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April 2000

Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1998

How to Obtain Copies

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For Further Information

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For more information regarding climate change and greenhouse gas emissions see EPA web side at http://www.epa.gov/globalwarming/emissions/national.

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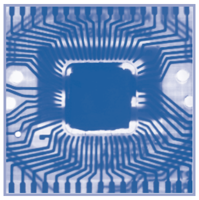
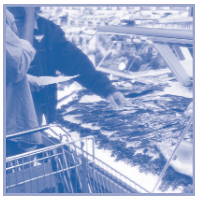
High GWP Gas Emissions from Industrial Processes

The processes and applications pictured on the front and back cover of this report can lead to anthropogenic emissions of long-lived fluorinated compounds, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). HFCs, PFCs and SF_6 are not harmful to the stratospheric ozone layer, but they are powerful greenhouse gases that can be thousands of times more potent than CO_2 and may have extremely long atmospheric lifetimes.



Semiconductors: The semiconductor industry uses a variety of long-lived fluorinated gases (PFCs, HFC-23, SF_6 and NF_3) in dry etching and cleaning chemical vapor deposition tool chambers. Dry etching using fluorinated gases in a plasma provides pathways to electrically connect individual circuit components in the silicon. Chemical vapor deposition chambers, used for depositing insulating and conducting materials, are cleaned periodically using PFCs and other fluorinated gases.



Refrigerant (grocery): Cold food found in supermarkets, convenience stores, restaurants and other food service establishments are typically displayed in refrigeration units that may use HFC-134a, blends of HCFCs and HFCs, or other refrigerants. This type of equipment can range in size from small reach-in refrigerators and freezers, to refrigerated display cases, to walk-in coolers and freezers. Supermarkets usually employ large systems that contain many display cases connected by means of extensive piping. Because this piping may be miles long, the amount of refrigerant in these units can be very high.

HCFC-22: HCFC-22 is primarily used in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. HFC-23, which has a global warming potential 11,700 times that of CO_2, is a by-product of HCFC-22 manufacture. Once separated from HCFC-22, the HFC-23 is generally vented to the atmosphere or may be captured for use in a limited number of applications. Because HCFC-22 depletes stratospheric ozone, HCFC-22 production for non-feedstock uses is scheduled to be phased out by 2020 under the U.S. Clean Air Act. Feedstock production is permitted to continue indefinitely.

Electrical Transmission and Distribution: The largest use for sulfur hexafluoride (SF_6) is as an electrical insulator in equipment that transmits and distributes electricity. Many gas-insulated substations, circuit breakers and other switchgear contain SF_6 because of its dielectric strength and arc-quenching characteristics. Fugitive emissions of SF_6 can escape from this equipment through seals, especially from older equipment, or when the equipment is opened for servicing.

Inventory of U.S. Greenhouse Gas Emissions and Sinks:

1990 – 1998

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Within the EPA, many Offices contributed data, analysis and technical review for this report. The EPA Office of Atmospheric Programs developed methodologies and provided detailed emission estimates for numerous source categories, particularly for methane, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. The Office of Mobile Sources and the Office of Air Quality Planning and Standards provided analysis and review for several of the source categories addressed in this report. The Office of Solid Waste and the Office of Research and Development also contributed analysis and research.

Other government agencies have contributed data as well, including the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, and the Federal Aviation Administration.

We would especially like to thank the staff of the Global Environmental Issues Group at ICF Consulting for synthesizing this report and preparing many of the individual analyses.

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[1] See http://www.epa.gov/globalwarming/inventory

Preface

The United States Environmental Protection Agency (EPA) prepares the official *U.S. Inventory of Greenhouse Gas Emissions and Sinks* to comply with existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC)[1]. Under a decision of the UNFCCC Conference of the Parties, national inventories for most UNFCCC Annex I parties should be provided to the UNFCCC Secretariat each year by April 15.

In an effort to engage the public and researchers across the country, the EPA has instituted an annual public review and comment process for this document. The availability of the draft document is announced via Federal Register Notice and is posted on the EPA web page.[2] Copies are also mailed upon request. The public comment period is generally limited to 30 days; however, comments received after the closure of the public comment period are accepted and considered for the next edition of this annual report. The EPA's policy is to allow at least 60 days for public review and comment when proposing new regulations or documents supporting regulatory development—unless statutory or judicial deadlines make a shorter time necessary—and 30 days for non-regulatory documents of an informational nature such as the Inventory document.

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[1] See http://www.unfccc.de

[2] See http://www.epa.gov/globalwarming/emissions/national

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Executive Summary

Central to any study of climate change is the development of an emissions inventory that identifies and quantifies a country's primary anthropogenic[1] sources and sinks of greenhouse gas emissions. This inventory adheres to both (1) a comprehensive and detailed methodology for estimating sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent mechanism that enables signatory countries to the United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission sources and greenhouse gases to climate change. Moreover, systematically and consistently estimating national and international emissions is a prerequisite for accounting for reductions and evaluating mitigation strategies.

In June of 1992, the United States signed the UNFCCC. The objective of the UNFCCC is "to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[2]

Parties to the Convention, by signing, make commitments "to develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"[3] The United States views this report as an opportunity to fulfill this commitment under UNFCCC.

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 1998. To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC signatory countries, the estimates presented here were calculated using methodologies consistent with those recommended in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). For most source categories, the IPCC default methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that con-

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[1] The term "anthropogenic", in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC/UNEP/OECD/IEA 1997).

[2] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <http://www.unfccc.de>.

[3] Article 4 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (also identified in Article 12). See <http://www.unfccc.de>.

tain bromine are referred to as halons. CFCs, HCFCs, and halons are stratospheric ozone depleting substances and are covered under the Montreal Protocol. Other fluorine containing halogenated substances include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). HFCs, PFCs, and SF_6 do not deplete stratospheric ozone.

There are also several gases that do not have a direct global warming effect but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone. These gases referred to as ozone precursors include carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane volatile organic compounds (NMVOCs).[4] Aerosols extremely small particles or liquid droplets often produced by emissions of sulfur dioxide (SO_2) can also affect the absorptive characteristics of the atmosphere.

Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, their atmospheric concentrations have been affected by human activities. Since pre-industrial time (i.e., since about 1750), concentrations of these greenhouse gases have increased by 28, 145, and 13 percent, respectively (IPCC 1996). This build-up has altered the composition of the earth's atmosphere, and affects the global climate system.

Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODSs) increased by nearly 10 percent per year until the mid-1980s, when international concern about ozone depletion led to the signing of the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Since then, the consumption of ODSs has been undergoing a phase-out. In contrast, use of ODS substitutes such as HFCs, PFCs, and SF_6 has grown significantly during this time.

Recent Trends in U.S. Greenhouse Gas Emissions

Total U.S. greenhouse gas emissions rose in 1998 to 1,834.6 million metric tons of carbon equivalents (MMTCE)[5] (11.2 percent above 1990 baseline). The single year increase in emissions from 1997 to 1998 was 0.4 percent (6.8 MMTCE), less than the average annual rate of increase for 1990 through 1998 (1.2 percent). Figure ES-1 through Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute change since 1990. Table ES-1 provides a

Figure ES-1

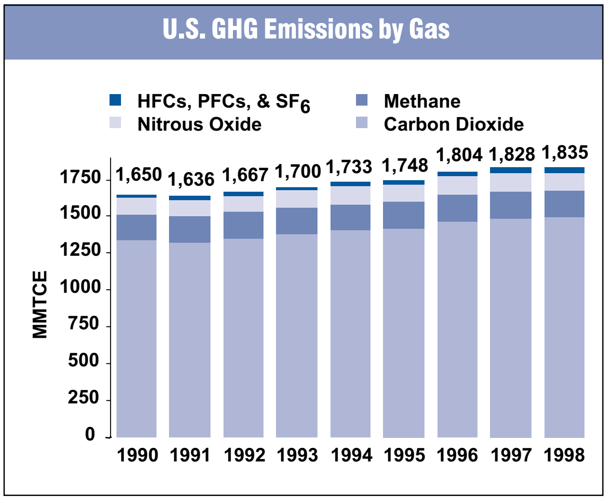
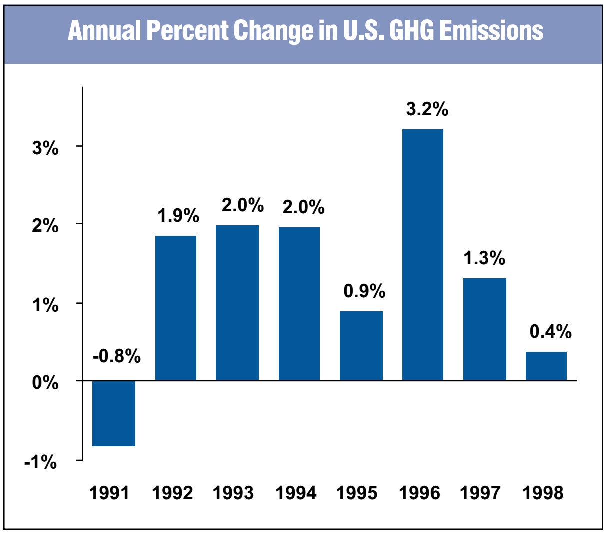


Figure ES-2



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[4] Also referred to in the U.S. Clean Air Act as "criteria pollutants."

