	0.26	0.25
Total Energy Sources	**11.90**	**12.00**	**11.97**	**11.24**	**11.27**	**11.58**	**11.17**	**11.18**	**10.88**	**10.94**	**11.01**
Waste Management											
Landfills	11.21	11.07	10.91	10.68	10.39	10.17	9.65	9.19	8.70	8.42	7.82
Wastewater Treatment	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.17
Total Waste Management	**11.36**	**11.23**	**11.07**	**10.84**	**10.55**	**10.33**	**9.81**	**9.35**	**8.86**	**8.59**	**7.99**
Agricultural Sources											
Enteric Fermentation	5.16	5.30	5.39	5.46	5.59	5.61	5.46	5.42	5.41	5.43	5.54
Animal Waste	2.69	2.79	2.81	2.87	2.95	2.95	2.92	3.07	3.09	3.03	3.05
Rice Paddies	0.40	0.40	0.44	0.40	0.47	0.44	0.40	0.44	0.46	0.49	0.43
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
Total Agricultural Sources	**8.29**	**8.52**	**8.68**	**8.77**	**9.06**	**9.04**	**8.83**	**8.98**	**9.00**	**9.00**	**9.06**
Industrial Processes	**0.12**	**0.11**	**0.12**	**0.12**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.14**
Total	**31.67**	**31.86**	**31.84**	**30.96**	**31.00**	**31.08**	**29.94**	**29.64**	**28.88**	**28.66**	**28.19**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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/globalwarming/ publications/emissions/index.html.

Table 14. U.S. Methane Emissions from Coal Mining and Post-Mining Activities, 1990-2000

(Million Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Surface Mining											
Mining	0.43	0.42	0.42	0.42	0.45	0.45	0.46	0.47	0.49	0.50	0.50
Post-Mining	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
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	1.66
Ventilation (Nongassy Mines)	0.03	0.03	0.02	0.02	0.03	0.03	0.04	0.04	0.03	0.04	0.04
Degasification	1.26	1.23	1.17	1.05	1.06	1.21	1.02	1.06	1.04	0.92	0.92
Post-Mining	0.64	0.61	0.61	0.53	0.60	0.60	0.62	0.63	0.63	0.59	0.56
Methane Recovery for Energy (-)	0.29	0.29	0.37	0.47	0.56	0.60	0.65	0.80	0.84	0.83	0.83
Net Emissions	**4.22**	**4.08**	**3.99**	**3.41**	**3.47**	**3.63**	**3.24**	**3.24**	**3.20**	**3.03**	**2.89**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1995-1999). Methane recovery rates from U.S. Environmental Protection Agency, Office of Air and Radiation, Climate Protection Partnerships Division, 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, Climate Protection Partnerships Division, Coalbed Methane Outreach Program.

Table 15. U.S. Methane Emissions from Natural Gas Systems, 1990-2000
(Million Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Production	1.47	1.49	1.49	1.51	1.55	1.57	1.58	1.65	1.66	1.65	1.71
Gas Processing	0.65	0.71	0.70	0.71	0.71	0.72	0.73	0.71	0.70	0.71	0.73
Transmission and Storage	2.10	2.21	2.23	2.15	2.11	2.14	2.11	2.20	1.98	2.11	2.24
Distribution	1.36	1.39	1.44	1.48	1.49	1.52	1.55	1.55	1.59	1.72	1.72
Total	**5.58**	**5.80**	**5.86**	**5.85**	**5.86**	**5.95**	**5.97**	**6.12**	**5.94**	**6.20**	**6.40**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, July 2001); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Table 16. U.S. Methane Emissions from Petroleum Systems, 1990-2000
(Million Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Refineries	0.02	0.02	0.02	0.02	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
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
Total	**1.29**	**1.30**	**1.26**	**1.20**	**1.17**	**1.16**	**1.14**	**1.14**	**1.10**	**1.04**	**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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000
(Thousand Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Residential											
Coal	*	*	*	*	*	*	*	*	*	*	*
Distillate Fuel	4	4	4	5	4	4	5	5	4	4	4
Natural Gas	4	4	5	5	5	5	5	5	4	5	5
LPG	*	*	*	*	*	*	1	1	1	1	1
Wood	512	541	569	483	474	526	525	382	341	365	382
Total	**521**	**550**	**578**	**493**	**483**	**535**	**535**	**392**	**350**	**374**	**392**
Commercial											
Coal	1	1	1	1	1	1	1	1	1	1	1
Distillate Fuel	1	1	1	1	1	1	1	*	*	*	*
Natural Gas	3	3	3	3	3	4	4	4	4	4	4
LPG	*	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*	*
Total	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
Industrial											
Coal	7	6	6	6	6	6	6	6	5	5	5
Distillate Fuel	1	1	1	1	1	1	1	1	1	1	1
Natural Gas	11	12	12	13	13	14	14	14	14	14	15
LPG	2	2	3	2	3	3	3	3	3	3	3
Wood	4	3	4	4	4	5	5	5	5	5	5
Total	**26**	**25**	**26**	**27**	**28**	**28**	**29**	**29**	**28**	**29**	**30**
Electric Power											
Coal	10	10	10	10	10	10	11	11	12	12	12
Distillate Fuel	1	1	1	1	1	*	*	*	1	1	*
Natural Gas	*	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*	*
Total	**11**	**11**	**11**	**11**	**11**	**11**	**12**	**12**	**13**	**13**	**13**
Total All Fuels											
Coal	17	17	17	17	17	17	18	18	18	18	18
Distillate Fuel	7	7	7	7	7	7	7	7	6	6	6
Natural Gas	19	20	20	21	21	22	23	23	22	22	24
LPG	3	3	3	3	3	3	4	4	3	4	4
Wood	517	544	573	487	478	530	530	387	346	371	387
Total	**563**	**590**	**620**	**536**	**527**	**580**	**581**	**438**	**395**	**421**	**439**

*Less than 500 metric tons of methane.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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(01/07) (Washington, DC, July 2001), and *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, July 2001).

Table 18. U.S. Methane Emissions from Mobile Sources, 1990-2000
(Thousand Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Motor Vehicles											
Passenger Cars	142	132	131	126	117	109	107	105	105	106	101
Buses	1	1	1	1	1	1	1	1	1	1	1
Motorcycles	4	4	4	4	4	4	4	4	4	4	4
Light-Duty Trucks	63	63	63	75	85	99	92	91	91	108	100
Other Trucks	12	12	12	13	14	14	15	15	16	16	16
Total	**222**	**212**	**212**	**219**	**221**	**228**	**219**	**217**	**217**	**236**	**223**
Other Transport	23	23	24	22	22	23	23	21	22	24	26
Total Transport	**245**	**235**	**235**	**241**	**243**	**250**	**242**	**238**	**239**	**259**	**249**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).

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, and 1994 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, 1990-2000
(Million Metric Tons Methane)

Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Gross Emissions from Landfills	12.2	12.4	12.5	12.5	12.6	12.6	12.6	12.6	12.6	12.6	12.7
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
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
Net Emissions	**11.2**	**11.1**	**10.9**	**10.7**	**10.4**	**10.2**	**9.6**	**9.2**	**8.7**	**8.4**	**7.8**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).

Sources: Municipal solid waste landfilled from "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. 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, Climate Protection Partnerships Division, 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	P2000
Cattle.	4.87	5.01	5.10	5.18	5.31	5.35	5.20	5.16	5.15	5.19	5.30
Sheep	0.15	0.15	0.14	0.13	0.13	0.12	0.11	0.10	0.10	0.09	0.09
Pigs.	0.08	0.09	0.09	0.09	0.09	0.09	0.08	0.09	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
Horses.	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05
Total	**5.16**	**5.30**	**5.39**	**5.46**	**5.59**	**5.61**	**5.46**	**5.42**	**5.41**	**5.43**	**5.54**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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/globalwarming/publications/emissions/us2000/index.html; and P.J. Crutzen, I. Aselmann, and W.S. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," *Tellus*, Vol. 38B (1986), pp. 271-284.

Table 21. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1990-2000

(Thousand Metric Tons Methane)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Cattle											
Beef Cattle	249	264	271	278	284	286	275	275	273	275	280
Dairy Cattle	917	923	927	964	1,011	1,045	1,073	1,105	1,112	1,119	1,137
Swine											
Market Swine	861	912	924	919	954	931	896	981	1,005	961	960
Breeding Swine.	487	515	506	510	498	482	468	495	476	445	446
Poultry											
Caged Layers	83	84	86	88	90	91	92	94	97	100	96
Broilers	73	77	81	91	95	100	102	105	106	110	111
Other Animals											
Sheep	5	5	5	5	4	4	4	4	3	3	3
Goats	1	1	1	1	1	1	1	1	1	1	1
Horses.	12	11	11	11	12	12	13	13	13	14	14
Total	**2,688**	**2,792**	**2,812**	**2,867**	**2,949**	**2,951**	**2,923**	**3,071**	**3,086**	**3,026**	**3,048**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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/globalwarming/publications/emissions/ us2000/index.html.

Table 22. U.S. Methane Emissions from Industrial Processes, 1990-2000
(Thousand Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Chemical Production											
Ethylene	17	18	19	19	20	21	22	23	23	25	25
Ethylene Dichloride	3	2	3	3	3	3	3	4	4	4	4
Styrene	15	15	16	18	20	21	22	21	21	22	22
Methanol	8	8	7	10	10	10	11	12	11	11	11
Carbon Black	14	13	15	16	16	17	17	17	18	18	18
Total	**56**	**57**	**60**	**66**	**70**	**72**	**75**	**77**	**77**	**80**	**80**
Iron and Steel Production											
Coke[a]	11	9	9	9	8	9	8	7	7	6	7
Sinter	6	5	6	6	6	6	6	6	5	6	5
Pig Iron	45	40	43	43	44	46	44	45	43	42	43
Total	**62**	**54**	**57**	**58**	**59**	**61**	**59**	**58**	**56**	**54**	**55**
Total Industrial Processes	**117**	**111**	**117**	**124**	**129**	**132**	**134**	**134**	**133**	**133**	**135**

[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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000

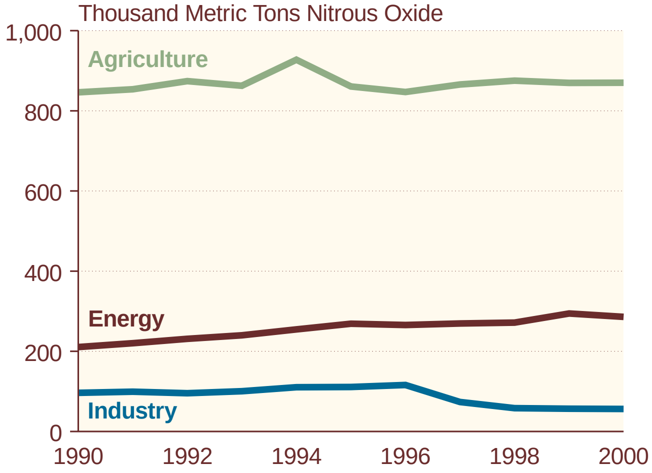
	Nitrous Oxide	Carbon Equivalent
Estimated 2000 Emissions (Thousand Metric Tons)	1,231	99,357
Change Compared to 1999 (Thousand Metric Tons)	-8	-647
Change from 1999 *(Percent)*	*-0.6%*	*-0.6%*
Change Compared to 1990 (Thousand Metric Tons)	62	4,995
Change from 1990 *(Percent)*	*5.3%*	*5.3%*

Estimated U.S. anthropogenic nitrous oxide emissions totaled 1,231 thousand metric tons in 2000, 0.6 percent less than in 1999 and 5.3 percent above 1990 levels (Table 23). Nearly all the increase from 1990 can be attributed to emissions from mobile combustion, which grew by 69 thousand metric tons, between 1990 and 2000, more than offsetting the 40 thousand metric ton decrease from industrial sources (adipic acid and nitric acid production).

The largest component of U.S. anthropogenic nitrous oxide emissions is emissions from agricultural activities. Nitrogen fertilization of agricultural soils represents 73.2 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 870 thousand metric tons in 2000, 0.1 percent above 1999 levels and 2.9 percent above 1990 levels (Figure 5).

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

Figure 5. U.S. Emissions of Nitrous Oxide by Source, 1990-2000



Source: Estimates presented in this chapter.

Principal Sources of U.S. Anthropogenic Nitrous Oxide Emissions, 1990-2000

	Thousand Metric Tons Nitrous Oxide		*Percent Change*	
Source	1990	2000	1990-2000	1999-2000
Energy Use	210	285	*35.8%*	*-2.9%*
Agriculture	846	860	*1.6%*	*-1.1%*
Industrial	96	56	*-41.7%*	*-0.9%*

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 285 thousand metric tons of nitrous oxide in 2000, 2.9 percent lower than in 1999 but 35.8 percent higher than in 1990.

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[65] 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.

Industrial production of adipic acid and nitric acid, which releases nitrous oxide as a byproduct, accounted for emissions of 56 thousand metric tons of nitrous oxide in 2000, a 41.7-percent decrease from 1990 levels and a 0.9-percent decline from 1999 levels (Table 23). 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 Use, 1990-2000

Estimated 2000 Emissions (Thousand Metric Tons Nitrous Oxide)	285
Change Compared to 1999 (Thousand Metric Tons Nitrous Oxide)	-8
Change from 1999 *(Percent)*	*-2.9%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	75
Change from 1990 *(Percent)*	*35.8%*

The energy use category includes nitrous oxide emissions from both mobile and stationary sources as byproducts of fuel combustion. Estimated 2000 energy-related emissions were 285 thousand metric tons, 23.1 percent of total U.S. anthropogenic nitrous oxide emissions (Table 23). Emissions from energy use are dominated by mobile combustion (82.5 percent of nitrous oxide emissions from energy use in 2000).

Mobile Combustion

Nitrous oxide emissions from mobile source combustion in 2000 were 235 thousand metric tons, 3.9 percent below 1999 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 93.9 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, and the gradual replacement of low emitting pre-1983 vehicles in the fleet with higher emitting post-1983 vehicles. The shift to advanced three-way catalytic converters in 1996 through 2000 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

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 are typically low. In 2000, estimated nitrous oxide emissions from stationary combustion sources were 50 thousand metric tons, 2.2 percent higher than in 1999 and 14.7 percent higher than in 1990 (Table 25). More than three-quarters (82.6 percent) of the emissions increase from this source between 1990 and 2000 can be attributed 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. Much of the remainder is attributed to wood combustion in industrial boilers. Coal-fired combustion systems produced 63.6 percent of the 2000 emissions of nitrous oxide from stationary combustion, and the electric power sector accounted for 58.4 percent of all nitrous oxide emissions from stationary combustion sources.

Agriculture

On a global scale, agricultural practices contribute approximately 70.0 percent of anthropogenic nitrous oxide emissions.[66] Similarly, in the United States, agricultural activities were responsible for 70.7 percent of 2000 nitrous oxide emissions. Nitrogen fertilization of agricultural soils accounted for 73.2 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

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[66] 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.

U.S. Nitrous Oxide Emissions from Agriculture, 1990-2000

Estimated 2000 Emissions (Thousand Metric Tons Nitrous Oxide)	870
Change Compared to 1999 (Thousand Metric Tons Nitrous Oxide)	1
Change from 1999 *(Percent)*	*0.1%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	24
Change from 1990 *(Percent)*	*2.9%*

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 2000. Nitrous oxide emissions from agricultural activities grew by 2.9 percent between 1990 and 2000.

Nitrogen Fertilization of Agricultural Soils

Nitrogen uptake and nitrous oxide emissions occur naturally as a result of nitrification and denitrification processes in soil and crops, generally through bacterial action. When nitrogen compounds are added to the soil, bacterial action is stimulated, and emissions generally increase, unless the application precisely matches plant uptake and soil capture.[67] Nitrogen may be added to the soil by synthetic or organic fertilizers, nitrogen-fixing crops, and crop residues. Nitrogen-rich soils, called "histosols," may also stimulate emissions.

Adding excess nitrogen to the soil also enriches ground and surface waters, such as rivers and streams, which generate indirect emissions of nitrous oxide. Additional indirect emissions occur from "atmospheric deposition," in which soils emit other nitrogen compounds that react to form nitrous oxide in the atmosphere. EIA estimates that a total of 637 thousand metric tons of nitrous oxide was released into the atmosphere as a result of direct and indirect emissions associated with fertilization practices in 2000 (Table 26). Estimated emissions increased by 3.5 percent compared with 1990 and increased by 0.2 percent compared with 1999. Nitrous oxide emissions from the application of nitrogen-based fertilizers and biological fixation in crops accounted for 61.2 percent of total nitrous oxide emissions from this source during 2000.