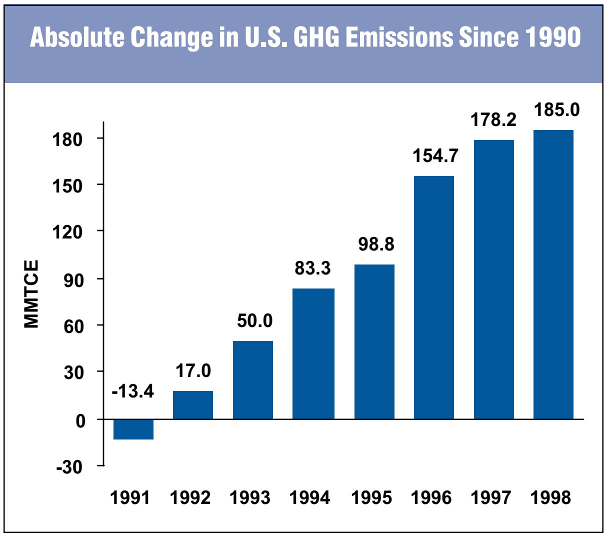
[5] Estimates are presented in units of millions of metric tons of carbon equivalents (MMTCE), which weights each gas by its GWP value, or Global Warming Potential (see following section).

detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 1998.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 1998. The primary greenhouse gas emitted by human activities was CO_2. The largest source of CO_2 and of overall greenhouse gas emissions in the United States was fossil fuel combustion. Methane emissions resulted primarily from decomposition of wastes in landfills, manure and enteric fermentation associated with domestic livestock, natural gas systems, and coal mining. Emissions of N_2O were dominated by agricultural soil management and mobile source fossil fuel combustion. The substitution of ozone depleting substances and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate HFC emissions. PFC emissions came mainly from primary aluminum production, while electrical transmission and distribution systems emitted the majority of SF_6.

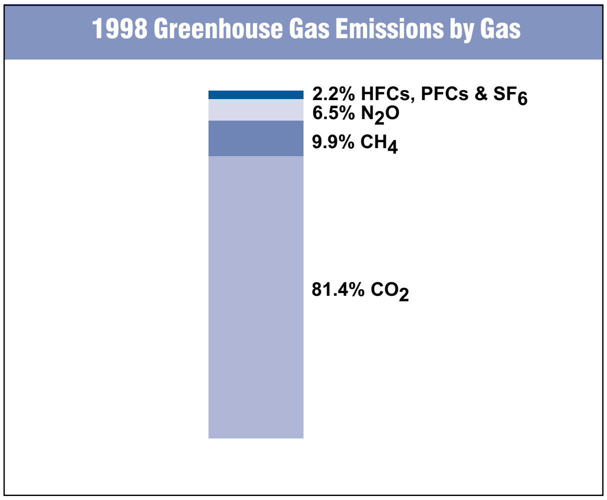
As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion, accounted for 80 percent of weighted emissions in 1998. Emissions from this source grew by 11 percent (148.1 MMTCE) from 1990 to 1998 and were also responsible for over 80 percent of the increase in national emissions during this period. The annual increase in CO_2 emissions from this source was only 0.5 percent in 1998 lower than the source's average annual rate of 1.3 percent during the 1990s despite a strong 3.9 percent increase in U.S. gross domestic product.

Figure ES-3



Absolute Change in U.S. GHG Emissions Since 1990

Figure ES-4



1998 Greenhouse Gas Emissions by Gas

In addition to economic growth, changes in CO_2 emission from fossil fuel combustion are also correlated with energy prices and seasonal temperatures. Exceptionally mild winter conditions in 1998 moderated growth in CO_2 emissions from fossil fuel combustion below what would have been expected given the strength of the economy and continued low fuel prices. Table ES-2 shows annual changes in emissions during the last few years of the 1990s for particular fuel types and sectors.

Carbon dioxide emissions from fossil fuel combustion increased dramatically in 1996, due primarily to two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as to colder winter conditions and the associated rise in demand for natural gas from residential, commercial and industrial customers for heating caused gas prices to rise sharply; and 2) higher consumption of petroleum fuels for transportation. Milder weather conditions in summer and winter moderated the growth in emissions in 1997; however, the shut-down of several nuclear power plants lead electric utilities to increase their consumption of coal to offset the lost capacity. In 1998, weather conditions were a dominant factor in slowing the growth in emissions. Warm winter temperatures resulted in a significant drop in residential, commercial, and industrial natural gas consumption. This drop in emissions from natural gas used for heating was primarily offset by two factors: 1) electric utility emissions, which increased in part due to a hot summer and its associated air conditioning de-

Table ES-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**1,340.3**	**1,326.1**	**1,350.4**	**1,383.3**	**1,404.8**	**1,416.5**	**1,466.2**	**1,486.4**	**1,494.0**
Fossil Fuel Combustion	1,320.1	1,305.8	1,330.1	1,361.5	1,382.0	1,392.0	1,441.3	1,460.7	1,468.2
Cement Manufacture	9.1	8.9	8.9	9.4	9.8	10.0	10.1	10.5	10.7
Natural Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.2	3.9
Lime Manufacture	3.0	3.0	3.1	3.1	3.2	3.4	3.6	3.7	3.7
Waste Combustion	2.8	3.0	3.0	3.1	3.1	3.0	3.1	3.4	3.5
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.9	2.0	2.3	2.4
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2
Carbon Dioxide Consumption	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4
Land-Use Change and Forestry (Sink)[a]	(316.4)	(316.3)	(316.2)	(212.7)	(212.3)	(211.8)	(211.3)	(211.1)	(210.8)
International Bunker Fuels[b]	32.2	32.7	30.0	27.2	26.7	27.5	27.9	29.9	31.3
CH_4	**177.9**	**177.7**	**179.4**	**178.7**	**181.6**	**184.1**	**183.1**	**183.8**	**180.9**
Landfills	58.2	58.1	59.1	59.6	59.9	60.5	60.2	60.2	58.8
Enteric Fermentation	32.7	32.8	33.2	33.7	34.5	34.9	34.5	34.2	33.7
Natural Gas Systems	33.0	33.4	33.9	34.6	34.3	34.0	34.6	34.1	33.6
Manure Management	15.0	15.5	16.0	17.1	18.8	19.7	20.4	22.1	22.9
Coal Mining	24.0	22.8	22.0	19.2	19.4	20.3	18.9	18.8	17.8
Petroleum Systems	7.4	7.5	7.2	6.9	6.7	6.7	6.5	6.5	6.3
Rice Cultivation	2.4	2.3	2.6	2.4	2.7	2.6	2.4	2.6	2.7
Stationary Sources	2.3	2.4	2.4	2.4	2.4	2.5	2.6	2.3	2.3
Mobile Sources	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.3
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Petrochemical Production	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Agricultural Residue Burning	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Silicon Carbide Production	+	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	+	+	+	+	+	+	+	+	+
N_2O	**108.2**	**110.5**	**113.3**	**113.8**	**121.5**	**118.8**	**121.5**	**122.4**	**119.4**
Agricultural Soil Management	75.3	76.3	78.2	77.3	83.5	80.4	82.4	84.2	83.9
Mobile Sources	13.8	14.6	15.7	16.5	17.1	17.4	17.5	17.3	17.2
Nitric Acid	4.9	4.9	5.0	5.1	5.3	5.4	5.6	5.8	5.8
Stationary Sources	3.8	3.8	3.9	3.9	4.0	4.0	4.2	4.2	4.3
Manure Management	3.4	3.6	3.5	3.7	3.8	3.7	3.8	3.9	4.0
Human Sewage	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2
Adipic Acid	5.0	5.2	4.8	5.2	5.5	5.5	5.7	4.7	2.0
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[b]	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
HFCs, PFCs, and SF_6	**23.3**	**22.0**	**23.5**	**23.8**	**25.1**	**29.0**	**33.5**	**35.3**	**40.3**
Substitution of Ozone Depleting Substances	0.3	0.2	0.4	1.4	2.7	7.0	9.9	12.3	14.5
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2	10.9
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	3.0	3.0	3.0
Aluminum Production	5.4	4.7	4.4	3.8	3.2	3.1	3.2	3.0	2.8
Semiconductor Manufacture	0.8	0.8	0.8	1.0	1.1	1.5	1.9	1.9	2.1
Total Emissions	**1,649.7**	**1,636.2**	**1,666.6**	**1,699.7**	**1,733.0**	**1,748.5**	**1,804.4**	**1,827.9**	**1,834.6**
Net Emission (Sources and Sinks)	**1,333.3**	**1,320.0**	**1,350.5**	**1,487.0**	**1,520.7**	**1,536.6**	**1,593.1**	**1,616.8**	**1,623.8**

+ Does not exceed 0.05 MMTCE

[a] Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

[b] Emissions from International Bunker Fuels are not included in totals.

Note: Totals may not sum due to independent rounding.

Table ES-2: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMTCE and Percent)

Sector	Fuel Type	1995 to 1996		1996 to 1997		1997 to 1998	
Electric Utility	Coal	24.5	5.7%	14.3	3.1%	5.5	1.2%
Electric Utility	Petroleum	1.4	10.0%	2.2	14.4%	7.3	41.6%
Electric Utility	Natural Gas	(6.9)	(14.6%)	3.3	8.1%	4.2	9.8%
Transportation[a]	Petroleum	13.8	3.3%	1.1	0.2%	7.2	1.7%
Residential	Natural Gas	5.8	8.1%	(3.8)	(4.9%)	(7.4)	(10.0%)
Commercial	Natural Gas	1.9	4.2%	0.9	1.9%	(2.7)	(5.7%)
Industrial	Natural Gas	4.7	3.4%	(1.4)	(1.0%)	(2.9)	(2.0%)
All Sectors[b]	**All Fuels[b]**	**49.4**	**3.5%**	**19.4**	**1.3%**	**7.5**	**0.5%**

[a] Excludes emissions from International Bunker Fuels.
[b] Includes fuels and sectors not shown in table.

mand; and 2) increased motor gasoline consumption for transportation.

Overall, from 1990 to 1998, total emissions of CO_2, CH_4, and N_2O increased by 153.7 (11 percent), 3.1 (2 percent), and 11.1 MMTCE (10 percent), respectively. During the same period, weighted emissions of HFCs, PFCs, and SF_6 rose by 17.0 MMTCE (73 percent). Despite being emitted in smaller quantities relative to the other principle greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because of their extremely high Global Warming Potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests and in landfilled carbon, which were estimated to be 12 percent of total emissions in 1998.

Other significant trends in emissions from additional source categories over the nine year period from 1990 through 1998 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 14.2 MMTCE. This increase was partly offset, however, by reductions in PFC emissions from aluminum production by 2.6 MMTCE (48 percent), which were the result of both voluntary industry emission reduction efforts and lower domestic aluminum production.
- Combined N_2O and CH_4 emissions from mobile combustion rose by 3.3 MMTCE (22 percent), primarily due to increased rates of N_2O generation in highway vehicles.
- Methane emissions from the manure management activities have increased by 7.9 MMTCE (53 percent) as the composition of the swine and dairy industries shift toward larger facilities. An increased number of large facilities leads to an increased use of liquid systems, which translates into increased methane production.
- Methane emissions from coal mining dropped by 6.2 MMTCE (26 percent) as a result of the mining of less gassy coal from underground mines and the increased use of methane from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 8.5 MMTCE (11 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.
- By 1998, all of the three major adipic acid producing plants had voluntarily implemented N_2O abatement technology; as a result, emissions fell by 3.0 MMTCE (60 percent). The majority of this decline occurred from 1997 to 1998, despite increased production.
- The following sections describe the concept of Global Warming Potentials (GWPs), present the anthropogenic sources and sinks of greenhouse gas emissions in the United States, briefly discuss emission pathways, further summarize the emission estimates, and explain the relative importance of emissions from each source category.

Box ES-1: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

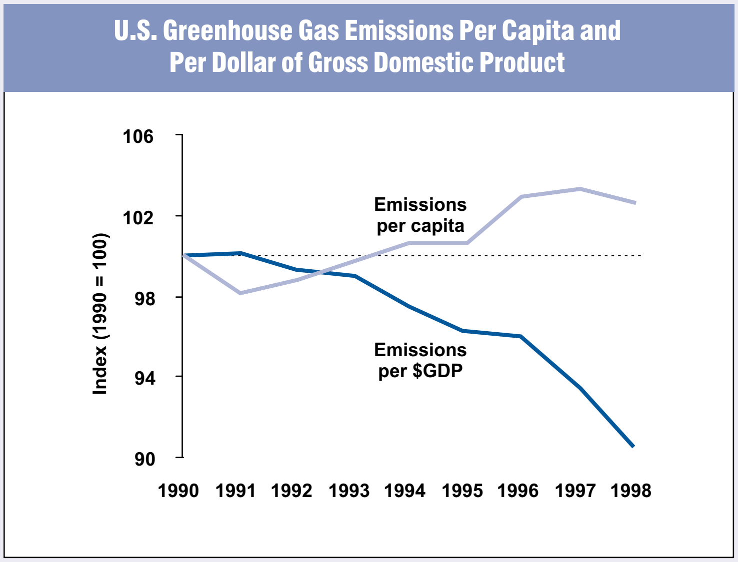
There are several ways to assess a nation's greenhouse gas emitting intensity. These measures of intensity could be based on aggregate energy consumption because energy-related activities[6] are the largest sources of emissions, on fossil fuel consumption only because almost all energy-related emissions involve the combustion of fossil fuels, on electricity consumption because electric utilities were the largest sources of U.S. greenhouse gas emissions in 1998, on total gross domestic product as a measure of national economic activity, or on a per capita basis. Depending upon which of these measures is used, the United States could appear to have reduced or increased its national greenhouse gas intensity. Table ES-3 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.3 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption thereby indicating an improved or lower greenhouse gas emitting intensity and much slower than that for either electricity consumption or overall gross domestic product. Emissions, however, are growing faster than national population, thereby indicating a worsening or higher greenhouse gas emitting intensity on a per capita basis (see Figure ES-5). Overall, atmospheric CO_2 concentrations a function of many complex anthropogenic and natural processes are increasing at 0.4 percent per year.

Table ES-3: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1991	1992	1993	1994	1995	1996	1997	1998	Growth Rate[f]
GHG Emissions[a]	99	101	103	105	106	109	111	111	1.3%
Energy Consumption[b]	100	101	104	106	108	112	112	112	1.4%
Fossil Fuel Consumption[b]	99	101	103	105	106	110	111	111	1.4%
Electricity Consumption[b]	102	102	105	108	111	114	116	119	2.2%
GDP[c]	99	102	104	108	110	114	118	123	2.6%
Population[d]	101	102	103	104	105	106	107	108	1.0%
Atmospheric CO_2 Concentration[e]	100	101	101	101	102	102	103	104	0.4%

[a] GWP weighted values
[b] Energy content weighted values. (DOE/EIA)
[c] Gross Domestic Product in chained 1992 dollars (BEA 1999)
[d] (U.S. Census Bureau 1999)
[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 1999)
[f] Average annual growth rate

Figure ES-5



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[6] Energy-related activities are those that involve fossil fuel combustion (industrial, transportation, residential, and commercial end-use sectors), and the production, transmission, storage, and distribution of fossil fuels.

pathways further summarize the emission estimates, and explain the relative importance of emissions from each source category.