Crop Residue Burning

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). In 2000, estimated emissions of nitrous oxide from crop residue burning were 2 thousand metric tons, up by less than 0.5 thousand metric tons (3.3 percent) from 1999 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.

Solid Waste of Domesticated Animals

Estimated 2000 nitrous oxide emissions from animal waste management were 231 thousand metric tons, down by 0.3 percent from 1999 levels and 0.9 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. Cattle populations grew during the first half of the decade, leading to higher emissions through 1995, but have since declined slowly, lowering emissions to levels that are close to the 1990 level.

Waste Management

Nitrous oxide emissions from waste management are estimated at 19 thousand metric tons for 2000, 1.6 percent of all U.S. anthropogenic nitrous oxide emissions (Table 23). During 2000, emissions from human sewage in wastewater were responsible for 95.7 percent of the estimated emissions from this source, and the remainder was associated with waste combustion. Estimated emissions from waste management grew by 16.7 percent

[67] 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).

U.S. Nitrous Oxide Emissions from Waste Management, 1990-2000

Estimated 2000 Emissions (Thousand Metric Tons Nitrous Oxide)	19
Change Compared to 1999 (Thousand Metric Tons Nitrous Oxide)	*
Change from 1999 *(Percent)*	*1.0%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	3
Change from 1990 *(Percent)*	*16.7%*

*Less than 0.5 thousand metric tons.

between 1990 and 2000 and by 1.0 percent between 1999 and 2000. 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 2000, estimated nitrous oxide emissions from waste combustion were 1 thousand metric tons, 4.1 percent above 1999 levels but 9.8 percent below 1990 levels. While the share of waste burned is estimated to be unchanged between 1999 and 2000, total waste generated increased by 8.4 percent. The total volume of waste generated in the United States increased by 38.3 percent between 1990 and 2000; however, the share of waste burned in 2000 was just 7.5 percent, compared with 11. 5 percent in 1990.[68]

Human Sewage in Wastewater

Nitrous oxide is emitted from wastewater that contains nitrogen-based organic materials, such as those found in human or animal waste. It is produced by two natural processes: nitrification and denitrification. 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),[69] and nitrogen concentration.

In 2000, nitrous oxide emissions from wastewater were 19 thousand metric tons, a 0.8-percent increase from 1999 levels and an 18.3-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 10.1 percent since 1990. U.S. per capita protein intake rose steadily between 1990 and 2000, with a brief respite in 1995 and 1996. Today, U.S. per capita protein intake is 7.4 percent above 1990 levels. Data on protein intake are taken from the United Nations Food and Agriculture Organization (FAO).[70]

Industrial Processes

U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-2000

Estimated 2000 Emissions (Thousand Metric Tons Nitrous Oxide)	56
Change Compared to 1999 (Thousand Metric Tons Nitrous Oxide)	*
Change from 1999 *(Percent)*	*-0.9%*
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	-40
Change from 1990 *(Percent)*	*-41.7%*

*Less than 0.5 thousand metric tons.

Nitrous oxide is emitted as a byproduct of certain chemical production processes. Table 28 provides estimates of emissions from the production of adipic acid and nitric acid, the two principal known sources. Emissions from the combination of these two processes were 56 thousand metric tons in 2000, a decrease of 40 thousand metric tons (41.7 percent) since 1990 and less than 0.5 thousand metric tons (0.9 percent) since 1999.

Adipic Acid Production

Adipic acid is a fine white powder that is used primarily in the manufacture of nylon fibers and plastics, such as carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizer for polyvinyl chloride and polyurethane resins, lubricants, insecticides, and dyes.

In the United States, three companies, which operate a total of four plants, manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid. Nitrous oxide is an intrinsic byproduct of this chemical reaction. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.[71] Between 1990 and 1994,

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

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

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

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

emissions from adipic acid manufacture grew by 17.7 percent reaching 67 thousand metric tons (Table 28). After remaining relatively stable in 1995 and 1996, emissions dropped sharply to 12 thousand metric tons in 1998, and they remained at that level in 1999 and 2000.

Through 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 emissions from the plants.[72] During the first quarter of 1997, a third plant installed emissions controls, increasing the share of adipic acid production employing emissions abatement controls from 74.1 percent in 1996 to 91.6 percent in 1997. With emissions controls in place for the full year, 97.4 percent of emissions from U.S. adipic acid production were controlled in 1998.[73] Estimated emissions of nitrous oxide from uncontrolled adipic acid production decreased from 22 thousand metric tons in 1997 to 7 thousand metric tons in 2000, and 2000 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

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. The 7,981 thousand metric tons of nitric acid manufactured in 2000 resulted in estimated emissions of 44 thousand metric tons of nitrous oxide (Table 28). This estimate was 1.7 percent lower than 1999 levels but 10.9 percent higher than 1990 levels. The emissions factor used to estimate nitrous oxide emissions from the production of nitric acid was based on measurements at a single DuPont plant, which indicated an emissions factor of 2 to 9 grams of nitrous oxide emitted per kilogram of nitric acid manufactured, suggesting an uncertainty of plus or minus 75 percent in the emissions estimate.[74]

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

[73] 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).

[74] 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, 1990-2000
(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Energy Use											
Mobile Sources	166	176	186	195	209	222	217	221	223	245	235
Stationary Combustion	43	43	43	44	45	45	47	48	48	49	50
Total	**210**	**219**	**230**	**239**	**253**	**268**	**264**	**268**	**270**	**293**	**285**
Agriculture											
Nitrogen Fertilization of Soils	616	621	639	624	686	617	607	628	640	636	637
Crop Residue Burning	2	2	2	1	2	2	2	2	2	2	2
Solid Waste of Domesticated Animals	229	231	234	237	239	242	238	236	233	232	231
Total	**846**	**854**	**874**	**862**	**927**	**861**	**847**	**866**	**875**	**870**	**870**
Waste Management											
Waste Combustion	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
Total	**17**	**17**	**17**	**17**	**18**	**18**	**18**	**18**	**18**	**19**	**19**
Industrial Sources	**96**	**99**	**95**	**100**	**110**	**111**	**116**	**74**	**58**	**57**	**56**
Total	**1,169**	**1,189**	**1,217**	**1,219**	**1,309**	**1,257**	**1,245**	**1,226**	**1,222**	**1,239**	**1,231**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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/ globalwarming/publications/emissions/us2001/index.html.

Table 24. U.S. Nitrous Oxide Emissions from Mobile Sources, 1990-2000
(Thousand Metric Tons Nitrous Oxide)

Item	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Motor Vehicles											
Passenger Cars	99	107	115	112	111	108	109	109	110	112	108
Buses	*	*	*	*	*	*	*	*	*	*	*
Motorcycles	*	*	*	*	*	*	*	*	*	*	*
Light-Duty Trucks	49	51	53	64	78	94	88	91	92	111	104
Other Trucks	6	6	6	6	7	7	7	8	8	8	8
Total	**154**	**164**	**174**	**183**	**196**	**210**	**205**	**208**	**210**	**231**	**221**
Other Mobile Sources	**12**	**12**	**12**	**12**	**12**	**12**	**13**	**12**	**13**	**13**	**14**
Total	**166**	**176**	**186**	**195**	**209**	**222**	**217**	**221**	**223**	**245**	**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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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 Sources, 1990-2000

(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Residential											
Coal	*	*	*	*	*	*	*	*	*	*	*
Fuel Oil	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
Commercial											
Coal	*	*	*	*	*	*	*	*	*	*	*
Fuel Oil	1	1	*	*	*	*	*	*	*	*	*
Natural Gas	*	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*	*
Industrial											
Coal	4	4	4	4	4	4	3	3	3	3	3
Fuel Oil	5	5	5	5	5	5	5	6	6	6	6
Natural Gas	1	1	1	1	1	1	1	1	1	1	1
Wood	5	5	5	5	5	6	6	6	6	7	7
Electric Power											
Coal	23	23	23	24	24	24	26	27	27	27	28
Fuel Oil	1	1	1	1	1	*	*	*	1	1	*
Natural Gas	*	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*	*
Fuel Totals											
Coal	27	27	27	28	28	28	29	30	30	31	32
Fuel Oil	7	7	7	7	7	7	7	7	7	8	7
Natural Gas	2	2	2	2	2	2	2	2	2	2	2
Wood	7	7	8	7	8	8	8	8	8	9	9
Total	**43**	**43**	**43**	**44**	**45**	**45**	**47**	**48**	**48**	**49**	**50**

*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 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(2001/08) (Washington, DC, August 2001).

Table 26. U.S. Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils, 1990-2000

(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Direct Emissions											
Nitrogen Fertilizers	179	182	183	193	195	173	159	159	161	161	160
Animal Manure	6	6	6	6	6	6	6	6	6	6	6
Crop Residues	94	91	104	86	112	94	106	114	116	113	116
Soil Mineralization	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	230
Total	**484**	**487**	**504**	**482**	**543**	**490**	**489**	**511**	**522**	**517**	**519**
Indirect Emissions											
Soil Leaching	112	114	115	121	122	109	100	101	101	102	101
Atmospheric Deposition	19	20	20	21	21	19	17	17	17	17	17
Total	**132**	**134**	**135**	**142**	**143**	**128**	**118**	**118**	**119**	**119**	**114**
Total	**616**	**621**	**639**	**624**	**686**	**617**	**607**	**628**	**640**	**636**	**637**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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; 1995-1999, 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, Livestock, Dairy and Poultry 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). 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/globalwarming/publications/emissions/us2001/index.html.

Table 27. U.S. Nitrous Oxide Emissions from Solid Waste of Domesticated Animals, 1990-2000

(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Cattle	215	217	219	223	225	228	224	221	218	218	217
Swine	5	5	5	5	6	5	5	6	6	6	6
Poultry	3	3	3	4	4	4	4	4	4	4	5
Sheep	3	3	3	3	3	3	3	2	2	2	2
Goats	1	1	1	1	1	1	1	1	1	1	1
Horses	1	1	1	1	1	1	1	1	1	1	1
Total	**229**	**231**	**234**	**237**	**239**	**242**	**238**	**236**	**233**	**232**	**231**

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. 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/.

Table 28. U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-2000

(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Adipic Acid											
Controlled Sources	3	4	3	3	4	4	4	5	5	5	5
Uncontrolled Sources	54	56	52	56	63	63	66	22	7	7	7
Adipic Acid Subtotal	**57**	**60**	**55**	**59**	**67**	**67**	**70**	**27**	**12**	**12**	**12**
Nitric Acid.	**40**	**40**	**41**	**41**	**43**	**44**	**46**	**47**	**46**	**45**	**44**
Total Known Industrial Sources. . . .	**96**	**99**	**95**	**100**	**110**	**111**	**116**	**74**	**58**	**57**	**56**

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000). 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, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	46.8
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	2.0
Change from 1999 *(Percent)*	*4.5%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	17.1
Change from 1990 *(Percent)*	*57.8%*

In addition to the three principal gases (carbon dioxide, methane, and nitrous oxide), there are other gases that account for 2.5 percent of U.S. greenhouse gas emissions when weighted by global warming potential (GWP) (see box on page 58). These gases are engineered chemicals that occur on a very limited basis in nature.[75] Although they are more potent greenhouse gases and tend to have comparatively high GWPs, they are emitted in such small quantities that their overall impact is currently small.

The guidelines of the Intergovernmental Panel on Climate Change (IPCC) define three classes of these gases that "count" for emissions estimation: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). This chapter describes emissions sources and gives emissions estimates for HFCs, PFCs, and SF_6.

HFCs, PFCs, and SF_6 are emitted in small quantities, but they have disproportionate effects because of their large GWPs. PFCs and SF_6 have particularly high GWPs because of their scarcity in the atmosphere and long atmospheric lifetimes. SF_6 is the most potent of the greenhouse gases, with a GWP of 22,200. PFCs 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.[76]

Table 29 summarizes U.S. emissions of HFCs, PFCs, and SF_6 from 1990 to 2000, and Table 30 shows the corresponding emissions in million metric tons carbon equivalent. The U.S. Environmental Protection Agency (EPA) estimates total emissions of HFCs, PFCs, and SF_6 in 2000 at 46.8 million metric tons carbon equivalent—a 4.5-percent increase over 1999 emissions and a 57.8-percent increase over 1990 emissions.[77]

In summary, emissions of HFCs and PFCs are rising, and new data for SF_6 show a decline. In the case of HFCs, the rise in emissions reflects the use of HFCs as replacements for CFCs, whose use is being phased out under the Montreal Protocol because they damage the Earth's ozone layer. CFCs had been widely used as refrigerants, aerosol propellants, and foam blowing agents for many years, but with 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 used as interim substitutes for CFCs are also phased out under the provisions of the Copenhagen Amendments to the Montreal Protocol.

Emissions of PFCs and perfluoropolyethers (PFPEs) have also been rising since 1990 (although not as rapidly as HFC emissions), mainly because of the recent commercial introduction of new PFCs and PFPEs both as CFC substitutes and for use in various applications in the semiconductor manufacturing industry. New data for SF_6 show an overall decline in emissions, 41.4 percent since 1990, as opposed to previous years' estimations. The change is the result of lower estimates of emissions from electrical transmissions and distribution.[78]

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

[77] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa/gov/globalwarming/ (preliminary estimates, 2001). 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 (see box on page 58).

[78] 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/globalwarming/publications/emissions/us2001/index.html.

The emissions estimates in Table 29 are taken from data supplied by the EPA's Office of Air and Radiation.[79] The estimates in Table 30 are based on data provided by the EPA's Office of Air and Radiation in units of native gas, which were converted to carbon-equivalent units by EIA, using GWP values from the IPCC's 2001 Third Assessment Report (see box on page 58). The 2000 preliminary estimates are advance estimates developed by the EPA and provided to EIA. They include some relatively minor revisions to the historical emissions estimates for HFCs, based on recent runs of the EPA's Vintaging Model, as well as significant revisions to historical emissions estimates for SF_6 based on new data for SF_6 emissions from electrical equipment (see boxes on page 60 and page 61). The revisions to the historical estimates are reflected in the emissions estimates presented in this chapter.

IPCC Calculates New Global Warming Potentials in 2001

Global warming potentials (GWPs) provide a means of comparing the abilities of different greenhouse gases to trap heat in the atmosphere. The GWP index converts emissions of various gases into a common measure, described as the ratio of the radiative forcing that would result from the emissions of one kilogram of a greenhouse gas to that from emissions of one kilogram of carbon dioxide (CO_2) over a period of time.[a]

In 2001, the Intergovernmental Panel on Climate Change (IPCC) Working Group I released its Third Assessment Report, *Climate Change 2001: The Scientific Basis*. Table 6.7 in the IPCC report gives revised GWPs for a number of the "other gases" included in this chapter.[b] In the table below, the revised GWPs are compared with those published in 1996 in the IPCC's Second Assessment Report, *Climate Change 1995: The Science of Climate Change*.[c]

The 2001 direct GWPs are based on an improved calculation of CO_2 radiative forcing and new values for the radiative forcing and lifetimes of a number of halocarbons.[d] One significant revision, drawn from a 1999 report by the World Meteorological Organization, *Scientific Assessment of Ozone Depletion*, is the radiative efficiency (per kilogram) of CO_2, updated to a value that is 12 percent lower than the IPCC's 1995 estimated value, at 0.01548 Wm^{-2}/ppmv (watts per square meter per part per million by volume).[d] Another significant revision is the updating of several radiative efficiencies (per kilogram), most notably, that of CFC-11. The radiative forcing estimates for halocarbon replacement gases, which are scaled relative to that of CFC-11 when their GWPs are calculated, are also affected by this change.[e]

Comparison of 1996 and 2001 IPCC Values for the Global Warming Potentials (GWPs) of "Other Gases"

Gas	1996 IPCC GWP	2001 IPCC GWP
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

[a] The GWPs shown here are based on a time horizon of 100 years.

[b] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 388-389.

[c] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 121.

[d] *Climate Change 2001*, p. 386.

[e] *Climate Change 2001*, p. 387.

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[79] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

Hydrofluorocarbons (HFCs)

U.S. Emissions of Hydrofluorocarbons, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	28.1
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	2.2
Change from 1999 *(Percent)*	*8.3%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	18.1
Change from 1990 *(Percent)*	*181.4%*

HFCs are compounds containing carbon, hydrogen, and fluorine. They do not destroy ozone. The market for HFCs is expanding as CFCs are being phased out. Since 1990, HFC emissions have accounted for a growing share (almost 70 percent in 2000) of total carbon-equivalent emissions of HFCs, PFCs, and SF_6 combined. The EPA estimates U.S. emissions of all HFCs in 2000 at 28.1 million metric tons carbon equivalent, an 8.3-percent increase from 1999 emissions and a 181.4-percent increase from 1990.[80]

Trifluoromethane (HFC-23)

Although emissions of HFC-23 are relatively small, its high GWP (12,000)[81] gives it a substantial direct effect. HFC-23 is created as a byproduct in the production of HCFC-22 and is generally vented to the atmosphere.

The EPA estimates 2000 HFC-23 emissions at 2,546 metric tons of gas.[82] Annual emissions have fluctuated since 1990, reaching a low point in 1995 at 2,310 metric tons and peaking at 3,432 metric tons in 1998 (Table 29). The estimate for 2000 is 15 percent lower than the estimate of 1990 emissions. Consumption of HCFC-22 continues to grow, although at a slower rate than in past years. It continues to dominate the refrigerant market for stationary refrigeration and air conditioning (including chillers, room air conditioners, and dehumidifiers).[83] In addition, HCFC-22 is manufactured as a feedstock for production of polytetrafluoroethylene (PTFE) and other chemicals. The EPA administers a voluntary program with HCFC-22 producers to reduce HFC-23 emissions, which may help to offset the rising demand for HCFC-22 in the short term. In the long term, domestic production of HCFC-22 for use as a refrigerant will be phased out by 2010 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 will be allowed to continue indefinitely.[84]

1,2,2,2-Tetrafluoroethane (HFC-134a)

HFC-134a, with a GWP of 1,300,[85] has been the industry standard for replacing CFCs in automotive air conditioners since 1994. Emissions in 1990 were estimated at 562 metric tons of gas, but since then they have grown rapidly to 33,669 metric tons in 2000 (Table 29). The 2000 estimate is 10.8 percent higher than that for 1999.

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.[86] 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,[87] 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 been developing. Spurred by rising prices for CFC-12, 5 million cars were retrofitted for HFC-134a use in 1997.[88] 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 rising.[89] Furthermore,

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[80] 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 (see box on page 58).

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

[82] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

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

[84] See web site www.epa.gov/ozone/index.html.

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

[86] 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.

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

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

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

many of the air conditioners in mid-1990s 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 will eventually be about twice the size of the original equipment market.[90] The automotive aftermarket is already responsible for much of the growth in current HFC-134a demand.[91]

HFC-134a is also used in refrigerant blends (e.g. R-404) in most new refrigerators built in the U. S. 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 because most of the HFC-134a used will be emitted to the atmosphere within a short period of time.

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 2001, which includes emissions estimates through 2000, incorporates a number of revisions to the estimates of HFC, PFC, and SF_6 emissions before 1999. 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:

- In 1999, the EPA launched its Voluntary SF_6 Emissions Reduction Partnership to reduce emissions of SF_6 from equipment used to transmit and distribute electricity, such as high voltage circuit breakers, substations, transformers, and transmissions lines. Three new pieces of information were received under the EPA's voluntary program: (1) actual 1999 emissions estimates for electric power systems from participants in the program, (2) analysis of the likely relationship between the emissions estimates provided by the program participants and total emissions from U.S. electric power systems, and (3) information on world sales of SF_6 to electric power systems during the 1990s.[b]
- Estimates of SF_6 emissions from the magnesium industry were also revised on the basis of new information provided by the Voluntary SF_6 Emissions Reduction Partnership, which includes 100 percent of U.S. magnesium primary production and approximately 70 percent of magnesium casting. The U.S. Geological Survey provides U.S. magnesium metal production (primary and secondary) and consumption data for 1993-1999. These revisions and others combined to result in a total decrease in SF_6 emissions of 1,662 metric tons of gas (4.8 percent) from 1990 to 1999.[c]
- The Voluntary Aluminum Industrial Partnership Program and EPA's Global Programs Division provided data to revise the estimation methods for emissions from aluminum production.[d]
- The methodology for estimating emissions from semiconductor manufacturing has been updated to include production data for 1990-1994 and data reported directly by semiconductor manufacturers for other years. The revisions resulted in an average decrease in annual HFC, PFC, and SF_6 emissions from semiconductor manufacturing of 0.1 million metric tons carbon equivalent (5 percent) for 1990-1998.[e]
- 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, in particular related to cleaning solvents, stationary refrigeration, and fire extinguishing equipment. The revisions resulted in an average decrease in annual emissions of HFCs, PFCs and SF_6 from their use as ODS substitutes of 2.1 million metric tons carbon equivalent (19 percent) for 1994-1998.[d]

[a] 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/globalwarming/publications/emissions/us2001/index.html.

[b] E-mail correspondence with U.S. Environmental Protection Agency, Office of Air and Radiation, August 2001.

[c] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, p. 3-30.

[d] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, p. xiv.

[e] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, p. xix.

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

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

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 downward trend, as sales of HFC-134a totaled 14,300 metric tons in 1999.[92]

In January 1999, the major marketers of tire inflaters 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.[93]

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.[94] 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. SRI International predicts that global demand will reach 20 million pounds by 2001; and 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.[95] 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) that is now under a global ban, 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.

1,1-Difluoroethane (HFC-152a)

As a non-ozone-depleting substance with a GWP of 120,[96] HFC-152a is an attractive potential replacement for CFCs. It can be used as a blowing agent, an

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) to estimate actual versus potential emissions of various ODS substitutes, including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). The model estimates the quantities of ODS-containing equipment and products sold each year, 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 they leak 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 Gases and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), Annex I, web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

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[92] Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of Fluorocarbons Through 1999*, web site www.afeas.org/prodsales_download.html.

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

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

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

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

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.[97] 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.[98] The company reported on its 1999 Form EIA-1605 that 1994 HFC-152a emissions peaked at 200 metric tons. By 1998, however, DuPont's reported emissions had dropped to 40 metric tons. The EPA estimates HFC-152a emissions in 2000 at 1,552 metric tons of gas, an increase of 3.5 percent over the 1990 estimate.[99]

Other HFCs

Other hydrofluorocarbons with considerable radiative forcing potential include HFC-125 (C_2HF_5), HFC-143a ($C_2H_3F_3$), HFC-227ea (C_3HF_7), HFC-236fa ($C_3H_2F_6$), and HFC-4310 ($C_5H_2F_{10}$), with 100-year GWPs of 3,400,4,300, 3,500, 9,400, and 1500 respectively.[100] The EPA estimates total emissions of this group of "other HFCs" at 4.4 million metric tons carbon equivalent in 2000, representing 9.5 percent of all emissions of HFCs, PFCs, and SF_6 reported (Table 30).[101] Emissions of these HFCs are small but growing rapidly, as they continue to find applications as substitutes for CFCs. Emissions of "other HFCs" have increased by 10.5 percent since 1999.

HFC-125 is used in the blend R-410A, which is designed to replace HCFC-22 as the refrigerant of choice for stationary refrigeration and air conditioning applications. Some manufacturers have already introduced air conditioners that use R-410A, but as yet the product has captured 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.[102] The EPA estimates emissions of HFC-125 at 236 metric tons of gas in 1992, increasing to 1,561 metric tons in 2000 (Table 29). The estimate for 2000 is 21.1 percent higher than the estimate for 1999.[103]

HFC-143a is a halocarbon used in refrigeration and air conditioning, in blends such as R-404A, R-406A, R-408A, and R-507A. HFC-143a is used as a substitute because it contains neither chlorine or 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 or those in the blend R-502. The EPA estimates 1993 emissions of for HFC-143a at 16 metric tons of gas, increasing to 903 metric tons in 2000. The 2000 estimate is 33.6 percent higher than the estimate for 1999.[104]

HFC-236fa is also used as a refrigerant, in particular by the U.S. Navy for shipboard applications.[105] The EPA estimates 1997 emissions of HFC-236fa at 14 metric tons of gas, increasing to 297 metric tons in 2000. The estimate for 2000 is 39.4 percent higher than the estimate for 1999.[106] Other HFCs and HFC blends are also likely to gain market share as a result of the phaseout, 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.[107]

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).

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

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

[99] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

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

[101] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001). 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 (see box on page 58).

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

[103] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

[104] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

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

[106] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

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

Among the potential replacements, HFC-245fa appears to be the strongest contender.[108]

Honeywell is building a world-scale plant in Louisiana for the production of HFC-245fa which will become fully operational by July 2002. Semi-commercial quantities of the product will be available from the plant in the third quarter of 2000.[109] 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.[110] For some applications, non-fluorochemical alternatives (e.g., hydrocarbons) have been identified.[111]

Perfluorocarbons (PFCs)

U.S. Emissions of Perfluorocarbons, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	8.7
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	-0.34
Change from 1999 *(Percent)*	*-3.7%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	-1.5
Change from 1990 *(Percent)*	*-14.4%*

*Less than 0.05 million metric tons.

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])[112] 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. The EPA estimates 2000 emissions of PFCs at 8.7 million metric tons carbon equivalent, slightly lower than 1999 emissions and 14.4 percent lower than 1990 emissions (Table 30).[113]

The principal quantifiable source of PFCs is as a byproduct of aluminum smelting created by the frequency and duration of anode effects during periods of process inefficiency. The EPA estimates U.S. emissions from aluminum production at 1,096 metric tons of perfluoromethane and 90 metric tons of perfluoroethane in 2000.[114] Reductions in primary aluminum production and efficiency improvements to reduce anode effects have reduced emissions of perfluoromethane and perfluoroethane since 1990 by 55 percent and 64 percent, respectively. Many of the efficiency improvements have been achieved as a result of the EPA's Voluntary Aluminum Partnership, which was launched in 1995. According to the U.S. Geological Survey, strong demand for aluminum in manufacturing passenger cars and light trucks is expected to increase overall consumption;[115] however, domestic aluminum production declined in 2000 due to high energy costs and subsequent smelter production cutbacks.[116]

Another source of PFC emissions is semiconductor manufacturing. Perfluoromethane and perfluoroethane are used as etchants and cleaning agents in semiconductor manufacturing. The United States consumed an estimated 800 tons of perfluoroethane and perfluoromethane in 1995.[117] For 2000, the EPA estimates emissions of perfluoromethane and perfluoroethane from semiconductor manufacturing at 286 metric tons and 431 metric tons of gas, respectively.[118] Both estimates are 4.6 percent lower than the corresponding estimates for 1999 emissions. It is difficult to assess trends in PFC emissions from the semiconductor industry. On the one hand, the continued rapid expansion of the worldwide semiconductor market may lead to increased PFC use and emissions. On the other hand, industry efforts to

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

[109] Honeywell, "Honeywell Set To Commercialize Non-Ozone-Depleting HFC-245fa Blowing Agent Product," News Release (March 27, 2000), web site www.genetron.com / applications / blowingagents / pdfs / blowing_agents_march27_2000.pdf.

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

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

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

[113] 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 (see box on page 58).

[114] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov / globalwarming / (preliminary estimates, October 2001).

[115] 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 / globalwarming / publications / emissions / us2001 / index.html.

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

[117] "PFCs Can Be Recycled with New Technology," American Institute of Chemical Engineers, Press Release (March 12, 1997).

[118] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov / globalwarming / (preliminary estimates, October 2001).

curb emissions may help to offset these market forces to some extent.

A number of semiconductor manufacturing firms have joined an EPA program to reduce PFC emissions voluntarily.[119] In 1999, the World Semiconductor Council, comprising manufacturers from Europe, the United States, Japan, and Korea, voluntarily committed to reduce emissions of PFCs by 10 percent from 1995 levels by 2010. In addition, a number of PFC distributors are developing PFC emissions control equipment.[120] Abatement and other control options are commercially available and substitute chemicals that result in reduced emissions are being adopted.[121]

A variety of other perfluorinated compounds are used in the semiconductor industry, including C_3F_8 (which is manufactured by 3M and has a GWP of 8,600), C_4F_{10} (GWP 8,600), C_6F_{14} (GWP 9,000), NF_3 (manufactured by Air Products), and CHF_3.[122]

Sulfur Hexafluoride (SF_6)

U.S. Emissions of Sulfur Hexafluoride, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	5.5
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	-0.25
Change from 1999 *(Percent)*	*-4.3%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	-3.9
Change from 1990 *(Percent)*	*-41.4%*

Sulfur hexafluoride (SF_6) is used primarily as a dielectric in electrical transmission and distribution systems, specifically as an insulator for circuit breakers, switch gear, and other electrical equipment. In addition, its extremely low atmospheric concentration makes it useful as an atmospheric tracer gas for a variety of experimental purposes. 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. Other sources of SF_6 emissions include fugitive emissions from certain semiconductor manufacturing processes, and the occasional use of SF_6 in experimental and specialized casting operations by the aluminum industry as a cover gas or a fluxing and degassing agent (using an industry-wide estimated 230,000 kilograms of SF_6 per year in the United States and Canada).[123] However, the latter estimate is highly uncertain and so slight that it is not included in models for SF_6 emissions.

SF_6 has a very high GWP of 22,200,[124] but it is not emitted in large quantities. Recent improvements to EPA's estimation methods have changed previous estimates of SF_6 emissions (see box on page 60). Based on new information, mainly from the Voluntary SF_6 Emission Reduction Partnerships for Electric Power Systems and for the Magnesium Industry, the most recent EPA estimates show a steady decrease in U.S. SF_6 emissions, from a peak of 1,672 metric tons of gas in 1993 to 909 metric tons in 2000, representing an overall decrease of 41.4 percent since 1990.[125] While there is a growing demand for magnesium products from U.S. casting companies to meet the requirements of changing automobile designs, no substantial expansion in the U.S. magnesium production industry is expected. Foreign magnesium producers are expected to supply the growing U.S. demand.[126]

Ozone-Depleting Substances and Criteria Pollutants

In previous years, this chapter included emissions estimates and accompanying discussions for a variety of gases that have ambiguous effects on climate, including ozone-depleting substances—chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and bromofluorocarbons (halons). This chapter also covered the criteria pollutants—carbon monoxide (CO), nitrogen oxides (NO_x), and nonmethane volatile organic compounds (NMVOCs)—which have indirect effects on

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[119] "Environmental Protection Drives Emissions Reduction Effort," *Electronic Design* (December 1, 1997).

[120] "EPA Launches PFC Reduction Program," *Chemical Week* (July 31, 1996). Without emissions control efforts, PFC emissions would be expected to rise as the use of PFCs in the semiconductor industry increases.

[121] E-mail correspondence with U.S. Environmental Protection Agency, Global Programs Division, October 18, 2000.

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

[123] 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. 3-23, web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

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

[125] U.S. Environmental Protection Agency, Office of Air and Radiation, web site www.epa.gov/globalwarming/ (preliminary estimates, October 2001).

[126] 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/globalwarming/publications/emissions/us2001/index.html.

climate through their effects on atmospheric concentrations of greenhouse gases. Currently, emissions estimates for those gases are not included in this chapter, because the ozone-depleting substances and criteria pollutants were excluded from the Kyoto Protocol. Furthermore, production of the ozone-depleting gases is being phased out under the Montreal Protocol. Although no longer included in the main body of this report, emissions estimates for ozone-depleting substances and criteria pollutants can be found in Appendix D, “Emissions Sources Excluded.”

Table 29. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2000

(Thousand Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Hydrofluorocarbons											
HFC-23	3.0	2.6	3.0	2.7	2.7	2.3	2.7	2.6	3.4	2.6	2.6
HFC-134a	0.6	0.6	0.6	2.9	6.4	14.4	19.0	23.5	26.9	30.4	33.7
HFC-152a	W	W	W	W	W	W	W	W	W	W	W
HFC-125	*	*	0.2	0.5	0.3	0.5	0.7	0.9	1.1	1.3	1.6
HFC-227ea	W	W	W	W	W	W	W	W	W	W	W
HFC-143a	*	*	*	*	0.1	0.1	0.2	0.3	0.5	0.7	0.9
HFC-4310mee	W	W	W	W	W	W	W	W	W	W	W
HFC-236fa	*	*	*	*	*	*	*	*	0.1	0.2	0.3
Perfluorocarbons											
CF_4	5.1	4.8	4.7	4.6	4.4	4.4	4.5	4.3	4.1	4.1	4.0
C_2F_6	0.7	0.7	0.6	0.7	0.7	0.8	0.7	0.8	0.8	0.8	0.8
C_4F_{10}	*	*	*	*	*	*	*	*	*	*	*
PFCs/PFPEs	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**	**1.4**	**1.4**	**1.1**	**1.0**	**0.9**

*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, October 2001).