Global Warming Potentials

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself is a greenhouse gas; indirect radiative forcing occurs when chemical transformations of the original gas produce a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The concept of a Global Warming Potential (GWP) has been developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. Carbon dioxide was chosen as the reference gas to be consistent with IPCC guidelines.

Global Warming Potentials are not provided for the criteria pollutants CO, NO_x, NMVOCs, and SO_2 because there is no agreed upon method to estimate the contribution of gases that have only indirect effects on radiative forcing (IPCC 1996).

All gases in this executive summary are presented in units of million metric tons of carbon equivalents (MMTCE). Carbon comprises $12/44^{\text{ths}}$ of carbon dioxide by weight. The relationship between gigagrams (Gg) of a gas and MMTCE can be expressed as follows:

$$\text{MMTCE} = (\text{Gg of gas}) \times \left(\frac{\text{MMT}}{1{,}000\ \text{Gg}}\right) \times (\text{GWP}) \times \left(\frac{12}{44}\right)$$

The GWP of a greenhouse gas is the ratio of global warming, or radiative forcing—both direct and indirect—from one unit mass of a greenhouse gas to that of one unit mass of carbon dioxide over a period of time. While any time period can be selected, the 100 year GWPs recommended by the IPCC and employed by the United States for policy making and reporting purposes were used in this report (IPCC 1996). GWP values are listed below in Table ES-6.

Box ES-2: Greenhouse Gas Emissions from Transportation Activities

Motor vehicle usage is increasing all over the world, including in the United States. Since the 1970s, the number of highway vehicles registered in the United States has increased faster than the overall population, according to the Federal Highway Administration (FHWA). Likewise, the number of miles driven up 21 percent from 1990 to 1998 and gallons of gasoline consumed each year in the United States have increased relatively steadily since the 1980s, according to the FHWA and Energy Information Administration, respectively. These increases in motor vehicle usage are the result of a confluence of factors including population growth, economic growth, increasing urban sprawl, and low fuel prices.

One of the unintended consequences of these changes is a slowing of progress toward cleaner air in both urban and rural parts of the country. Passenger cars, trucks, motorcycles, and buses emit significant quantities of air pollutants with local, regional, and global effects. Motor vehicles are major sources of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nonmethane volatile organic compounds (NMVOCs), nitrogen oxides (NO_x), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). Motor vehicles are also important contributors to many serious air pollution problems, including ground-level ozone (i.e., smog), acid rain, fine particulate matter, and global warming. Within the United States and abroad, government agencies have taken actions to reduce these emissions. Since the 1970s, the EPA has required the reduction of lead in gasoline, developed strict emission standards for new passenger cars and trucks, directed states to enact comprehensive motor vehicle emission control programs, required inspection and maintenance programs, and more recently, introduced the use of reformulated gasoline. New vehicles are now equipped with advanced emissions controls, which are designed to reduce emissions of nitrogen oxides, hydrocarbons, and carbon monoxide.

Table ES-4 summarizes greenhouse gas emissions from all transportation-related activities. Overall, transportation activities excluding international bunker fuels accounted for an almost constant 26 percent of total U.S. greenhouse gas emissions from 1990 to 1998. These emissions were primarily CO_2 from fuel combustion, which increased by 11 percent from 1990 to 1998. However, because of larger increases in N_2O and HFC emissions during this period, overall emissions from transportation activities actually increased by 13 percent.

Table ES-4: Transportation-Related Greenhouse Gas Emissions (MMTCE)

Gas/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**399.6**	**391.5**	**401.1**	**409.1**	**422.3**	**427.7**	**441.7**	**443.4**	**450.3**
Passenger Cars	169.1	167.6	171.7	173.3	172.2	175.0	178.5	180.0	185.1
Light-Duty Trucks	77.4	77.1	77.1	80.4	87.1	88.9	91.1	92.1	94.6
Other Trucks	56.3	54.2	55.9	59.1	62.1	63.6	67.7	70.1	70.3
Buses	2.7	2.8	2.9	3.0	3.3	3.5	3.0	3.2	3.2
Aircraft[a]	48.2	46.1	45.5	45.8	48.0	46.8	49.1	48.8	49.4
Boats and Vessels	15.1	14.4	18.5	17.3	17.0	17.0	18.1	13.7	12.5
Locomotives	7.3	6.8	7.3	6.7	7.9	8.1	8.7	9.0	9.0
Other[b]	23.6	22.3	22.3	23.6	24.8	24.8	25.4	26.5	26.3
International Bunker Fuels[c]	32.2	32.7	30.0	27.2	26.7	27.5	27.9	29.9	31.3
CH_4	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.4**	**1.4**	**1.4**	**1.3**
Passenger Cars	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5
Light-Duty Trucks	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.5
Other Trucks and Buses	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Aircraft	+	+	+	+	+	+	+	+	+
Boats and Vessels	+	+	+	+	+	+	+	+	+
Locomotives	+	+	+	+	+	+	+	+	+
Other[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[c]	+	+	+	+	+	+	+	+	+
N_2O	**13.8**	**14.6**	**15.7**	**16.5**	**17.1**	**17.4**	**17.5**	**17.3**	**17.2**
Passenger Cars	8.1	8.0	8.4	8.6	8.8	8.9	8.9	8.7	8.6
Light-Duty Trucks	4.2	5.1	5.8	6.4	6.6	6.8	6.8	6.8	6.8
Other Trucks and Buses	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.9	1.0
Aircraft[d]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Boats and Vessels	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other[d]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
International Bunker Fuels[c]	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
HFCs	**+**	**+**	**0.2**	**0.7**	**1.8**	**2.6**	**3.7**	**4.7**	**4.7**
Mobile Air Conditioners[e]	+	+	0.2	0.7	1.8	2.6	3.7	4.7	4.7
Total[c]	**414.8**	**407.5**	**418.4**	**427.8**	**442.7**	**449.2**	**464.3**	**466.8**	**473.5**

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

[a] Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.

[b] "Other" CO_2 emissions include motorcycles, construction equipment, agricultural machinery, pipelines, and lubricants.

[c] Emissions from International Bunker Fuels include emissions from both civilian and military activities, but are not included in totals.

[d] "Other" CH_4 and N_2O emissions include motorcycles, construction equipment, agricultural machinery, gasoline-powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel-powered recreational, industrial, lawn and garden, light construction, airport service.

[e] Includes primarily HFC-134a

Box ES- 3: Greenhouse Gas Emissions from Electric Utilities

Like transportation, activities related to the generation, transmission, and distribution of electricity in the United States result in significant greenhouse gas emissions. Table ES-5 presents greenhouse gas emissions from electric utility-related activities. Aggregate emissions from electric utilities of all greenhouse gases increased by 16 percent from 1990 to 1998, and accounted for a relatively constant 29 percent of U.S. greenhouse emissions during the same period.[7] The majority of these emissions resulted from the combustion of coal in boilers to produce steam that is passed through a turbine to generate electricity. Overall, the generation of electricity results in a larger portion of total U.S. greenhouse gas emissions than any other activity.

Table ES-5: Electric Utility-Related Greenhouse Gas Emissions (MMTCE)

Gas/Fuel Type or Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**476.6**	**473.2**	**472.7**	**490.5**	**493.9**	**494.0**	**513.0**	**532.8**	**549.9**
Coal	409.0	407.2	411.8	428.7	429.5	433.0	457.5	471.8	477.3
Natural Gas	41.2	41.1	40.7	39.5	44.0	47.2	40.3	43.6	47.8
Petroleum	26.4	24.9	20.2	22.3	20.5	13.9	15.3	17.5	24.8
Geothermal	0.1	0.1	0.1	0.1	+	+	+	+	+
CH_4	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Stationary Combustion (Utilities)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**	**2.1**	**2.2**	**2.3**	**2.3**
Stationary Combustion (Utilities)	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.3	2.3
SF_6	**5.6**	**5.9**	**6.2**	**6.4**	**6.7**	**7.0**	**7.0**	**7.0**	**7.0**
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0	7.0
Total	**484.3**	**481.2**	**481.0**	**499.1**	**502.9**	**503.2**	**522.4**	**542.2**	**559.3**

\+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding.