Table 30. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2000
(Million Metric Tons Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Hydrofluorocarbons											
HFC-23	9.74	8.61	9.74	8.92	8.83	7.62	8.76	8.48	11.27	8.63	8.48
HFC-134a	0.20	0.20	0.22	1.02	2.26	5.12	6.75	8.34	9.54	10.78	11.94
HFC-125	*	*	0.22	0.45	0.28	0.44	0.63	0.82	1.04	1.20	1.45
HFC-143a	*	*	*	*	0.06	0.13	0.24	0.39	0.57	0.79	1.06
HFC-236fa	*	*	*	*	*	*	*	*	0.31	0.55	0.76
Total	**9.99**	**8.84**	**10.19**	**10.43**	**12.49**	**15.54**	**18.98**	**21.24**	**26.26**	**25.95**	**28.12**
Perfluorocarbons											
CF_4	7.96	7.46	7.23	7.15	6.81	6.87	6.99	6.75	6.37	6.38	6.15
C_2F_6	2.24	2.11	2.06	2.14	2.13	2.47	2.40	2.54	2.61	2.69	2.58
C_4F_{10}	*	*	*	*	*	*	*	*	*	*	*
Total	**10.20**	**9.58**	**9.29**	**9.29**	**8.95**	**9.34**	**9.39**	**9.29**	**8.98**	**9.07**	**8.73**
Other HFCs, PFCs/PFPEs	**0.05**	**0.02**	**0.01**	**0.02**	**1.06**	**2.22**	**2.59**	**3.17**	**3.54**	**4.02**	**4.44**
Sulfur Hexafluoride	**9.41**	**9.73**	**9.14**	**10.13**	**9.42**	**8.31**	**8.36**	**8.19**	**6.93**	**5.76**	**5.51**
Total Emissions	**29.65**	**28.14**	**28.62**	**29.85**	**31.92**	**35.42**	**39.32**	**41.89**	**45.72**	**44.79**	**46.80**

*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, October 2001). 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 (see box on page 58).

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 cleared for agriculture, lumber, or fuel in the hundred years prior to 1920. Since then, much agricultural and pasture land has reverted to forest land.

The amount of carbon being sequestered annually is uncertain, in part because of an absence of data and because of difficulties in measuring sequestration. Moreover, in addition to technical uncertainties, there is also policy or accounting ambiguity about which aspects of the biological carbon cycle ought to 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) include rules to direct the inclusion of carbon sequestration through land use and forestry in national inventories.[127] The U.S. Environmental Protection Agency (EPA), drawing upon the work of U.S. Forest Service researchers Richard Birdsey and Linda Heath, estimates annual U.S. carbon sequestration at 270 million metric tons carbon equivalent (Table 31).[128] Under the IPCC guidelines, this quantity is considered an offset to gross greenhouse gas emissions from other sources, such as the electric power industry. Thus, the 270 million metric tons carbon equivalent sequestered through land use change and forestry practices represents an offset of approximately 17.7 percent of total U.S. anthropogenic carbon dioxide emissions from 1990 through 1999. The total net carbon sequestration resulting from land use and forestry activities declined by approximately 7 percent between 1990 and 1999. The decline resulted in large part from increasing forest harvests and land-use changes, which resulted in lower net sequestration rates for forests.[129]

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, employing methodologies that are consistent with the 1996 IPCC guidelines. Estimates for sequestration in

Table 31. Net Carbon Dioxide Sequestration from U.S. Land Use Change and Forestry, 1990 and 1995-1999
(Million Metric Tons Carbon Equivalent)

Component	1990	1995	1996	1997	1998	1999
Forests	273	256	257	246	245	247
Agricultural Soils	11	19	19	19	21	21
Landfilled Yard Trimmings	5	3	3	3	2	2
Total	**289**	**278**	**279**	**268**	**268**	**270**

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 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html, drawing on the work of Richard Birdsey and Linda Heath of the U.S. Forest Service.

[127] 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.

[128] 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/globalwarming/publications/emissions/us2001/index.html.

[129] 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/globalwarming/publications/emissions/us2001/index.html.

agricultural soil involve mineral and organic soil carbon stock changes 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. Estimates for yard trimming carbon stocks in landfills were derived using the EPA's method of examining life cycle greenhouse gas emissions and sinks associated with solid waste management.[130] The estimates for carbon fluxes from landfilled yard trimmings trend downward over time, based on EPA estimates.

The EPA's carbon flux estimates for forests and agricultural soils are based on surveys of U.S. forest lands and soils carried out at 5-year intervals by the U.S. Forest Service. 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. Further, the most current national forest and soil surveys were completed for the year 1997; thus, carbon flux estimates from forests are based in part on model projections.[131]

Total forestry carbon fluxes have fallen from 289 million metric tons carbon equivalent in 1990 to 270 million metric tons carbon equivalent in 1999. The decrease is due mainly to maturation and slowing in the spread of forest cover, as well as a reduction in landfilled yard trimmings. As can be seen from the estimates, the vast majority of the carbon fluxes are from forests (247 million metric tons carbon equivalent or 91.5 percent of total forestry carbon fluxes), followed by agricultural soils (21 million metric tons carbon equivalent or 7.8 percent of total forestry carbon fluxes) and landfilled yard trimmings (2 million metric tons carbon equivalent or 0.7 percent of total forestry carbon fluxes).

To put these figures into perspective, carbon fluxes from forestry offset 18 percent of energy-related carbon dioxide emissions, which totaled 1,500.8 million metric tons carbon equivalent in 1999. The 270 million metric tons carbon equivalent sequestered through land use and forestry activities in 1999 would also act to offset total U.S. emissions of greenhouse gases by 14.2 percent. If the EPA's estimate of 270 million metric tons carbon equivalent holds for 2000, then sequestration will offset approximately 17 percent of the 1,547.4 million metric tons carbon equivalent emitted through the burning of fossil fuels in 2000.

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 by carbon sequestration as a result of forest regrowth in the Northern Hemisphere.[132] 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.[133]

Forests are multifaceted ecosystems with numerous interrelated components, each of which stores carbon. These components include:

- Trees (living trees, dead trees, roots, stems, branches, and foliage)
- Understory vegetation (shrubs and bushes)
- Forest floor (fine woody debris, tree litter, and humus)
- Down dead wood (logging residue and other dead wood on the ground)
- 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

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[130] 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/globalwarming/publications/emissions/us2001/index.html.

[131] 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/globalwarming/publications/emissions/us2001/index.html.

[132] 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/globalwarming/publications/emissions/us2001/index.html.

[133] 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/globalwarming/publications/emissions/us2001/index.html.

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. For these reasons, the EPA uses the term "apparent flux" for its estimates.[134]

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 conversion of cropland to forests. Forest harvests have also affected carbon sequestration. The majority of the timber harvested 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.[135]

According to the EPA (Table 32), between 1990 and 1999, U.S. forest and harvested wood components accounted for an average annual net sequestration of 247 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 10 percent in the overall rate of annual sequestration. Table 33 details carbon stock estimates for forests and harvested wood. All carbon stocks increased over time and thus sequestered carbon over the periods examined.

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 Land Use, Land Use Change and Forestry (LULUCF) activities in a binding agreement that limits greenhouse gas emissions is of the utmost importance; however, the issues of whether and how terrestrial carbon sequestration could be accepted for meeting various commitments and targets have remained the subjects of complex and difficult international negotiations in regard to the issue of 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

Table 32. Net Carbon Dioxide Sequestration in U.S. Forests, 1990 and 1995-1999
(Million Metric Tons Carbon Equivalent)

Description	1990	1995	1996	1997	1998	1999
Apparent Forest Flux	**216**	**201**	**201**	**188**	**188**	**188**
Trees	113	105	105	106	106	106
Understory	1	1	1	1	1	1
Forest Floor	16	15	15	14	14	14
Forest Soils	69	62	62	50	50	50
Logging Residues	17	17	17	17	17	17
Apparent Harvested Wood Flux	**57**	**55**	**57**	**58**	**56**	**59**
Apparent Wood Product Flux	13	15	15	16	14	17
Apparent Landfilled Wood Flux	44	41	41	42	42	42
Total Net Flux	**273**	**256**	**257**	**246**	**245**	**247**

Notes: "Apparent" indicates that the estimate is a measure of net change in carbon stocks rather than an actual flux to or from the atmosphere. Total flux is an estimate of the actual flux. 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 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

[134] 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/globalwarming/publications/emissions/us2001/index.html.

[135] 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/globalwarming/publications/emissions/us2001/index.html.

accounting rules. According to researchers at the Pew Center on Global Climate Change,[136] 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.

Land Use Data Issues

Uncertainties in the EPA inventory 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, the U.S. Territories, or urban trees (although net carbon fluxes from these stocks are anticipated to be insignificant).[137]

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.[138]

Aside from the land use data issues and uncertainties discussed above, which are specific to the methodologies used for the EPA inventory, 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 period suggested during international climate change negotiations. This concern is especially problematic if the carbon stocks are large and the stock changes

Table 33. Estimates of U.S. Forest Carbon Stocks, 1987, 1992, 1997, and 2000
(Million Metric Tons Carbon Equivalent)

Description	1987	1992	1997	2000
Forests (Excluding Logging Residues)	**36,251**	**37,243**	**38,160**	**38,672**
Trees	12,709	13,273	13,798	14,115
Understory	557	564	571	574
Forest Floor	3,350	3,428	3,504	3,545
Forest Soils	19,635	19,978	20,287	20,438
Logging Residues	NA	NA	NA	NA
Harvested Wood	**1,920**	**2,198**	**2,479**	**2,651**
Wood Products	1,185	1,245	1,319	1,366
Landfilled Wood	735	953	1,159	1,285

NA = not available.

Note: Excludes forest stocks in Alaska, Hawaii, U.S. territories, and urban trees. Wood product stocks include exports and exclude imports. 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 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), web site www.epa.gov/globalwarming/publications/emissions/us2001/index.html.

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[136] 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.

[137] 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/globalwarming/publications/emissions/us2001/index.html.

[138] 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/globalwarming/publications/emissions/us2001/index.html.

are comparatively small.[139] 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.[140]

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.[141]

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.[142] The authors of the study, Dr. John Lichter and Dr. William Schlesinger, concluded that while forests do sequester carbon dioxide from the air and store it in the soil, the majority of the sequestered carbon is ultimately released back into the atmosphere as carbon dioxide when organic soil material decomposes. They maintain that their findings highlight the uncertainty of the role of soils as long-term carbon storage pools and assert that considerable long-term net carbon sequestration in forest soils may be unlikely. 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.[143]

Thus, while there are sound estimates of 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.

Current Global Carbon Sequestration

In August 2000, the U.S. Government submitted its views regarding methodologies related to the handling of LULUCF activities under an international climate change agreement to the UNFCCC. The document, *United States Submission on Land-Use, Land-Use Change and Forestry*, was presented in fulfillment of a request made by the Subsidiary Body for Scientific and Technological Advice (SBSTA). The document includes U.S. estimates of carbon stocks and flux from forest land, cropland, and grazing land. The estimates differ slightly from those in the EPA inventory for two main reasons:

- The SBSTA requested stock and flux estimates for a different set of forest areas and activities than those that are accounted for in national greenhouse gas inventories required under the UNFCCC.
- Both the EPA inventory and the U.S. submission reflect temporary results of forest carbon modeling improvements that are currently underway at the USDA Forest Service.[144]

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[139] 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.

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

[141] 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.

[142] W.H. Schlesinger and J. Lichter, "Limited Carbon Storage in Soil and Litter of Experimental Forest Plots Under Increased Atmospheric CO_2, *Nature*, No. 6836 (2001), pp. 466-468.

[143] M. MacKinnon, "Canada's Stance on Pollution Debunked," *The Globe and Mail* (June 5, 2001).

[144] 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 / globalwarming / publications / emissions / us2001 / index.html.

Further, a separate 2000 report by the IPCC on LULUCF activities provides different values for carbon sequestration. 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 difficulties in measuring sequestration. Further, 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 due to LULUCF activities. According to the IPCC, from 1850 to 1998, combined carbon dioxide emissions resulting from fossil fuel burning, industrial processes, and land-use change led to an increase in the atmospheric content of carbon dioxide of 176±10 billion metric tons carbon equivalent. Atmospheric carbon dioxide concentrations increased from approximately 285 to 366 parts per million. About 43 percent of the carbon dioxide emitted from 1850 to 1998 remains in the atmosphere. The remainder, about 230±60 billion metric tons carbon equivalent, has likely been taken up in approximately equal amounts by oceans and terrestrial ecosystems.[145]

The IPCC's 2000 report offers further estimates for future terrestrial carbon sequestration (although it should be noted that different definitions and accounting approaches would result in different estimates of carbon stock changes). 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. 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.

- 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.

- 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.

The IPCC definitional scenario involves transitions between forest and non-forest land uses and assumes that not only planting but also other forms of stand establishment (e.g., natural establishment) are considered to be afforestation or reforestation activities. The IPCC definitional scenario results in estimated Annex I emissions of 44 to 83 million metric tons carbon equivalent per year.[146]

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[145] 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.

[146] Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 11, web site www.ipcc.ch/pub/srlulucf-e.pdf. For more information on IPCC estimates of current and future carbon sequestration, see Chapter 6 (pages 68-71) in Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).

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www.greenhouse.gov.au

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http://cdiac.esd.ornl.gov

Centre for the Analysis and Dissemination of Demonstrated Energy Technologies.
www.caddet-re.org
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Center for Renerable Energy and Sustainable Technology.
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Union of Concerned Scientists.
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United Nations Development Program.
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United Nations Food and Agriculture Program.
www.fao.org

United Nations Framework Convention on Climate Change.
www.unfccc.de

U.S. Agency for International Development.
www.usaid.gov

U.S. Country Studies Program.
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U.S. Department of Agriculture, Global Change Program Office.
www.usda.gov/oce/gcpo/

U.S. Department of Energy, Environmental Quality.
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U.S. Department of Energy, Climate Challenge Program.
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Related Links

U.S. Energy Information Administration, Greenhouse Gas Emissions and Climate Change Publications.
www.eia.doe.gov/env/ghg.html

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

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

U.S. Global Change Research Office.
http://gcrio.gcrio.org

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U.S. National Aeronautics and Space Administration (NASA), Global Change Master Directory.
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U.S. National Oceanographic and Atmospheric Administration (NOAA), Office of Global Programs.
www.ogp.noaa.gov

U.S. White House, Initiative on Global Climate Change.
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World Resources Institute.
www.wri.org

Worldwatch Institute.
www.worldwatch.org

World Wildlife Fund, Climate Change Campaign.
www.panda.org/climate/

Glossary

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

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

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

Aerosols: Airborne particles.

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

Agglomeration: The clustering of disparate elements.

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

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

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

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

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

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

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

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

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

API Gravity: A scale expressing the density of petroleum products as established by the American Petroleum Institute.

Asphalt: A dark-brown to black cement-like material obtained by petroleum processing, containing bitumens as the predominant constituents. Includes crude asphalt as well as the following finished products: cements, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cutback asphalts.

Associated gas: Natural gas found mixed with crude oil in underground reservoirs, released as a byproduct of oil production.

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: A measurement of the difference between the reported amount of natural gas produced and the reported amount consumed.

Biofuels: Organic materials, such as wood, waste, and alcohol fuels, burned for energy purposes.

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

Biogenic: Produced by the actions of living organisms.

Biomass: Materials that are biological in origin, including organic material (both living and dead) from above and below ground, for example, trees, crops, grasses, tree litter, roots, and animals and animal waste.

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. Other greenhouse gases are measured in relation to the global warming potential (GWP) 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.

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

Chlorofluorocarbons (CFCs): A family of inert, nontoxic, easily liquefied chemicals used in refrigeration, air conditioning, packaging, and insulation, or as solvents or aerosol propellants.

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

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

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

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

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

Coal coke: See *Coke (coal)*.

Coalbed methane: Methane produced from coalbeds in the same way that natural gas is produced from other strata. See “methane.”

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.

Ethyl tertiary butyl ether (ETBE): A colorless, flammable, oxygenated hydrocarbon blend stock.

Ethylene: An olefinic hydrocarbon recovered from refinery or petrochemical processes.

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 natural gas: Natural gas burned in flares on the well site 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: Any naturally occurring organic fuel formed in the earth's crust, such as petroleum, coal, or 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 exploiting poor-quality coal and thin coal seams by burning the coal in place to produce combustible gas that can be collected and 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: The most common sulfate mineral. Used in wallboard.

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

Halons: See *Bromofluorocarbons*.

Heating degree-day: The number of degrees per day that the average daily temperature is below 65 degrees Fahrenheit.

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: See *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: A liquid produced as water percolates through wastes, collecting contaminants.

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 (LPG): Ethane, ethylene, propane, propylene, normal butane, butylene, and isobutane produced at refineries or natural gas processing plants, including plants that fractionate new natural gas plant liquids.

Lubricant: A substance used to reduce friction between bearing surfaces or as a process material, either incorporated into other materials used as aids in manufacturing processes or as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Other substances may be added to impart or improve useful properties. Does not include byproducts of lubricating oil from solvent extraction or tars derived from de-asphalting. Lubricants include all grades of lubricating oils from spindle oil to cylinder oil and those used in greases. Lubricant categories are paraffinic and naphthenic.