Table ES-6: Global Warming Potentials (100 Year Time Horizon)

Gas	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)*	21
Nitrous oxide (N_2O)	310
HFC-23	11,700
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF_4	6,500
C_2F_6	9,200
C_4F_{10}	7,000
C_6F_{14}	7,400
SF_6	23,900

Source: (IPCC 1996)
* The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Hundreds of billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (sinks) and are emitted to the atmosphere annually through natural processes (sources). When in equilibrium, carbon fluxes among these various reservoirs are roughly balanced.

Since the Industrial Revolution, this equilibrium of atmospheric carbon has been altered. Atmospheric concentrations of CO_2 have risen about 28 percent (IPCC 1996), principally because of fossil fuel combustion, which accounted for 98 percent of total U.S. CO_2 emissions in 1998. Changes in land use and forestry practices can also emit CO_2 (e.g., through conversion of forest land to agricultural or urban use) or can act as a sink for CO_2 (e.g., through net additions to forest biomass).

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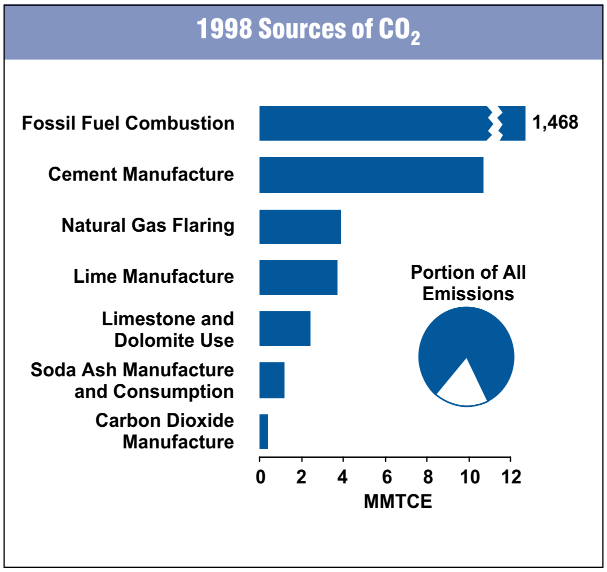
[7] Emissions from nonutility generators are not included in these estimates. Nonutilties were estimated to produce about 10 percent of the electricity generated in the United States in 1998 (DOE and EPA 1999).

Figure ES-6



1998 Sources of CO_2

Figure ES-6 and Table ES-7 summarize U.S. sources and sinks of CO_2. The remainder of this section then discusses CO_2 emission trends in greater detail.

Energy

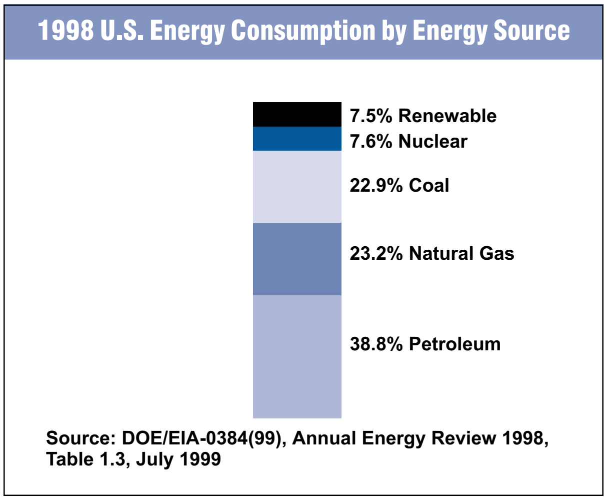
Energy-related activities accounted for almost all U.S. CO_2 emissions for the period of 1990 through 1998. Carbon dioxide from fossil fuel combustion was the dominant contributor. In 1998, approximately 85 percent of the energy consumed in the United States was produced through the combustion of fossil fuels. The remaining 15 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar (see Figure ES-7 and Figure ES-8). A discussion of specific trends related to CO_2 emissions from energy consumption is presented below.

Fossil Fuel Combustion

As fossil fuels are combusted, the carbon stored in them is almost entirely emitted as CO_2. The amount of carbon in fuels per unit of energy content varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of energy, while petroleum has about 25 percent less carbon than coal, and natural gas about 45 percent less. From 1990 through 1998, petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent of total energy consumption. Natural gas and coal followed in order of importance, accounting for an average of 24 and 22 percent of total energy consumption, respectively. Most petroleum was consumed in the transportation sector, while the vast majority of coal was used by electric utilities, and natural gas was consumed largely in the industrial and residential sectors.

Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.3 percent from 1990 to 1998. The fundamental factors behind this trend include (1) a robust domestic economy, (2) relatively low energy prices, and (3) fuel switching by electric utilities. After 1990, when CO_2 emissions from fossil fuel combustion were 1,320.1 MMTCE, there was a slight decline in emissions in 1991, due in large part to an economic recession, followed by a relatively steady in-

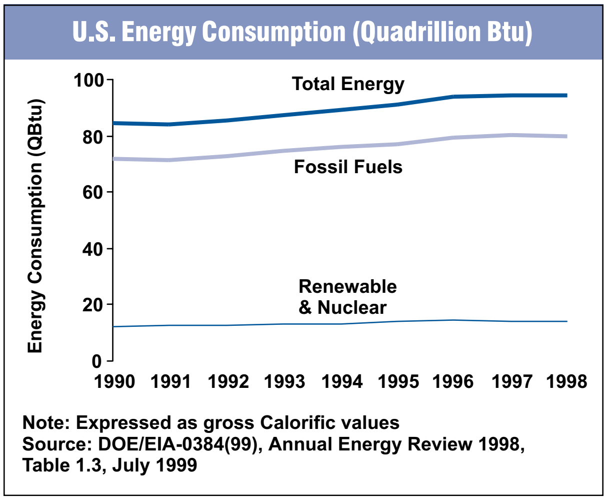
Figure ES-7



1998 U.S. Energy Consumption by Energy Source

Source: DOE/EIA-0384(99), Annual Energy Review 1998, Table 1.3, July 1999

Figure ES-8



U.S. Energy Consumption (Quadrillion Btu)

Note: Expressed as gross Calorific values
Source: DOE/EIA-0384(99), Annual Energy Review 1998, Table 1.3, July 1999

Table ES-7: U.S. Sources of CO_2 Emissions and Sinks (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
Fossil Fuel Combustion	1,320.1	1,305.8	1,330.1	1,361.5	1,382.0	1,392.0	1,441.3	1,460.7	1,468.2
Cement Manufacture	9.1	8.9	8.9	9.4	9.8	10.0	10.1	10.5	10.7
Natural Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.2	3.9
Lime Manufacture	3.0	3.0	3.1	3.1	3.2	3.4	3.6	3.7	3.7
Waste Combustion	2.8	3.0	3.0	3.1	3.1	3.0	3.1	3.4	3.5
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.9	2.0	2.3	2.4
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2
Carbon Dioxide Consumption	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4
Land-Use Change and Forestry (Sink)[a]	(316.4)	(316.3)	(316.2)	(212.7)	(212.3)	(211.8)	(211.3)	(211.1)	(210.8)
International Bunker Fuels[b]	32.2	32.7	30.0	27.2	26.7	27.5	27.9	29.9	31.3
Total Emissions	**1,340.3**	**1,326.1**	**1,350.4**	**1,383.3**	**1,404.8**	**1,416.5**	**1,466.2**	**1,486.4**	**1,494.0**
Net Emissions (Sources and Sinks)	**1,023.9**	**1,009.8**	**1,034.2**	**1,170.6**	**1,192.5**	**1,204.7**	**1,254.9**	**1,275.3**	**1,283.2**

[a] Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

[b] Emissions from International Bunker Fuels are not included in totals.

Note: Totals may not sum due to independent rounding.

crease to 1,468.2 MMTCE in 1998. Overall, CO_2 emissions from fossil fuel combustion increased by 11 percent over the nine year period and rose by 0.5 percent in the final year.

In 1998, mild weather and low petroleum prices comprised the major forces affecting emission trends. A very mild winter more than offset the effects of a slightly hotter summer, resulting in significantly lower fuel consumption for residential and commercial heating compared to previous years. Emissions from the combustion of petroleum products grew the most (11.5 MMTCE or 1.9 percent) due in large part to low prices. Alone, emissions from the combustion of petroleum by electric utilities increased by 7.3 MMTCE (42 percent) from 1997 to 1998. Emissions from the combustion of coal in 1998 increased by 5.5 MMTCE (1 percent) from the previous year, driven almost entirely by increased emissions by electric utilities. These increases were offset by a decrease in natural gas combustion emissions in every sector (9.1 MMTCE or 3 percent).