Methane (CH_4): A hydrocarbon gas that is the principal constituent of natural gas. Methane has a 100-year Global Warming Potential of 21.

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: A generic term applied to a petroleum fraction with an approximate boiling range between 122 and 400°F.

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

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

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

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

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

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

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

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

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

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

Organic waste: Waste material of animal or plant origin.

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

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

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

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

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

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

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

Petrochemical feedstock: Feedstock derived from petroleum, used principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics. The categories reported are naphthas (endpoint less than 401°F) and other oils (endpoint equal to or greater than 401°F).

Petroleum: Hydrocarbon mixtures, including crude oil, lease condensate, natural gas, products of natural gas processing plants, refined products, semifinished products, and blending materials.

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: Energy obtained from sources that are essentially inexhaustible (unlike, for example, the fossil fuels, of which there is a finite supply). Renewable sources of energy include wood, waste, geothermal, wind, photovoltaic, and solar thermal energy.

Residual fuel oil: 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: Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. Principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Used as a refinery fuel and as a petrochemical feedstock.

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: A well that produces 60 million cubic feet of gas per day or less for a period of three consecutive months while producing at its maximum flow rate.

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 (TAME): 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. 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).

Waxes: Solid or semisolid materials derived from petroleum distillates or residues. Light-colored, more or less translucent crystalline masses, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Included are all marketable waxes, whether crude scale or fully refined. Used primarily as industrial coating for surface protection.

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 top of, or a structure built over, a well.

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, and charcoal.

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. 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°F, petrochemical feedstocks with a boiling temperature ≥401°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.

Methodology for Reallocating Nonutility Power Producers' Fuel Emissions from the Industrial Sector to the Electric Power Sector for Sharing Out to End-Use Sectors

Last year the report *Emissions of Greenhouse Gases in the United States, 1999* contained: "Table 10 U.S. Carbon Dioxide Emissions from Electricity Generation, 1990-1999" that estimated carbon dioxide emissions for both electric utilities and nonutility power producers (NUPPs). This was a standalone table and the emissions from this table were

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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.

not integrated with the rest of the report where all fuel inputs to NUPPs were counted in the industrial sector – with the exception of coal consumed by Other Power Producers (OPPs).[3]

As EIA is in the process of changing its integrated data systems for fuel inputs over to a combined electric power sector rather than an electric utility sector, when this process is complete there will be an integrated data series from which to obtain the data needed for this Emissions Report. In the interim (i.e. the 2000 data year) to do this on an integrated basis for the Emissions Report there has been a methodology developed that not only estimates emissions for the electric power sector but that allocates those emissions to all end-use sectors and subtracts the appropriate amount of emissions from fuel inputs for electricity generation from the industrial sector.

The methodology outlined below describes the four-step process employed.

STEP ONE -- Estimate and separate the electrical energy component from the thermal energy component of the fuel consumed by nonutility power producers (NUPPs). For recent years (1999 and 2000), EIA has separated the thermal and electrical component of NUPP data. Therefore it is possible to derive a heat rate (the amount of input energy per kilowatthour of electricity) by comparing the amount of energy consumed with the amount of electricity generated. By using this heat rate as a proxy for heat rates previous to 1999, the thermal energy can be separated from the energy used to generate electricity by multiplying that heat rate times the number of kilowatthours of generation (a number that is known going back to 1989).

Coal

The coal consumed by OPPs for both process heat and electricity generation is counted in the electric power sector in the integrated data in for example Table 2.6 of the Monthly Energy Review (MER).[4] Because of this and because the data on NUPPs elsewhere in the MER contain OPP data, a subtraction of NUPP coal consumption for electricity generation from the total industrial coal category will not work. The coal emissions must first be built from the bottom up within the industrial sector. After this is completed a "net difference" can be calculated. The net difference will not correspond directly to the removal of NUPP energy for electricity, but will be the difference when OPPs are added back into the NUPP power pool and both are subtracted from the industrial sector. This will still represent a net decrease in industrial sector energy.

Method:

- Begin with total coal consumption in quadrillion Btu from Table 1.4 of the MER. From this amount subtract out residential coal consumption (Table 2.2) and commercial coal consumption (Table 2.3).
- Electric utility coal consumption has to be calculated separately because the numbers in Table 2.6 contain data for OPPs. This number is obtained my multiplying the heat content given in Table A5 times the physical unit values for electric utilities given in Tables 6.2 or 7.7.
- The remaining value represents industrial sector coal consumption for coke plants, thermal energy and electricity generation.
- Coking coal in Btu can be calculated by multiplying its physical amount in Table 6.2 times its heat content in table A5.
- When coking coal is subtracted this leaves only coal for thermal output and electric generation in the industrial sector.

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[3] EIA currently uses several terms that are very similar, and that can mean the same thing or have slightly different meanings. The term nonutility generators (NUGs) and nonutility power producers (NUPPs) are synonymous. Independent Power Producers are NUPPs engaged only in the generation of electricity. The other category of NUPP consists of cogenerators. Cogenerators are further divided into conventional cogenerators that produce industrial process heat for their own use and produce electricity as a co-product or by-product and special cogenerators that produce both heat and electricity, but sell both to other parties. These are also called "Other Power Producers." Currently the coal inputs for both the heat and electricity generation of Other Power Producers are counted as input to the electric power sector in EIA's integrated data.

[4] All the table numbers referred to in this discussion are for the Monthly Energy Review, July 2001, unless otherwise specified. A copy of the Monthly Energy Review can be found at http://www.eia.doe.gov/emeu/mer/contents.html

- Table 7.8 gives NUPP coal consumption. For 1999 and 2000 these data contain only coal for electricity generation.

- Using billion kilowatthours of generation (Table 7.4) backcast the electricity only number to 1990 by using the heat rate calculated for 1999 and multiplying it times the generation numbers.
- The above values are used to separate thermal and electricity fuel inputs going back to 1990.

The thermal coal energy stays in the industrial sector and the electricity coal energy value is reallocated from the industrial sector to the electric power sector that is shared out to end-use sectors by electricity sales. It is assumed for this analysis that both direct use and sales to end users by NUPPs in Table 7.5 are industrial uses of electricity. While some of the direct sales to end-users may be to large commercial consumers, the vast majority of it will be to other industrial customers. This may entail some double counting as there is evidence that some sales of end-users is of purchased electricity. However, the data are not currently available to disentangle these values.

Natural Gas

Because all NUPP natural gas consumption is included in the industrial sector data, it is a more straight forward calculation.

Method:

- Take the value for thermal and electric in the industrial sector directly from table 2.4 as it includes all NUPP natural gas consumption. (This number can be checked using the same method used for coal.)
- Starting the same way as with the coal calculation, use table 1.4 to obtain total natural gas consumption from which is subtracted residential and commercial consumption from tables 2.2 and 2.3 respectively.
- Electric utility natural gas consumption can be taken directly from table 2.6 as it is consistent with the data published elsewhere in the MER (i.e. the physical units in Tables 4.4 or 7.7).
- In addition, transportation natural gas consumption from Table 2.5 needs to be subtracted. The resulting value can be compared with the Btu value in Table 2.4. While Table 2.4 can be used directly for the calculation a validation check reveals that the numbers are within plus 6 and minus 8 trillion Btu out of 8,000 to 10,000 trillion Btu.
- Using the natural gas data in Tables 7.4 and 7.8 perform the same calculation as above in order to separate the thermal and electrical energy fuel input for years prior to 1999.

Petroleum

While petroleum provides a relatively small amount of fuel for NUPP electricity generation, it is a complex calculation due to the various types of petroleum-based fuels.

Method:

- Using the same method as for natural gas above one can arrive at a calculated value that can be checked against the value for petroleum in Table 2.4. A check indicates that for most cases the same number as in Table 2.4 was produced and where there are differences they are extremely small.
- There are three different petroleum fuel types: light, heavy and petroleum coke. As in the above method, Table 7.4 (generation) was used to arrive at a heat rate and to backcast using the 1999 value for the years 1990 to 1998 for the electricity only portion of petroleum consumption. This is a small number compared to the other fossil fuels.

STEP TWO – Subtract out the energy value of the fuel used by NUPPs to generate electricity from the total fuel used in the industrial sector. Now that there has been a value calculated by fuel for the electrical energy component of industrial energy consumption, that value can be subtracted from the industrial sector fuel use. This leaves only the energy that is consumed directly in the industrial sector for process heat and other non-electric applications.

Coal

As mentioned above the coal calculation is complicated by the inclusion of the OPPs in the electric power sector rather than in the industrial sector in the MER data set upon which the greenhouse gas estimates are based. This difference is quite large. For example, total industrial coal consumption in Table 2.4 is 2.257 quadrillion Btu. When this value is calculated to include all NUPP including OPPs this value is 4.8 quadrillion Btu – over twice the amount. Therefore simply subtracting the NUPP coal for electricity from the existing industrial sector data will yield a double subtraction because the NUPP electricity coal calculation contains OPP electricity coal while the MER-based industrial sector coal does not. For coal then the entire category needs to be built up from the bottom – adding thermal to coking coal. When this amount is calculated the difference from the MER-based industrial sector coal value can be calculated as a subtraction. This subtraction represents the net change that results from the following:

- Add back both electrical and thermal energy from coal for OPPs in the industrial sector,
- Calculate the coal-fired thermal and electrical energy for all NUPPs,
- Leave the thermal component in the industrial sector,
- Include the coal electrical generation component in the total for electric power generation to be shared out to all the sectors,
- Subtract the net difference from the industrial sector.

Natural Gas

Because all natural gas associated with NUPPs is included in the industrial sector data, the value associated with electricity generation can be directly subtracted from the industrial sector total.

Petroleum

This adjustment is relatively small and can be made the same way as the natural gas adjustment – i.e. as a direct subtraction from the total. The complexity in the petroleum estimate is due to the different types of fuel with differing emission factors. For that reason they are calculated separately.

STEP THREE – Apply the appropriate emission factors to the energy values of the fuels reallocated from the industrial sector to the electric power sector. Now that the fossil fuel used to generate electricity has been reallocated from the industrial sector to the electric power sector, the emissions associated with that energy consumption can be estimated. The reallocated amounts of energy are multiplied times the appropriate emissions factor for that sector. Because emission factors can vary by sector (even for the same fuel) this part of the reallocation can cause small changes in total emissions. The amounts of these changes are in the range of 0.1 to 0.2 MMTCe out of total energy emissions of over 1,500 MMTCe in recent years.

STEP FOUR – Combine all the electricity-related emissions and share them out to the end use sectors to produce new total emissions by sector. To complete the process the total emissions for the electric power sector including electric utilities, nonutility power producers and the electricity component of industrial cogenerators is shared out to each end-use sector by using the sector's share of total electricity sales. It is assumed that NUPP direct sales to end-users are all to other large industrials since data are not available to determine how much of the electricity may be going to large commercial customers.

Once the Btu value of electrical energy has been removed by fuel from thermal energy that value is used to calculate carbon dioxide emissions that are combined with emissions from electric utilities and shared out to all end-use sectors by electricity consumption. This is a relatively straight-forward calculation, however some adjustments must be made. Table 7.5 is the source for the electricity end-use data upon which the shares are calculated. In this table the end-use sectors are: residential, commercial, industrial and "Other." Other is a combination of transportation (railroads and railways) and sales to public authorities for streetlights and similar uses.

All the NUPP electricity in the categories "Direct Use," or "Sales to End Users," are assumed to be industrial sector electricity since most of the sales to end-users are other industrial concerns. The remaining electricity is already included in the electric-utility retail sales category. The amount of electricity that is sold through the grid to other sectors can be calculated by subtracting the NUPP total from Table 7.5 from the total on Table 7.4. For example in 2000 the total from Table 7.5 is 208.4 billion kWh, while the total from Table 7.4 is 784.6 billion kWh. This indicates that 576.2 billion kWh are generated by NUPPs and sold through the grid, some of which in turn ends up being purchased by industrial customers, but some of which is purchased by commercial, residential and transportation customers.

The additional amount shared out to the residential, commercial and transportation customers by virtue of the inclusion of NUPP fuel inputs represents the amount of the transfer from the industrial sector to these other sectors. The emissions from fossil fuels are shared out among sectors based on total generation (i.e. fossil and non-fossil), regardless of the type of generation, as there is not a way to map generation types to end-use customers within sectors.

Implementation within Greenhouse Gas Spreadsheets

To implement these changes a new spreadsheet was created (alternative01). This spreadsheet calculates the above values and then transmits the Btu values to the appropriate sectoral spreadsheets where they are multiplied times the emission factors in the same way as the original method. The spreadsheets are marked with an "N" to indicate the new method (e.g. NResidential). The old method is maintained as a point of reference. The new sectoral allocations are added together in "Totalsnew." These spreadsheets look the same as those developed for the original method. Once the integrated data within EIA has incorporated nonutility power producers into the electric power sector, this method will no longer be needed and the data will draw upon the older and more direct methodology. For the calculated reallocation of emissions see Table A1.

Table A1. Changes in Values for the Old Versus the New Method for the Treatment of Nonutility Power Producers, 1990 to 2000

(Million Metric Tons of Carbon Equivalent)

Energy Sector Totals	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Residential (old)	255.27	259.28	258.53	274.19	271.95	273.40	289.65	288.61	289.30	291.58	302.34
Residential (new)	257.04	261.62	261.81	278.35	275.80	277.85	293.92	292.75	293.70	298.79	313.36
Commercial (old)	208.70	208.30	207.81	213.55	216.95	220.59	229.24	241.45	244.78	246.16	257.32
Commercial (new)	210.28	210.37	210.76	217.22	220.40	224.62	233.06	245.38	250.42	253.06	267.83
Industrial (old)	455.90	444.37	461.55	460.95	470.74	469.38	483.96	489.72	479.77	480.03	487.20
Industrial (new)	452.66	439.81	455.06	452.89	463.26	461.07	476.05	481.54	469.54	465.79	465.71
Transportation (old)	431.76	424.24	431.07	436.36	449.30	457.75	468.86	473.64	481.55	499.45	514.82
Transportation (new)	431.76	424.24	431.07	436.36	449.30	457.75	468.86	473.64	481.55	499.45	514.82
Total (old)	1351.63	1336.19	1358.96	1385.05	1408.94	1421.13	1471.71	1493.42	1495.40	1517.22	1561.67
Total (new)	1351.73	1336.03	1358.71	1384.83	1408.76	1421.29	1471.89	1493.30	1495.22	1517.09	1561.71
Electric Power (old)	483.15	479.53	480.52	497.67	504.59	504.28	523.82	543.57	562.98	558.67	573.26
Electric Power (new)	506.98	505.98	512.03	532.43	540.71	542.53	562.15	583.07	607.21	612.60	641.58
Differences											
Residential (new-old)	1.77	2.34	3.28	4.16	3.85	4.45	4.27	4.14	4.40	7.21	11.02
Commercial (new-old)	1.58	2.07	2.95	3.67	3.45	4.03	3.82	3.93	5.64	6.90	10.50
Industrial (new-old)	-3.25	-4.57	-6.49	-8.06	-7.49	-8.31	-7.91	-8.19	-10.23	-14.24	-21.48
Transportation (new-old)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total (new-old)	0.10	-0.16	-0.26	-0.23	-0.19	0.17	0.19	-0.12	-0.18	-0.13	0.04
Electric Power (new-old)	23.83	26.45	31.52	34.77	36.12	38.25	38.32	39.50	44.22	53.93	68.32

Source: Methodology outlined in this report.

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 appreciable amounts of 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 less than 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*.[5] 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.

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

Table A2. Fossil Fuel Consumption for Nonfuel Use, 1990,1992-2000
(Quadrillion Btu)

	1990	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Petroleum										
Asphalt and Road Oil	1.17	1.10	1.15	1.17	1.18	1.18	1.22	1.26	1.32	1.28
LPG	1.20	1.39	1.35	1.55	1.59	1.65	1.67	1.60	1.81	1.86
Pentanes Plus	0.08	0.06	0.28	0.26	0.30	0.32	0.30	0.27	0.33	.31
Lubricants	0.36	0.33	0.34	0.35	0.35	0.34	0.35	0.37	0.37	.37
Industrial	0.19	0.17	0.17	0.18	0.18	0.17	0.18	0.19	0.19	.19
Transportation	0.18	0.16	0.16	0.17	0.17	0.16	0.17	0.18	0.18	.18
Petro-chem Feed	1.12	1.20	1.22	1.26	1.21	1.21	1.40	1.40	1.31	1.34
Petroleum Coke	0.18	0.25	0.17	0.18	0.19	0.21	0.18	0.31	0.38	.23
Special Naphtha	0.11	0.10	0.10	0.08	0.07	0.07	0.07	0.11	0.15	.10
Other: Waxes & Misc., Dist., and Resid.	0.23	0.20	0.20	0.20	0.20	0.19	0.20	0.22	0.21	.21
Total Petroleum	4.46	4.64	4.80	5.05	5.08	5.17	5.40	5.54	5.88	5.69
Coal	0.02	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02	.03
Natural Gas	0.59	0.61	0.61	0.69	0.67	0.68	0.70	0.73	0.75	.71
to Fertilizers	0.28	0.35	0.33	0.34	0.33	0.34	0.34	0.37	0.38	.34
Total	5.07	5.29	5.45	5.77	5.79	5.88	6.12	6.27	6.61	6.43

P = preliminary data.