The four end-use sectors contributing to CO_2 emissions from fossil fuel combustion include: industrial, transportation, residential, and commercial. Electric utilities also emit CO_2, although these emissions are produced as they consume fossil fuel to provide electricity to one of the four end-use sectors. For the discussion below, electric utility emissions have been distributed to each end-use sector based upon their fraction of aggregate electricity consumption. This method of distributing emissions assumes that each end-use sector consumes electricity that is generated with the national average mix of fuels according to their carbon intensity. In reality, sources of electricity vary widely in carbon intensity. By giving equal carbon-intensity weight to each sector's electricity consumption, for example, emissions attributed to the residential sector may be overestimated, while emissions attributed to the industrial sector may be underestimated. Emissions from electric utilities are addressed separately after the end-use sectors have been discussed. Emissions from U.S. territories are also calculated separately due to a lack of end-use-specific consumption data. Table ES-8, Figure ES-9, and Figure ES-10 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Industrial End-Use Sector. Industrial CO_2 emissions resulting from direct fossil fuel combustion and from the generation of electricity consumed by the sector accounted for 33 percent of U.S. emissions from fossil fuel combustion in 1998. About two-thirds of these emissions resulted from producing steam and process heat from fossil fuel combustion, while the remaining third resulted from consuming electricity for powering motors, electric furnaces, ovens, and lighting.

Transportation End-Use Sector. Transportation

Table ES-8: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMTCE)*

End-Use Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Residential	252.9	257.0	255.8	271.6	268.2	269.8	285.4	284.7	286.8
Commercial	206.7	206.3	205.4	212.0	213.8	218.3	225.9	238.0	239.3
Industrial	451.7	440.3	458.0	458.0	466.2	464.4	477.3	482.5	478.9
Transportation	399.6	391.5	401.1	409.1	422.3	427.7	441.7	443.4	450.3
U.S. Territories	9.2	10.7	9.8	10.7	11.5	11.8	11.0	12.0	13.0
Total	**1,320.1**	**1,305.8**	**1,330.1**	**1,361.5**	**1,382.0**	**1,392.0**	**1,441.3**	**1,460.7**	**1,468.2**

* Emissions from fossil fuel combustion by electric utilities are allocated based on electricity consumption by each end-use sector.
Note: Totals may not sum due to independent rounding.

activities excluding international bunker fuels accounted for 31 percent of CO_2 emissions from fossil fuel combustion in 1998.[8] Virtually all of the energy consumed in this end-use sector came from petroleum products. Two thirds of the emissions resulted from gasoline consumption in motor vehicles. The remaining emissions came from other transportation activities, including the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircraft.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 20 and 16 percent, respectively, of CO_2 emissions from fossil fuel consumption in 1998. Both sectors relied heavily on electricity for meeting energy needs, with 67 and 75 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were largely due to the consumption of natural gas and petroleum, primarily for meeting heating and cooking needs.

Electric Utilities. The United States relies on electricity to meet a significant portion of its energy demands, especially for lighting, electric motors, heating, and air conditioning. Electric utilities are responsible for consuming 29 percent of U.S. energy from fossil fuels and emitted 37 percent of the CO_2 from fossil fuel combustion in 1998. The type of fuel combusted by utilities has a significant effect on their emissions. For example, some electricity is generated with low CO_2 emitting energy technologies, particularly non-fossil options such as nuclear, hydroelectric, or geothermal energy. However, electric utilities rely on

Figure ES-9

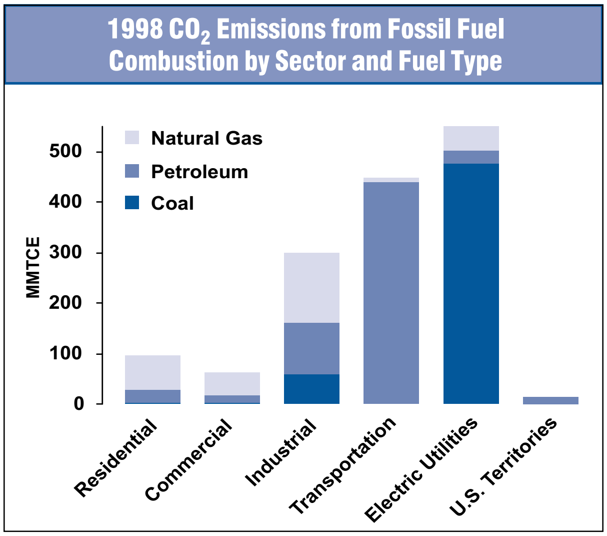
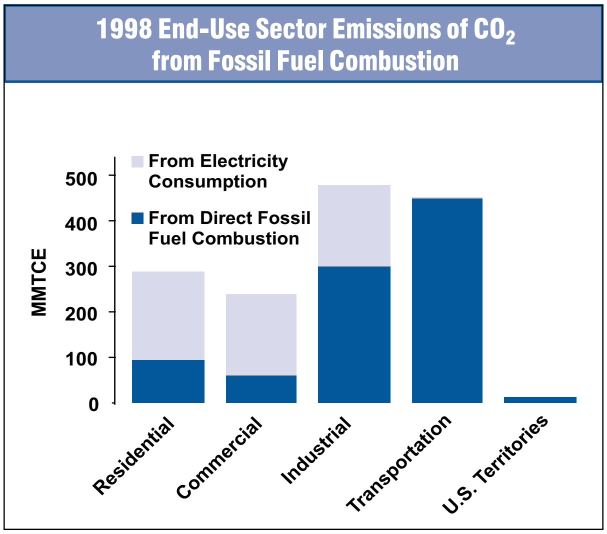

1998 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure ES-10


1998 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

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[8] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 33 percent of U.S. emissions from fossil fuel combustion in 1998.

coal for over half of their total energy requirements and accounted for 88 percent of all coal consumed in the United States in 1998. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Natural Gas Flaring

Carbon dioxide is produced when natural gas from oil wells is flared (i.e., combusted) to relieve rising pressure or to dispose of small quantities of gas that are not commercially marketable. In 1998, flaring activities emitted approximately 3.9 MMTCE, or about 0.2 percent of U.S. CO_2 emissions.

Biomass Combustion

Biomass in the form of fuel wood and wood waste was used primarily by the industrial end-use sector, while the transportation end-use sector was the predominant user of biomass-based fuels, such as ethanol from corn and woody crops. Ethanol and ethanol blends, such as gasohol, are typically used to fuel public transport vehicles.

Although these fuels do emit CO_2, in the long run the CO_2 emitted from biofuel consumption does not increase atmospheric CO_2 concentrations if the biogenic carbon emitted is offset by the growth of new biomass. For example, fuel wood burned one year but re-grown the next only recycles carbon, rather than creating a net increase in total atmospheric carbon. Net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands are accounted for under Land-Use Change and Forestry.

Gross CO_2 emissions from biomass combustion were 66.2 MMTCE, with the industrial sector accounting for 81 percent of the emissions, and the residential sector 15 percent. Ethanol consumption by the transportation sector accounted for only 3 percent of CO_2 emissions from biomass combustion.

Industrial Processes

Emissions are often produced as a by-product of various non-energy-related activities. For example, industrial processes can chemically transform raw materials. This transformation often releases greenhouse gases such as CO_2. The production processes that emit CO_2 include cement manufacture, lime manufacture, limestone and dolomite use (e.g., in iron and steel making), soda ash manufacture and consumption, and CO_2 consumption. Total CO_2 emissions from these sources were approximately 18.4 MMTCE in 1998, accounting for about 1 percent of total CO_2 emissions. Since 1990, emissions from each of these sources increased, except for emissions from soda ash manufacture and consumption, which remained relatively constant.

Cement Manufacture (10.7 MMTCE)

Carbon dioxide is produced primarily during the production of clinker, an intermediate product from which finished Portland and masonry cement are made. Specifically, CO_2 is created when calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime and CO_2. This lime combines with other materials to produce clinker, while the CO_2 is released into the atmosphere.

Lime Manufacture (3.7 MMTCE)

Lime is used in steel making, construction, pulp and paper manufacturing, and water and sewage treatment. It is manufactured by heating limestone (mostly calcium carbonate, $CaCO_3$) in a kiln, creating calcium oxide (quicklime) and CO_2, which is normally emitted to the atmosphere.