Notes: Asphalt and lubricants are as reported in EIA's *State Energy Data Report 1997*, DOE/EIA-0214(97) (Washington, DC, September 1999) for 1990-1997, and *Monthly Energy Review*, DOE/EIA-0035(2001/07) (Washington, DC, July 2001) for 1998-2000. Some slight differences exist between this table and the *Annual Energy Review*. 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).

Source: Energy Information Administration, *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, August 2001), 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.

- **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.[6]

- **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.

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[6] 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 www.iea.org/ipcc/invs6.htm.

- **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.

- **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.[7] 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). (1998-2000), Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(2001/07) (Washington, DC, July 2001); *Petroleum Supply Annual 2000*, DOE/EIA-0340(2000)/1

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

(Washington, DC, June 2001); *Natural Gas Annual 1999*, DOE/EIA-0131(99) (Washington, DC, October 2000); and *Renewable Energy Annual 2000*, DOE/EIA-0603(2000) (Washington, DC, December 2000).

Nonfuel Use of Energy and Biofuels Consumption: Energy Information Administration, *Annual Energy Review 2000*, DOE/EIA-384(2000) (Washington, DC, August 2001); 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.

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

1980-1999: Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, DC, various years), and the International Energy Database (March 2000). 2000: EIA estimate.

Table A4. U.S. Territories Primary Energy Consumption (Btu), 1990, 1992-2000 (Quadrillion Btu)

Territory	1990	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Puerto Rico	0.30	0.33	0.35	0.36	0.35	0.34	0.33	0.35	0.35	0.38
Virgin Islands, U.S.	0.12	0.12	0.12	0.12	0.19	0.16	0.20	0.26	0.28	0.29
American Samoa	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
Hawaiian Trade Zone	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U.S. Pacific Islands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wake Island	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**	**0.55**	**0.58**	**0.62**	**0.57**	**0.61**	0.68	**0.71**	0.75

*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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).

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 2000 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

Distillate and Residual Fuels (1980-1987): Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, DC, various years). (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, various years); EIA estimate. 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), 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 1990-1999* (Washington, DC 20460) April 2001.

Table A5. Consumption and Carbon emissions from International Bunker Fuels Supplied in the United States, 1990,1992-2000

Item	1990	1992	1993	1994	1995	1996	1997	1998	1999	P2000
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**
Residual	**15.2**	**14.3**	**11.4**	**11.2**	**11.1**	**11.4**	**12.2**	**12.7**	**10.4**	**9.4**
Total Marine	***16.9***	***15.8***	***13.0***	***12.6***	***12.7***	***12.7***	***13.4***	***14.4***	***11.3***	***10.2***
Aviation Bunkers										
US Carriers	**5.0**	**5.3**	**5.3**	**5.5**	**5.7**	**6.0**	**6.3**	**6.6**	**6.8**	**7.1**
Foreign Carriers	**5.3**	**5.6**	**5.8**	**6.0**	**6.6**	**6.8**	**7.6**	**7.6**	**8.5**	**7.8**
Total Aviation	***10.4***	***11.0***	***11.1***	***11.5***	***12.4***	***12.8***	***13.9***	***14.2***	***15.3***	***14.9***
Total	**27.3**	**26.7**	**24.2**	**24.1**	**25.1**	**25.4**	**27.3**	**28.6**	**26.6**	**25.1**
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**
Aviation	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**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**

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.[8] 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 and 2000 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 2001*.

Data Sources

Flaring (1980-1999): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). (2000): *Natural Gas Monthly*, DOE/EIA-0130(2000/08) (Washington, DC, August 2001). 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):

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

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).

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 (58 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.[9] 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.[10] 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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[9] 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

[10] 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 Data for U.S. Carbon Dioxide Emissions from Industrial Sources, 1990,1992-2000
(Thousand Metric Tons)

Source	1990	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Cement Clinker	63,326	62,184	65,745	69,787	69,983	70,361	72,686	74,523	76,003	78,500
Masonry Cement	2,911	2,806	2,962	3,613	3,603	3,469	3,634	3,989	4,000	5,000
Lime Produced	15,832	16,199	16,700	17,400	18,500	19,200	19,700	20,100	19,600	20,100
Limestone in Iron Smelting	3,955	3,098	2,561	2,538	2,615	2,538	2,549	2,477	2,379	2,600
Limestone in Steelmaking	682	612	1,087	1,225	1,126	949	750	798	612	1,029
Limestone in Glass	272	354	439	680	754	450	203	443	443	443
Limestone in FGD	4,369	4,479	4,274	4,621	5,815	6,125	6,595	6,322	6,835	6,835
Limestone in Dolomite Manufacture	986	641	549	526	428	691	673	654	295	295
Soda Ash Production (from Trona)	8,147	8,269	8,056	8,111	9,167	9,056	9,500	9,167	8,833	8,722
Soda Ash in Glass	3,177	3,082	3,095	3,150	3,130	3,040	3,130	3,220	3,270	3,270
Soda Ash in FGD	179	156	146	191	211	206	295	191	210	210
Sodium Silicate	740	827	913	914	1,091	1,002	1,101	1,096	948	1,075
Sodium Tripolyphosphate	451	419	419	419	419	419	419	205	181	181
Aluminum Manufacture	4,048	4,042	3,695	3,299	3,375	3,577	3,603	3,713	3,779	3,700
Copper Primary Smelting	1,577	1,710	1,790	1,840	1,930	2,010	2,070	2,140	1,890	1,610

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.[11] 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.[12] 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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[11] The Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), p. 46.

[12] 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.[13] 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.[14]

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 1999 and uses the 1999 estimate for 2000. 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 minerals.er.usgs.gov/pubs/commodity.

Cement and Clinker Production (1980-1999): U.S. Department of the Interior, U.S. Geological Survey, *Cement Annual Report* (Washington, DC, various years). **(2000):** U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries* (Washington, DC, 2001).

Lime Manufacture: (1980-2000): 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: (1980-1999): U.S. Department of the Interior, U.S. Geological Survey, *Crushed Stone Report* (Washington, DC, various years). **(2000):** EIA estimate. **Limestone Consumption in Flue Gas Desulfurization: (1980-1999):** Energy Information Administration, unpublished survey data, Form EIA-767, “Steam Electric Plant Operation and Design Report” (Washington, DC, various years). **(2000):** EIA estimate.

Soda Ash Manufacture and Soda Ash Consumption in Glass Making (1980-2000): U.S. Department of the Interior, U.S. Geological Survey, *Soda Ash Report* (Washington, DC, various years). **Soda Ash Consumption in Flue Gas**

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

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

Desulfurization (1980-1999): Energy Information Administration, unpublished survey data, Form EIA-767, "Steam Electric Plant Operation and Design Report" (Washington, DC, various years). **(2000):** EIA estimate. **Sodium Silicate and Sodium Tripolyphosphate: (1980-1996):** Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1998* (Washington, DC, September 1998), pp. 37-38. **(1997-2000):** 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 (1980-2000): U.S. Department of the Interior, U.S. Geological Survey, *Aluminum Report* (Washington, DC, various years).

Municipal Solid Waste (1990-1999, 2000 estimate): U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999* (Washington, DC, April 2001).

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.[15] 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 in conjunction with coal production data to develop emissions factors per ton of coal mined on a basin-by-basin level (Table A7).[16] Emissions factors for nonsample years are interpolated. The resulting emissions factors are then multiplied by production data (see Table A8) to estimate emissions from this source for the period through 1998. For 1999 and 2000 ventilation emissions from "gassy" mines are estimated based directly on a compilation of MSHA data by the U.S. EPA Office of Air and Radiation.

Table A7. Methane Emissions Factors for Gassy Underground Coal Mines, 1990-1998

Gassy Mines	Units	1990	1991	1992	1993	1994	1995	1996	1997	1998
Northern Appalachia	CFD/Ton	1.01	1.09	1.17	1.24	0.79	0.8	0.81	0.85	0.86
Central Appalachia	CFD/Ton	1.45	1.42	1.39	1.35	1.17	1.17	1.17	0.90	0.81
Warrior	CFD/Ton	4.62	4.48	4.34	4.2	5.31	4.63	3.94	3.62	3.91
Illinois	CFD/Ton	0.44	0.46	0.48	0.49	0.47	0.485	0.5	0.48	0.43
Western	CFD/Ton	1.51	1.33	1.15	0.96	1.11	0.98	0.85	0.99	0.86

Sources: Coal Production numbers from Energy Information Administration Form 7-A, *Coal Production,* DOE/EIA-0118 (Washington, DC, various years), and *Coal Industry Annual*, DOE/EIA-0584, Ventilation data for 1990 and 1993 provided by G. Finfinger, U.S. Department of Interior, Bureau of Mines, Pittsburgh Research Center. Ventilation data for 1994-1998 provided by U.S. Environmental Protection Agency, Coalbed Methane Outreach Program.

Table A8. U.S. Coal Production by Type of Mining and Basin, 1990-1998

(Million Metric Tons)

	1990	1991	1992	1993	1994	1995	1996	1997	1998
Underground									
Northern Appalachia	95.5	93.5	92.5	69.7	90.8	88.6	96.5	101.7	105.9
Central Appalachia	178.6	165.3	164.1	149.1	155.0	151.0	155.9	161.2	155.4
Warrior	15.9	15.5	14.5	14.1	13.1	16.0	16.5	16.8	15.7
Illinois	62.8	63.5	66.4	50.8	62.8	62.6	60.9	58.9	58.7
Western	31.3	30.8	31.1	34.1	40.3	40.8	41.6	43.0	43.3
Total	384.2	368.6	368.6	317.8	362.0	359.0	371.4	381.5	378.9
Surface	548.3	534.0	535.4	539.1	575.4	577.5	593.2	607.0	634.7
Total All Mines	933.4	903.4	904.7	857.5	937.4	936.8	965.0	988.5	1014.0

P = preliminary data. NA = data not available.

Sources: Energy Information Administration, *Coal Industry Annual*, DOE/EIA-0584 (various years).

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[15] 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.

[16] For purposes of this analysis, the Northern Appalachia basin includes Pennsylvania, Northern West Virginia, Maryland, and Ohio; the Central Appalachia basin 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.

Emissions from nongassy mines make up less than 2 percent of all emissions from underground mines.[17] 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 and 2000, 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 1999 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. For 2000, emissions from degasification systems were assumed to have remained constant from 1999 levels.

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.[18] 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.[19] 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 1999. For 2000, methane recovery levels are assumed to remain constant from 1999 levels.

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 1994-2000 were obtained from the EPA, Climate Protection Division, Coalbed Methane Outreach Program. Coal production data are reported to EIA on Form EIA-7A, "Coal Production Report." Basin-level emissions for nongassy 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 1999 are from the EPA's Office of Air and Radiation, Climate Protection 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 are reported to EIA on Form EIA-7A, "Coal Production Report."

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[17] 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.

[18] 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

[19] 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

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 are reported to EIA on Form EIA-7A, "Coal Production Report."

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 are reported to EIA on Form EIA-7A, "Coal Production Report."

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.[20] 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.

- **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

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[20] 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.

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).[21] 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 1990-2000. 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); transmission and distribution pipeline mileage are published annually by the American Gas Association in *Gas Facts*.

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[22]

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 - 2000 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.

Data Sources

Emission factors are fromr 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*.

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[21] 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.

[22] 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.)

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(01/07) (Washington, DC, July 2001) for 1998-2000. Residential woodfuel consumption data were derived from EIA's *Annual Energy Review 2000*, DOE/EIA-0384(00) (Washington, DC, July 2001).

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). 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.[23] 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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[23] 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.[24] 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 A9 shows the EMCON methane generation model parameters.

Waste flows were estimated from 1940 through 2000. 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 A9. 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 1999 (Table A9) were drawn from "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-2000). 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

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

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 demolition (C&D) waste and sludge, the Franklin data include only MSW going to landfills. For 2000, waste generation data were not yet available so 1999 estimates were scaled up by GDP growth of 4.1 percent to provide an estimate of waste generation in 2000. The volume of waste recycled or combusted rather than landfilled was assumed to have grown from 39% in 1999 to 40% in 2000.

Table A10. U.S. Solid Waste Generated and Landfilled, 1990-2000
(Million Metric Tons)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000P
Waste Generated	266.4	254.6	264.7	278.4	292.9	296.4	297.1	308.9	339.9	353.7	368.2
Waste Landfilled	205.2	193.6	190.6	197.7	196.3	186.8	184.2	188.5	207.4	215.8	221.0
Waste In Place	6868.7	7062.3	7252.9	7450.6	7646.9	7833.7	8017.9	8206.4	8413.7	8629.6	8850.6

Source: "Nationwide Survey: The State of Garbage in America," Biocycle (1988-2000).

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.[25]

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.[26] 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.[27] Anaerobic digestion is

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

[26] 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.

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

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.[28]

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. Therefore, it is necessary to base the current estimate of methane emissions from wastewater treatment on the highly simplified approach recommended by the IPCC,[29] 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.[30] It is assumed that recovery of methane at municipal wastewater treatment facilities is negligible.

Data Source

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.[31] 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

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

[29] 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

[30] 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.

[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), p. 272.

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 intake requirements.[32] 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 A11).

Table A11. Average Pre-Slaughter Live Weights for U.S. Cattle and Calves, 1990 -2000
(Pounds)

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

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.[33]

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.nass.usda.gov:81/ipedb/. Population data for goats and horses are extrapolated from the USDA's *Census of Agriculture* for the years 1987, 1992 and 1997.[34] 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,

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[32] 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.

[33] 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.

[34] 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).

in addition to providing a suitable anaerobic environment, provide the moisture necessary for methanogenic bacterial cell production and acid stabilization.[35] 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[36] 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.[37] 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.

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.[38] 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.

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

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

[37] 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.

[38] Personal communication (May 1993).

Estimation Methods

A range of daily emissions rates has been developed from studies of rice fields in California,[39] Louisiana,[40] and Texas.[41] 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). 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.

Burning of Crop Residues

Emissions Sources

Between 40 and 50 percent of dry matter in crop residue is carbon.[42] 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 percent in 1990 to 23 percent in 2000. The share of rice combusted throughout the remainder of the U.S. declines from 16 percent in 1990 to 9 percent in 2000.[43] To derive methane emissions, the dry weight and carbon content of each crop were determined and then multiplied by estimated combustion efficiencies (Table A12).

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[39] 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.

[40] 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.

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

[42] 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.

[43] 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 A12. 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 A13). Production figures for the chemicals are multiplied by those emissions factors.

Data Source

Chemical production figures were obtained from the Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years).

Table A13. 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.[44] 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 18 percent of 2000 emissions. It should be noted that the range of uncertainty associated with emissions from mobile combustion and fertilizer use is quite 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.

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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), p. 2.23,www.ipcc.ch/pub/guide.htm

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 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). 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(01/07) (Washington, DC, July 2001) for 1998-2000. Residential woodfuel consumption data were derived from EIA's *Annual Energy Review 2000*, DOE/EIA-0384(00) (Washington, DC, July 2001).

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.[45]

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.[46]

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 2000. 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 2000. The share of rice combusted throughout the remainder of the U.S. declines from 16 percent in 1990 to 9 percent in 2000.[47] The amount of crop residue burned is discounted by an assumed combustion

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[45] 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

[46] 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

[47] 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.

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.

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.[48] 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

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[48] Personal communication, May 1993.

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.[49] 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 2000 were based on 1999 data scaled to GDP growth of 4.1percent 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.

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.

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[49] 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.

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.[50] 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.[51] In 1999, 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 1999, 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.

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.[52] 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*

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[50] 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.

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

[52] 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

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 1999, 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 1990-1999*, EPA-236-R-00-001 (Washington, DC, April 2001). The preliminary 2000 emissions estimates for sulfur hexafluoride, PFCs, and most HFCs are advance estimates developed by the EPA and provided to the EIA, courtesy of the EPA's Climate Protection Division. The preliminary 1999 emissions estimates for HFC-152, HFC-227ea, and HFC-4310mee were derived by extrapolating the trends shown in the 1996 through 1998 estimates.

Data Sources

EPA estimates of emissions of HFCs, PFCs, and sulfur hexafluoride are from the U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-00-001 (Washington, DC, April 2001), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Appendix B
Carbon Coefficients Used in This Report

Overview

The first edition of *Emissions of Greenhouse Gases in the United States*, published in September 1993, applied emissions coefficients for petroleum and natural gas developed by Marland and Pippin[1] and adopted by the Intergovernmental Panel on Climate Change.[2] Those coefficients, developed for broad international use, covered only the six petroleum product categories in the International Energy Agency's taxonomy. The Energy Information Administration (EIA) collects data on more than 20 petroleum products, and U.S. petroleum products often differ in composition from those consumed abroad. In the first edition of this report, EIA estimated emissions coefficients for the remaining petroleum products based on their underlying chemical composition. EIA also used emissions coefficients for coal by rank (anthracite, bituminous, subbituminous, and lignite) and State of production, developed using 5,426 coal samples from the EIA coal analysis file.

In 1994, EIA developed specific and updated emissions coefficients for all petroleum products in their data collection system, based on their density, heat content, and carbon share. These variables were estimated on the basis of the underlying chemical composition of the fuels and, where available, ultimate analyses of product samples.[3] An emissions coefficient for natural gas was also generated, based on 6,743 gas samples in a Gas Technology Institute (formerly the Gas Research Institute) database. The magnitude of potential variation in emissions coefficients for fossil fuels is constrained by the limits imposed by the chemical properties of the hydrocarbon compounds that define the fuels.[4] In all but a few cases, the revised emissions coefficients differed from those developed by Marland and Pippin by less than 5 percent.

The composition of marketed petroleum products varies over time because of changes in exploration, recovery, and refining technology, economic changes (e.g., changes in the price of oil), and regulatory changes (e.g., requirements for reformulated gasoline in the Clean Air Act Amendments of 1990). Because motor gasoline consumption is a major contributor to U.S. greenhouse gas emissions and has experienced important changes in composition over the last decade, EIA provides annual updates of its emission coefficient (Table B1).

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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.

[2] Intergovernmental Panel on Climate Change, *Estimation of Greenhouse Gas Emissions and Sinks* (Paris, France, 1991), p. 2-18.

[3] An ultimate analysis provides an exact breakdown of the elements present in a compound or mixture.

[4] For a more detailed discussion of fossil fuel chemistry and emissions coefficients, see Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), Appendix A, pp. 73-92, web site www.eia.doe.gov/oiaf/1605/87-92rpt/appa.html.

Table B1. Full Combustion Carbon Coefficients

(Million Metric Tons of Carbon per Quadrillion Btu)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Petroleum											
Motor Gasoline	19.41	19.41	19.42	19.43	19.45	19.38	19.36	19.35	19.33[R]	19.33[R]	19.34
LPG	16.99	16.98	16.99	16.97	17.01	17.00	16.99	16.99	16.99	16.99	16.99
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33	19.33	19.33	19.33
Distillate Fuel	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Residual Fuel (All Other)	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Residual Fuel (Utility)	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29
Asphalt & Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Petrochem Feed	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Aviation Gas	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Special Naphtha	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86
Waxes & Misc.	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81
Other:	17.46	17.83	17.39	16.12	16.36	15.69	16.27	16.57	15.59	14.84	14.84
Coal 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 Indus. Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56	25.56
Coal Indus. Other	25.58	25.60	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63	25.63
Coal Electric Utility	25.68	25.69	25.69	25.71	25.72	25.74	25.74	25.76	25.76	25.76	25.76
Flare Gas	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92
Natural Gas	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Crude Oil	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24	20.24	20.19	20.23

R=revised data.

Source: Energy Information Administration, Emissions of Greenhouse Gases in the United States 1999, DOE/EIA-0573(99) and estimates presented in this report.

The EIA also provides annual updates of the emissions coefficient for crude oil. Crude oil consumption in the United States is a very small portion of carbon emissions, because nearly all crude is refined into finished petroleum products. However, crude oil refinery input can be used to develop a national mass balance estimate of carbon emissions that may be used as a benchmark for the more disaggregated estimation approach used by EIA. EIA has developed a regression equation reflecting the relationship between the density, sulfur content, and carbon content of crude oil. From these data a crude oil emissions coefficient can be calculated. This regression equation is applicable for any nation that collects these basic petroleum statistics and supports a mass balance approach to estimating emissions where detailed product data are not collected.

In 1997, EIA began publishing separate emissions coefficients for LPG fuel use and LPG nonfuel use. LPG may be used as fuel or as a petrochemical feedstock. A portion of the carbon in petrochemical feedstocks will be sequestered rather than emitted. Further, if the mix of paraffinic hydrocarbons used for petrochemical feedstock differs substantially from those used for fuel, using a single emissions coefficient for LPG will bias estimates of emissions. Thus, EIA now annually adjusts the emissions coefficient for LPG based on the mix of compounds used as fuel and feedstock.

Finally, the EIA provides annualized emissions coefficients for jet fuel consumed during the period 1990 through 1996. During that period jet fuel consumed in the United States underwent a dramatic change in composition. Until 1993, two types of jet fuel were widely used in the United States. Kerosene-based jet fuel was generally used in the commercial airline industry and naphtha-based jet fuels were used primarily by the U.S. Department of Defense. The emissions coefficient for naphtha-based jet fuels was about 3 percent higher than that for kerosene-based jet fuel. In 1989, 13 percent of all jet fuel consumed was naphtha-based. By 1996, that figure had fallen to 0.3 percent, and in 1997 total naphtha-based jet fuel consumption was negligible. Thus, the emissions coefficient for jet fuel, weighted by consumption of each fuel type, fell steadily between 1988 and 1996 and has now stabilized at the level of kerosene-based jet fuel. Notably, the emissions coefficient for jet fuel is now nearly the same as the coefficient for motor gasoline.

This appendix discusses the updated 2000 emissions coefficients for motor gasoline, crude oil, and liquified petroleum gases. Because the emissions coefficient for jet fuel is now static it will not be examined further here.[5]

Motor Gasoline

Motor gasoline consumption accounts for about 20 percent of all U.S. greenhouse gas emissions. Thus, changes in composition can have important effects on national emission levels. As with all petroleum products, the emissions coefficient for motor gasoline is a function of its density and carbon content. This relationship is particularly clear in the case of motor gasoline because the share of impurities found in the fuel must be kept very low to maintain the operating condition of modern automobile engines and limit the environmental effects of vehicle use. Motor gasoline density varies between summer and winter grades and from low octane to high octane. This variation takes into account the differing performance requirements of gasoline associated with temperature changes. Partly as a result of the leaded gasoline phaseout, the density of gasoline increased slowly and steadily across all octane grades and in all seasons from 1987 through 1994.[6] In order to maintain the "anti-knock" quality and octane ratings of motor gasoline in the absence of lead, the portion of aromatic hydrocarbons used in gasoline was increased. Aromatic hydrocarbons take the form of C_nH_{2n-2}, a lower ratio of hydrogen to carbon than other hydrocarbons typically found in gasoline. Because carbon is much heavier than hydrogen, this lower ratio results in increased fuel density and higher shares of carbon. As a result, the emissions coefficient for motor gasoline rose slowly from 19.39 million metric tons carbon per quadrillion Btu in 1988 to 19.45 million metric tons carbon per quadrillion Btu in 1994. Table B2 shows the increasing densities and emissions coefficients between 1990 and 1994.

Table B2. Changes in Motor Gasoline Density, 1990-2000

Fuel Grade	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Winter Grade											
Low Octane	62	61.8	61.4	61	60.1	59.8	60.6	61.5	61.8	61.6	61.6
Mid Octane	60.8	60.4	60.2	59.9	59.4	59.1	59.9	60.7	61.2	61.3	61.2
High Octane	59	59.3	59	58.7	58.5	58	58.5	59.3	60	60.3	59.7
Summer Grade											
Low Octane	58.2	58	57.4	56.1	55.7	56.1	56.9	57.1	57.6	57.7	56.8
Mid Octane	57.4	57.1	56.4	55.5	54.8	55.6	56.2	56.6	56.7	57.4	58
High Octane	55.5	55.7	55.6	54.4	53.8	55.1	55.3	56.4	55.7	57.4	55.8
Average Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)[a]	**19.41**	**19.41**	**19.42**	**19.43**	**19.45**	**19.38**	**19.36**	**19.35**	**19.33[r]**	**19.33[r]**	**19.34[r]**

[a] Emissions coefficient weighted for reformulated gasoline, which has a lower density than standard gasoline.
[r]=revised data.
Sources: National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* and *Motor Gasoline, Winter* (1990-2001); and M. DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, ANL/ESD/TM-22, Vol. 2, Appendices A-S (Chicago, IL: Argonne National Laboratory, November 1993), p. c-6. Properties of reformulated fuels from California Air Resources Board.

In 1995, a requirement for reformulated gasoline in non-attainment areas implemented under the Clean Air Act Amendments 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 added to standard gasoline to boost the oxygen content in the gasoline mixture. The increased oxygen reduces the emissions of carbon monoxide and unburnt hydrocarbons. This also results in a reduced carbon share in these mixtures. In contrast to an average carbon share of 86.6 percent for standard motor gasoline, MTBE is 68.2 percent carbon and TAME is 70.2 percent carbon (Table

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[5] For a more detailed discussion of jet fuel coefficients, see Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), Appendix A, pp. 73-92 web site www.eia.doe.gov/oiaf/1605/87-92rpt/appa.html.; and Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998), Appendix B, pp. 105-110 web site www.eia.doe.gov/oiaf/1605/98rpt/appendixb.html.

[6] National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer*, and *Motor Gasoline, Winter* (1984-1994).

B3). The average gallon of reformulated gasoline includes about 8.5 percent MTBE and 0.5 percent TAME. Thus, in 1995 the overall emissions coefficient for gasoline fell to 19.38 million metric tons per quadrillion Btu. About a third of motor gasoline consumed since 1998 was reformulated, leading to a consumption-weighted emission coefficient of 19.33 million metric tons per quadrillion Btu in 1998 and 1999 and 19.34 million metric tons per quadrillion Btu in 2000.

Table B3. Characteristics of Major Reformulated Fuel Additives

Additive	Density (Degrees API)	Carbon Share (Percent)	Emissions Factor (Million Metric Tons Per Quadrillion Btu)
MTBE	59.1	68.2	16.92
ETBE	59.1	70.5	17.07
TAME	52.8	70.5	17

Sources: California Air Resources Board and estimates developed for this report.

To derive an overall emissions coefficient for gasoline, individual coefficients for standard motor gasoline consumed in the winter and summer months, respectively, were developed. These coefficients were based on the densities of product samples collected by the National Institute on Petroleum and Energy Research used in conjunction with a carbon share of 86.6 percent as estimated by Mark DeLuchi.[7] Emissions coefficients for reformulated fuels consumed during the summer and winter were calculated using the following procedure. First, the carbon share of each additive used in reformulated gasoline was calculated from its chemical formula and combined with the additive's density and energy content as provided by the California Air Resources Board to produce individual coefficients for each fuel additive. Next, the reformulated fuel was separated into its standard fuel components and its additive portions based on fuel samples examined by NIPER.[8] The additive portions were defined as the net increase in MTBE or TAME as compared with the additives in standard fuel, since small amounts of these compounds are present in standard gasoline. The emissions coefficients for standard gasoline and for each of the additives were then weighted by their proportion in reformulated fuel to arrive at a coefficient for reformulated fuel in each season.

After independent coefficients were developed for both standard and reformulated fuel, each season's coefficients were combined by weighting according to the ratio of standard vs. reformulated consumption. The combined summer and winter coefficients were then weighted based on seasonal consumption, with just over half occurring in summer, to derive an overall emissions coefficient for motor gasoline.

Crude Oil

While crude oil composition is highly heterogeneous, the share of carbon in a fixed amount of crude oil (e.g., a gallon or barrel) varies somewhat systematically with such commonly available identifying characteristics as density and sulfur content. Because the economic value of a barrel of crude oil is largely a product of the oil's density and sulfur content these values are regularly recorded. Further, EIA maintains detailed data on the average density and sulfur content of crude oil entering U.S. refineries.[9] Thus, the annual emissions coefficient for crude oil is pegged to these two variables.

Ultimate analyses of 182 crude oil samples were used to derive a relationship between crude oil density, sulfur content, and the percentage of carbon in crude oil. The sulfur content and density of these samples was regressed

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[7] National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer*, and *Motor Gasoline, Winter* (1980-2000); and M. DeLuchi, *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity*, ANL/ESD/TM-22, Vol. 2, Appendixes A-S (Chicago, IL: Argonne National Laboratory, November 1993), p. c-6.

[8] National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* (1995-2000), and *Motor Gasoline, Winter* (1994-1995 to 2000-2001).

[9] Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

against their carbon content. This regression analysis produced the following equation, which is used to estimate the carbon content of crude oil:

*Percent Carbon = 76.99 + (10.19 * Specific Gravity) + (-0.76 * Sulfur Content)* .

Annualized emissions coefficients are developed by inserting the average density and sulfur content for crude oil entering U.S. refineries for each year from 1987 through 2000. This provides the share of carbon in an average barrel of oil during each year. After the share of carbon is derived, it is used in conjunction with fuel density to estimate the total mass of carbon in a barrel of crude oil. An emissions coefficient per unit of energy is then calculated using EIA's standard energy content for crude oil of 5.8 million Btu per barrel.

The 2000 emissions coefficient for crude oil is 20.23 million metric tons carbon per quadrillion Btu, up from the 1999 value of 20.19 million metric tons per quadrillion Btu. The density of crude oil entering U.S. refineries increased, while the sulfur content was nearly unchanged (Table B4).

Table B4. U.S. Crude Oil Characteristics, 1990-2000

Characteristic	1990	1991	1992	1993	1994	1995	1996	1997	998	1999	2000
Density (API Gravity)	31.86	31.64	31.32	31.30	31.39	31.30	31.13	31.07	30.98	31.31	30.99
Density (Specific Gravity)	0.8662	0.8674	0.8691	0.8692	0.8687	0.8692	0.8701	0.8704	0.8709	0.8691	0.8708
Sulfur Content (Percent)	1.1	1.13	1.16	1.15	1.14	1.13	1.15	1.25	1.31	1.33	1.34
Carbon Share (Percent)	84.98%	84.97%	84.96%	84.97%	84.98%	84.99%	84.98%	84.91%	84.87%	84.84%	84.85%
Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	**20.16**	**20.18**	**20.22**	**20.22**	**20.21**	**20.23**	**20.25**	**20.24**	**20.24**	**20.19**	**20.23**

Note: Emissions coefficients assume 100 percent combustion.
Sources: Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years); and Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), p. 91. Web site www.eia.doe.gov/oiaf/1605/87-92rpt/appa.html

Liquefied Petroleum Gases

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and *n*-butane. Because each of these hydrocarbons is a pure paraffinic compound, 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 ethane, C_2H_6, which has an atomic weight of 30, is 80 percent. The densities of these compounds are also well known, allowing emissions coefficients to be calculated easily. EIA collects data on consumption of each compound and then reports them as LPG in the *Petroleum Supply Annual*.[10] By weighting each compound's individual emissions coefficient by its share of energy consumed, an overall emissions coefficient for LPG is derived.

More than 95 percent of all ethane and just under 85 percent of butane consumed goes to nonfuel uses. In contrast, nearly all LPG used as fuel is propane. Thus, the emissions coefficient for LPG used as fuel is 17.18 million metric tons carbon per quadrillion Btu, which is just below the emissions coefficient for propane (Table B5). On the other hand, the carbon emissions coefficient for LPG for nonfuel use is pulled down to 16.87 million metric tons carbon per quadrillion Btu by the large presence of the lighter ethane and its emissions factor of 16.25 million metric tons per quadrillion Btu.

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[10] Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years), Table 2.