Limestone and Dolomite Use (2.4 MMTCE)

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$) are basic raw materials used by a wide variety of industries, including the construction, agriculture, chemical, and metallurgical industries. For example, limestone can be used as a purifier in refining metals. In the case of iron ore, limestone heated in a blast furnace reacts with impurities in the iron ore and fuels, generating CO_2 as a by-product. Limestone is also used in flue gas desulfurization systems to remove sulfur dioxide from the exhaust gases.

Soda Ash Manufacture and Consumption (1.2 MMTCE)

Commercial soda ash (sodium carbonate, Na_2CO_3)

is used in many consumer products, such as glass, soap and detergents, paper, textiles, and food. During the manufacturing of soda ash, some natural sources of sodium carbonate are heated and transformed into a crude soda ash, in which CO_2 is generated as a by-product. In addition, CO_2 is often released when the soda ash is consumed.

Carbon Dioxide Consumption (0.4 MMTCE)

Carbon dioxide is used directly in many segments of the economy, including food processing, beverage manufacturing, chemical processing, and a host of industrial and other miscellaneous applications. For the most part, the CO_2 used in these applications is eventually released to the atmosphere.

Land-Use Change and Forestry

When humans alter the biosphere through changes in land-use and forest management practices, they alter the natural carbon flux between biomass, soils, and the atmosphere. Improved forest management practices and the regeneration of previously cleared forest areas have resulted in a net uptake (sequestration) of carbon in U.S. forest lands, which cover about 298 million hectares (737 million acres) (Powell et al. 1993). This uptake is an ongoing result of land-use changes in previous decades. For example, because of improved agricultural productivity and the widespread use of tractors, the rate of clearing forest land for crop cultivation and pasture slowed greatly in the late 19th century, and by 1920 this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were brought out of crop production, primarily between 1920 and 1950, and were allowed to revert to forest land or were actively reforested.

Since the early 1950s, the managed growth of private forest land in the East has nearly doubled the biomass density there. The 1970s and 1980s saw a resurgence of federally sponsored tree-planting programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on reforesting previously harvested lands, improving timber-management, combating soil erosion, and converting marginal cropland to forests.

In 1998, the CO_2 flux from land-use change and forestry activities was estimated to have been a net uptake of 210.8 MMTCE. This carbon was sequestered in trees, understory, litter, soils in forests, wood products, and wood in landfills. This net carbon uptake represents an offset of about 14 percent of the CO_2 emissions from fossil fuel combustion in 1998. The amount of carbon sequestered through U.S. forestry and land-use practices is estimated to have declined by about a third between 1990 and 1998, largely due to the maturation of existing forests and the slowed expansion of Eastern forest cover and a gradual decrease in the rate of yard trimmings disposed in landfills. Due to the lack of a national survey of land use and management more recent than 1992, carbon flux estimates for non-forest mineral and organic soils were not calculated for the 1993 through 1998 period. Therefore, carbon flux estimates from non-forest soils are not included in the total fluxes reported.

Waste

Waste Combustion (3.5 MMTCE)

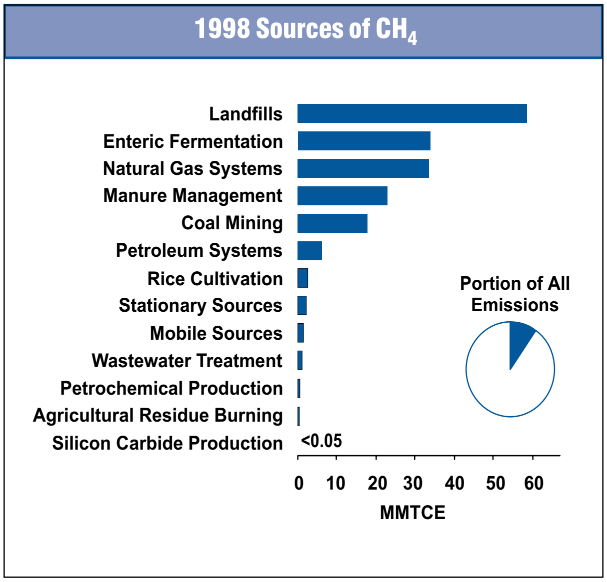
Waste combustion involves the burning of garbage and non-hazardous solids, referred to as municipal solid waste (MSW). In 1996, there were approximately 137 municipal waste combustion plants in operation within the United States (EPA 1998a). Most of the organic (i.e., carbon) materials in MSW are of biogenic origin. Therefore, the CO_2 emissions from their combustion are reported under the Land Use Change and Forestry Chapter. However, one component plastics is of fossil fuel origin, and is included as a source of CO_2 emissions.

Methane Emissions

Atmospheric methane (CH_4) is an integral component of the greenhouse effect, second only to CO_2 as a contributor to anthropogenic greenhouse gas emissions. Methane's overall contribution to global warming is significant because it is estimated to be 21 times more effective at trapping heat in the atmosphere than CO_2 (i.e., the GWP value of methane is 21). Over the last two centuries, methane's concentration in the atmosphere has more than doubled (IPCC 1996). Experts believe these atmospheric increases were due largely to increasing emissions from anthropogenic sources, such as landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes (see Figure ES-11 and Table ES-9).

Landfills

Figure ES-11


1998 Sources of CH_4

Landfills are the largest single anthropogenic source of methane emissions in the United States. In an environment where the oxygen content is low or nonexistent, organic materials, such as yard waste, household waste, food waste, and paper, can be decomposed by bacteria, resulting in the generation of methane and biogenic CO_2. Methane emissions from landfills are affected by site-specific factors such as waste composition, moisture, and landfill size.

Methane emissions from U.S. landfills in 1998 were 58.8 MMTCE, only a 1 percent increase since 1990. The relatively constant emission estimates are a result of two offsetting trends: (1) the amount of MSW in landfills contributing to methane emissions has increased (thereby increasing the potential for emissions); and (2) the amount of landfill gas collected and combusted by landfill operators has also increased (thereby reducing emissions). Emissions from U.S. municipal solid waste landfills, which received about 61 percent of the municipal solid waste generated in the United States, accounted for 93 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 26 percent of the methane generated in U.S. landfills in 1998 was recovered and combusted, often for energy.

Table ES-9: U.S. Sources of Methane Emissions (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
Landfills	58.2	58.1	59.1	59.6	59.9	60.5	60.2	60.2	58.8
Enteric Fermentation	32.7	32.8	33.2	33.7	34.5	34.9	34.5	34.2	33.7
Natural Gas Systems	33.0	33.4	33.9	34.6	34.3	34.0	34.6	34.1	33.6
Manure Management	15.0	15.5	16.0	17.1	18.8	19.7	20.4	22.1	22.9
Coal Mining	24.0	22.8	22.0	19.2	19.4	20.3	18.9	18.8	17.8
Petroleum Systems	7.4	7.5	7.2	6.9	6.7	6.7	6.5	6.5	6.3
Rice Cultivation	2.4	2.3	2.6	2.4	2.7	2.6	2.4	2.6	2.7
Stationary Sources	2.3	2.4	2.4	2.4	2.4	2.5	2.6	2.3	2.3
Mobile Sources	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.3
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Petrochemical Production	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Agricultural Residue Burning	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Silicon Carbide Production	+	+	+	+	+	+	+	+	+
International Bunker Fuels*	+	+	+	+	+	+	+	+	+
Total*	**177.9**	**177.7**	**179.4**	**178.7**	**181.6**	**184.1**	**183.1**	**183.8**	**180.9**

+ Does not exceed 0.05 MMTCE
* Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.

A regulation promulgated in March 1996 requires the largest U.S. landfills to begin collecting and combusting their landfill gas to reduce emissions of NMVOCs. It is estimated that by the year 2000, this regulation will have reduced landfill methane emissions by more than 50 percent.

Natural Gas and Petroleum Systems

Methane is the major component of natural gas. During the production, processing, transmission, and distribution of natural gas, fugitive emissions of methane often occur. Because natural gas is often found in conjunction with petroleum deposits, leakage from petroleum systems is also a source of emissions. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment conditions. In 1998, methane emissions from U.S. natural gas systems were estimated to be 33.6 MMTCE, accounting for approximately 19 percent of U.S. methane emissions.