Table B5. Emissions Coefficients for Liquefied Petroleum Gas, 1990-2000

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Carbon Content of LPG Consumption for Fuel Use (MMTC)											
Ethane	0.47	0.30	0.45	0.28	0.39	0.40	0.45	0.85	0.82	0.93	0.98
Propane	13.67	13.53	14.48	14.78	14.79	14.82	16.30	15.89	15.21	16.92	16.82
Butane	1.33	0.87	1.29	1.08	1.27	0.83	0.79	0.97	0.92	1.08	1.13
Total	15.46	14.70	16.22	16.14	16.45	16.06	17.54	17.71	16.95	18.93	18.92
Consumption of LPG for Fuel Use (Quadrillion Btu)											
Ethane	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.05	0.05	0.06	0.06
Propane	0.79	0.79	0.84	0.86	0.86	0.86	0.95	0.92	0.88	0.98	0.98
Butane	0.08	0.05	0.07	0.06	0.07	0.05	0.04	0.05	0.05	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
Weighted Average Fuel Use Emissions Coefficient (MMTC/Quad)											
	17.21	17.21	17.21	17.22	17.22	17.20	17.20	17.18	17.18	17.18	17.18
Carbon Content of LPG Non-fuel consumption (MMTC)											
Ethane	8.86	10.11	10.07	10.57	10.54	11.00	12.09	11.51	11.06	12.52	13.21
Propane	9.08	10.11	10.45	9.45	11.21	11.56	11.12	12.29	11.76	13.09	13.00
Butane	2.27	2.98	2.90	2.68	4.35	4.22	4.63	4.39	4.18	4.89	5.10
Total	20.22	23.20	23.42	22.70	26.10	26.78	27.85	28.19	27.00	30.50	31.31
Consumption of LPG for Non-Fuel Use (Quadrillion Btu)											
Ethane	0.55	0.62	0.62	0.65	0.65	0.68	0.74	0.71	0.68	0.77	0.81
Propane	0.53	0.59	0.61	0.55	0.65	0.67	0.65	0.71	0.68	0.76	0.76
Butane	0.13	0.17	0.16	0.15	0.25	0.24	0.26	0.25	0.24	0.28	0.29
Total	1.20	1.38	1.39	1.35	1.55	1.59	1.65	1.67	1.60	1.81	1.86
Weighted Average Non-Fuel Use Emissions Coefficient (MMTC/Quad)											
	16.83	16.84	16.84	16.80	16.88	16.87	16.86	16.88	16.87	16.88	16.87

Source: 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.

Appendix C
Tier 1 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.

EIA in 1998, in response to the IPCC's good practices guidelines, 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 activities.

EIA recently 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. The preliminary results of that analysis appear in a Box at the end of Chapter 1 of this report.

For either "Tier I" or "Tier II" analysis the sources of uncertainty fall into the categories outlined below:

- 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.

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[1] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC 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.

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, delineated in Chapter 1, estimated total uncertainty about a simulated mean of total carbon dioxide, methane and nitrous oxide emissions[4] to be -4.4% to 4.6%. When expressed as a percentage of total estimated 1999 emissions[5], 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 accounts 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 and sequestration 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 fuel 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.

- **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.

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[4] It is important to point out that the Tier 1 analysis includes all UNFCCC greenhouse gases while the Tier 2 analysis does not include HFCs, PFCs and SF_6 emissions in its simulation. The inclusion of these gases, which represent approximately 2.5 percent of total U.S. greenhouse gases, would have increased the uncertainty band in the Tier 2 analysis.

[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.

Table C1. Estimate of the Reliability of 1999 U.S. Emissions Estimates (Tier 1 Method)

Greenhouse Gas Source	Share of Total Emissions	Activity Data Bias Min	Activity Data Bias Max	Activity Data Random	Emissions Factor Bias Min	Emissions Factor Bias Max	Emissions Factor Random	Weighted by Total Emissions min	Weighted by Total Emissions 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.*

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.[6]

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[6] Every year, as this report is prepared for publication, a number of computational errors that have crept into the report are detected and fixed. Sometimes, the detected errors have been present for more than one year. The errors that have been detected are typically very small (about 0.01 to 0.1 percent of emissions) and subtle, and they tend to both raise and lower estimated emissions. EIA is not aware of any remaining computational errors, but it is assumed that any undetected errors generally are similar to, or smaller than, the errors that have been detected.

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.

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 2000 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, 1990-2000
(Million Metric Tons Carbon)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Municipal Solid Waste (biogenic only)	6.4	5.1	6.3	5.8	6.3	6.5	6.4	5.5	4.7	5.0	5.3
Alcohol Fuel	1.6	1.3	1.6	1.8	1.9	2.1	1.5	1.9	2.1	2.2	2.2
Wood and Wood Waste	49.7	49.1	51.1	49.1	51.0	54.1	55.3	52.5	52.5	57.1	57.4
Total Biofuels	57.8	55.5	59.0	56.6	59.2	62.7	63.1	59.9	59.2	64.3	65.0

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 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).
Sources: Underlying energy data from Energy Information Administration, Annual Energy Review 2000, DOE/EIA-0384(2000) (Washington, DC, August 2001), 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.

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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.

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.

"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. Evidence from the electric utility sector— where transmission companies report gas sales and electric utilities report gas purchases—suggests that there may be undercounting of natural gas consumption.

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.

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[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.

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,

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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).

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.

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.

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[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.

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.

Table D2. Estimated U.S. Emissions of Ozone-Depleting Substances, 1990-2000
(Thousand Metric Tons)

Item	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
CFCs											
CFC-11	30.7	31.7	15.7	14.6	13.2	11.5	9.6	9.1	8.4	7.8	7.2
CFC-12	209.8	212.6	217.4	211.7	135.0	61.2	69.6	62.1	52.6	62.7	59.5
CFC-113	39.0	39.8	33.8	27.5	17.9	7.6	*	*	*	*	*
Other CFCs	7.4	6.1	4.5	2.8	2.6	2.3	2.4	2.2	1.8	1.4	1.2
Halons	1.0	1.2	1.4	1.5	1.6	1.6	1.7	1.7	1.8	1.8	1.7
HCFCs											
HCFC-22	34.0	35.4	35.2	35.3	37.7	39.3	41.0	42.4	43.9	74.1	79.1
HCFC-141b	1.3	1.7	1.7	2.9	6.2	9.9	9.9	8.8	9.7	10.9	10.9
HCFC-142b	0.8	1.4	1.9	2.6	3.3	3.6	4.0	4.3	4.7	5.0	5.4
Other HCFCs	*	*	0.4	3.0	5.8	6.3	6.7	7.1	7.4	7.6	7.7
Other Chemicals											
Carbon Tetrachloride	25.1	25.6	20.9	16.0	10.9	5.5	*	*	*	*	*
Methyl Chloroform	27.9	28.5	23.8	19.0	13.9	8.7	1.6	*	*	*	*

*Less than 50 metric tons of gas.
P=Preliminary data.
Source: Environmental Protection Agency, Office of Air and Radiation, web site: www.epa.gov/globalwarming/.

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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.

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, 1990-2000
(Million Metric Tons of Gas)

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Carbon Monoxide	89.3	91.7	89.2	89.8	93.4	84.6	91.9	91.2	87.1	87.5	**N/A**
Nitrogen Oxides	21.8	21.9	22.3	22.6	22.9	22.5	23.4	23.7	23.4	22.8	**N/A**
Nonmethane VOCS	19.1	19.3	18.9	19.1	19.7	19.0	17.6	17.9	16.9	16.4	**N/A**

Note: Revised
Source: U.S. EPA, Office of Air Quality Planning and Standards, National Air Pollutant Emission Trends Summaries, June 2001, Table A-3.

Appendix E

Emissions of Energy-Related Carbon Dioxide in the United States, 1949-2000

Overview

This appendix presents estimates of U.S. carbon dioxide emissions for the period 1949-2000. The data were developed originally at the request of the President's Council of Economic Advisors, for inclusion in a graphic that appeared in the 1997 *Economic Report of the President*.[1] U.S. energy data have undergone a number of shifts over the years, and the estimates can be divided into three periods:

- **1980-2000.** The emissions estimates for this period were developed using the methods and sources described in this report. For 1980 though 1997, the energy data on which the emissions estimates are based come from the Energy Information Administration (EIA) data series published in the *State Energy Data Report*.[2] Estimates for 1998 through 2000, are based on energy data from EIA's *Monthly Energy Review*.
- **1960-1979.** 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 not as reliable as those for subsequent years. EIA has also not attempted to develop annual emissions coefficients for fuels in use before 1980, and the estimates do not reflect any changes in fuel quality. The energy data for this period are also drawn from the database of the *State Energy Data Report*.
- **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 drawn from the *Annual Energy Review*.[3]

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[1] Council of Economic Advisors, *Economic Report of the President* (Washington DC, February 1998), p. 167.

[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.

[3] Energy Information Administration, *Annual Energy Review 1998*, DOE/EIA-0384(98) (Washington, DC, July 1999), pp. 37, web site www.eia.doe.gov/emeu/aer/contents.html.

Table E1. Energy-Related Carbon Dioxide Emissions from the Residential and Commercial Sectors by Fuel Type, 1949-2000

(Million Metric Tons of Carbon)

	Residential					Commercial				
Year	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	19.2	2.3	149.1	210.8
1990	65.1	24.0	1.6	166.4	257.0	38.8	18.0	2.4	151.0	210.3
1991	67.5	24.5	1.4	168.2	261.6	40.4	17.1	2.2	150.7	210.4
1992	69.4	24.9	1.5	166.0	261.8	41.5	16.1	2.2	150.9	210.8
1993	73.4	26.3	1.5	177.2	278.4	42.4	14.9	2.2	157.7	217.2
1994	71.7	25.4	1.4	177.3	275.8	42.9	14.9	2.1	160.5	220.4
1995	71.8	25.8	1.4	178.9	277.9	44.9	14.1	2.1	163.5	224.6
1996	77.6	27.6	1.4	187.3	293.9	46.8	14.6	2.1	169.5	233.1
1997	73.8	27.1	1.5	190.4	292.8	47.7	13.9	2.2	181.5	245.4
1998	67.2	25.0	1.1	200.4	293.7	44.6	13.0	1.7	191.1	250.4
1999	69.9	27.3	1.2	200.3	298.8	45.1	13.1	1.8	193.1	253.1
P2000	73.2	27.5	1.2	211.5	313.4	49.3	14.2	1.8	202.5	267.8

Note: P = Preliminary

Sources:
1998-2000 Estimates documented in this report, based on energy data in the *Monthly Energy Review*.
1980-1997 Estimates documented in this report, based on energy data in the *State Energy Data Report*.
1960-1979 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, 1949-2000

(Million Metric Tons of Carbon)

	Industrial					Transportation				
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	75.4	162.3	484.2	9.4	368.1	0.0	0.6	378.1
1981	116.3	110.0	75.8	161.2	463.3	9.5	364.0	0.0	0.6	374.1
1982	100.1	104.0	61.2	142.9	408.2	8.8	356.1	0.0	0.6	365.6
1983	95.2	96.0	60.2	148.2	399.6	7.3	359.0	0.0	0.6	366.9
1984	104.1	105.8	69.3	157.3	436.5	7.8	370.5	0.0	0.7	379.0
1985	98.9	99.9	67.8	157.6	424.1	7.5	376.0	0.0	0.7	384.3
1986	93.1	101.8	64.7	152.8	412.5	7.2	391.0	0.0	0.7	399.0
1987	101.8	101.4	66.1	158.6	427.9	7.7	402.5	0.0	0.7	411.0
1988	106.9	104.8	71.1	165.1	447.9	9.1	417.5	0.0	0.7	427.3
1989	112.8	98.9	69.4	170.0	451.1	9.4	422.4	0.0	0.7	432.5
1990	101.2	98.9	63.4	189.0	452.7	9.8	421.2	0.0	0.7	431.8
1991	101.0	93.1	59.3	186.2	439.8	9.0	414.6	0.0	0.7	424.2
1992	102.7	101.2	56.1	194.2	455.1	8.8	421.6	0.0	0.7	431.1
1993	105.5	94.4	55.6	196.6	452.9	9.3	426.4	0.0	0.7	436.4
1994	106.6	97.5	55.8	201.9	463.3	10.2	438.2	0.0	0.9	449.3
1995	111.9	92.3	55.9	199.4	461.1	10.4	446.5	0.0	0.8	457.8
1996	116.5	100.1	54.2	204.6	476.1	10.6	457.4	0.0	0.8	468.9
1997	115.0	100.8	54.5	210.1	481.5	11.3	461.5	0.0	0.8	473.6
1998	106.5	96.2	50.4	214.7	469.5	9.5	471.2	0.0	0.9	481.5
1999	104.7	91.8	49.6	218.2	465.8	11.0	487.6	0.0	0.9	499.4
P2000	104.0	87.6	45.7	226.7	465.7	11.4	502.5	0.0	0.9	514.8

Note: P= Preliminary

Sources:
1998-2000 Estimates documented in this report, based on energy data in the Monthly Energy Review.
1980-1997 Estimates documented in this report, based on energy data in the State Energy Data Report.
1960-1979 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, 1949-2000,

(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	474.7
1989	268.4	210.8	451.1	432.5	1362.8	41.2	35.4	409.4	486.1
1990	257.0	210.3	452.7	431.8	1351.6	58.3	28.2	420.4	507
1991	261.6	210.4	439.8	424.2	1336.2	60.3	26.8	418.8	506
1992	261.8	210.8	455.1	431.1	1359.0	63.9	22.8	425.3	512
1993	278.4	217.2	452.9	436.4	1385.1	64.9	25.6	441.9	532.4
1994	275.8	220.4	463.3	449.3	1408.9	70.2	24.1	446.3	540.7
1995	277.9	224.6	461.1	457.8	1421.1	75.5	17.6	449.4	542.5
1996	293.9	233.1	476.1	468.9	1471.7	68.9	18.9	474.3	562.1
1997	292.8	245.4	481.5	473.6	1493.4	73.7	21.4	487.9	583.1
1998	293.7	250.4	469.5	481.5	1495.4	82.6	29.0	495.5	607.2
1999	298.8	253.1	465.8	499.4	1517.2	84.7	29.4	498.6	612.6
P2000	313.4	267.8	465.7	514.8	1561.7	93.2	26.0	522.4	641.6

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

P = Preliminary.

Sources:
1998-2000 Estimates documented in this report, based on energy data in the Monthly Energy Review.
1980-1997 Estimates documented in this report, based on energy data in the State Energy Data Report.
1960-1979 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

Permutations of SI Units

1 gC = 1 gram carbon (C)
1 GgC = gigagram carbon (C) = 1,000 metric tons carbon (C)
1 TgC = 1 teragram carbon (C) = 1 million metric tons carbon (C)
1 PgC = 1 petagram carbon (C) = 1 billion metric tons carbon (C)
1 ppmv = 1 part per million by volume in the atmosphere
1 ppbv = 1 part per billion by volume in the atmosphere
1 pptv = 1 part per trillion by volume in the atmosphere

Density

1 thousand cubic feet of methane = 42.28 pounds
1 thousand cubic feet carbon dioxide = 115.97 pounds
1 metric ton natural gas liquids = 11.6 barrels
1 metric ton unfinished oils = 7.46 barrels
1 metric ton alcohol = 7.94 barrels
1 metric ton liquefied petroleum gas = 11.6 barrels
1 metric ton aviation gasoline = 8.9 barrels
1 metric ton naphtha jet fuel = 8.27 barrels
1 metric ton kerosene jet fuel = 7.93 barrels
1 metric ton motor gasoline = 8.53 barrels
1 metric ton kerosene = 7.73 barrels
1 metric ton naphtha = 8.22 barrels
1 metric ton distillate = 7.46 barrels
1 metric ton residual oil = 6.66 barrels
1 metric ton lubricants = 7.06 barrels
1 metric ton bitumen = 6.06 barrels
1 metric ton waxes = 7.87 barrels
1 metric ton petroleum coke = 5.51 barrels
1 metric ton petrochemical feedstocks = 7.46 barrels
1 metric ton special naphtha = 8.53 barrels
1 metric ton miscellaneous products = 8.00 barrels

Alternative Measures of Greenhouse Gases

1 pound methane, measured in carbon units (CH_4-C) = 1.333 pounds methane, measured at full molecular weight (CH_4)
1 pound carbon dioxide, measured in carbon units (CO_2-C) = 3.6667 pounds carbon dioxide, measured at full molecular weight (CO_2)
1 pound carbon monoxide, measured in carbon units (CO-C) = 2.333 pounds carbon monoxide, measured at full molecular weight (CO)
1 pound nitrous oxide, measured in nitrogen units (N_2O-N) = 1.571 pounds nitrous oxide, measured at full molecular weight (N_2O)

Weight

1 kilogram = 2.205 pounds
1 short ton = 0.9072 metric tons
1 metric ton = 1.1023 short tons = 2,204.6 pounds
1 cubic meter = 35.3147 cubic feet
1 cubic centimeter = 3.531 ×× 10^{-5} cubic feet

Area

1 acre = 0.40468724 hectare (ha) = 4,047 m^2
1 hectare (ha) = 10,000 m^2 = 2.47 acres
1 kilometer = 0.6214 miles

Energy

1 joule = 947.9 ×× 10^{-21} quadrillion Btu
1 exajoule = 10^{18} joules = 0.9479 quadrillion Btu
1 quadrillion Btu = 1.0551 exajoule