Petroleum is found in the same geological structures as natural gas, and the two are retrieved together. Methane is also saturated in crude oil, and volatilizes as the oil is exposed to the atmosphere at various points along the system. Methane emissions from the components of petroleum systems including crude oil production, crude oil refining, transportation, and distribution generally occur as a result of system leaks, disruptions, and routine maintenance. In 1998, emissions from petroleum systems were estimated to be 6.3 MMTCE, or 3.5 percent of U.S. methane emissions.

From 1990 to 1998, combined methane emissions from natural gas and petroleum systems decreased by about 1 percent. Emissions from natural gas systems have remained fairly constant, while emissions from petroleum systems have declined gradually since 1990 primarily due to production declines.

Coal Mining

Produced millions of years ago during the formation of coal, methane trapped within coal seams and surrounding rock strata is released when the coal is mined. The quantity of methane released to the atmosphere during coal mining operations depends primarily upon the depth and type of the coal that is mined.

Methane from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed. Because methane in underground mines is explosive at concentrations of 5 to 15 percent in air, most active underground mines are required to vent this methane, typically to the atmosphere. At some mines, methane-recovery systems may supplement these ventilation systems. U.S. recovery of methane has been increasing in recent years. During 1998, coal mining activities emitted 17.8 MMTCE of methane, or 10 percent of U.S. methane emissions. From 1990 to 1998, emissions from this source decreased by 26 percent due to increased use of the methane collected by mine degasification systems.

Agriculture

Agriculture accounted for 33 percent of U.S. methane emissions in 1998, with enteric fermentation in domestic livestock and manure management accounting for the majority. Other agricultural activities contributing directly to methane emissions included rice cultivation and agricultural waste burning.

Enteric Fermentation (33.7 MMTCE)

During animal digestion, methane is produced through the process of enteric fermentation, in which microbes residing in animal digestive systems break down the feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest methane emissions among all animal types because they have a rumen, or large fore-stomach, in which methane-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have much lower methane emissions. In 1998, enteric fermentation was the source of about 19 percent of U.S. methane emissions, and more than half of the methane emissions from agriculture. From 1990 to 1998, emissions from this source increased by 3 percent. Emissions from enteric fermentation have been decreasing since 1995, primarily due to declining dairy cow and beef cattle populations.

Manure Management (22.9 MMTCE)

The decomposition of organic animal waste in an anaerobic environment produces methane. The most important factor affecting the amount of methane produced is how the manure is managed, because certain types of storage and treatment systems promote an oxygen-free environment. In particular, liquid systems tend to encourage anaerobic conditions and produce significant quantities of methane, whereas solid waste management approaches produce little or no methane. Higher temperatures and moist climatic conditions also promote methane production.

Emissions from manure management were about 13 percent of U.S. methane emissions in 1998, and 38 percent of the methane emissions from agriculture. From 1990 to 1998, emissions from this source increased by 53 percent—the largest increase of all the methane source categories. The bulk of this increase was from swine and dairy cow manure, and is attributed to the shift in the composition of the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use liquid management systems. Thus the shift towards larger facilities is translated into an increasing use of liquid systems, which in turn translates to increased methane production.

Rice Cultivation (2.7 MMTCE)

Most of the world's rice, and all of the rice in the United States, is grown on flooded fields. When fields are flooded, anaerobic conditions develop and the organic matter in the soil decomposes, releasing methane to the atmosphere, primarily through the rice plants. In 1998, rice cultivation was the source of 1.5 percent of U.S. methane emissions, and about 5 percent of U.S. methane emissions from agriculture. Emission estimates from this source have increased about 15 percent since 1990, due primarily to an increase in the area harvested.

Agricultural Residue Burning (0.2 MMTCE)

Burning crop residue releases a number of greenhouse gases, including methane. Agricultural residue burning is considered to be a net source of methane emissions because, unlike CO_2, methane released during burning is not reabsorbed by crop regrowth during the next growing season. Because field burning is not common in the United States, it was responsible for only 0.1 percent of U.S. methane emissions in 1998.

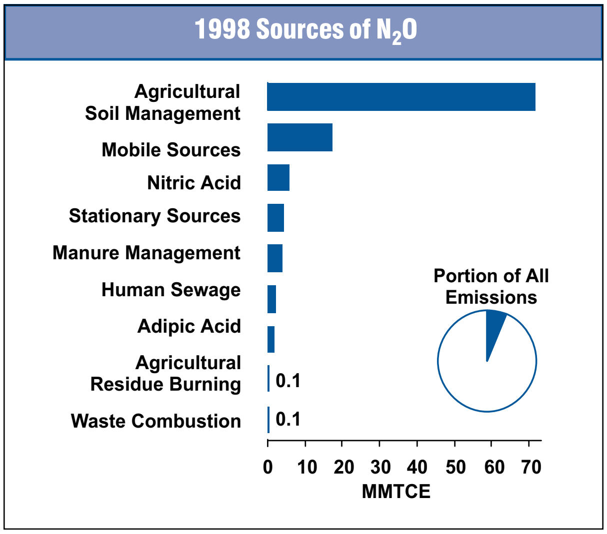
Other Sources

Methane is also produced from several other sources in the United States, including fuel combustion, wastewater treatment, and some industrial processes. Stationary and mobile combustion were responsible for methane emissions of 2.3 and 1.3 MMTCE, respectively, in 1998. The majority of emissions from stationary combustion resulted from the burning of wood in the residential sector. The combustion of gasoline in highway vehicles was responsible for the majority of the methane emitted from mobile combustion. Wastewater treatment was a smaller source of methane, emitting 0.9 MMTCE in 1998. Methane emissions from two industrial sources petrochemical and silicon carbide production were also estimated, totaling 0.4 MMTCE.

Nitrous Oxide Emissions

Nitrous oxide (N_2O) is a greenhouse gas that is produced both naturally—from a wide variety of biological sources in soil and water—and anthropogenically by a variety of agricultural, energy-related, industrial, and waste management activities. While N_2O emissions are much lower than CO_2 emissions, N_2O is approximately 310 times more powerful than CO_2 at trapping heat in the atmosphere (IPCC 1996). During the past two centuries, atmospheric concentrations of N_2O have risen by approximately 13 percent. The main anthropogenic activities producing N_2O in the United States were agricultural soil management, fuel combustion in motor vehicles, and adipic and nitric acid production (see Figure ES-12 and Table ES-10).

Figure ES-12



Agricultural Soil Management

Nitrous oxide (N_2O) is produced naturally in soils through microbial processes of nitrification and denitrification. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as N_2O by these microbial processes. Direct additions of nitrogen occur through the application of synthetic and organic fertilizers, cultivation of nitrogen-fixing crops, cultivation of high-organic-content soils, the application of livestock manure on croplands and pasture, the incorporation of crop residues in soils, and direct excretion by animals onto soil. Indirect emissions result from volatilization and subsequent atmospheric deposition of ammonia (NH_3) and oxides of nitrogen (NO_x) and from leaching and surface run-off. These indirect emissions originate from nitrogen applied to soils as fertilizer and from managed and unmanaged livestock wastes.

In 1998, agricultural soil management accounted for 83.9 MMTCE, or 70 percent of U.S. N_2O emissions. From 1990 to 1998, emissions from this source increased by 11 percent as fertilizer consumption and cultivation of nitrogen fixing crops rose.

Fuel Combustion

Nitrous oxide is a product of the reaction that occurs between nitrogen and oxygen during fuel combustion. Both mobile and stationary combustion emit N_2O, and the volume emitted varies according to the type of fuel, technology, and pollution control device used, as well as maintenance and operating practices. For example, catalytic converters installed to reduce highway vehicle pollution can result in the formation of N_2O.

In 1998, N_2O emissions from mobile combustion totaled 17.2 MMTCE, or 14 percent of U.S. N_2O emissions. Emissions of N_2O from stationary combustion were 4.3 MMTCE, or 4 percent of U.S. N_2O emissions. From 1990 to 1998, combined N_2O emissions from stationary and mobile combustion increased by 21 percent, primarily due to increased rates of N_2O generation in motor vehicles.

Table ES-10: U.S. Sources of Nitrous Oxide Emissions (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
Agricultural Soil Management	75.3	76.3	78.2	77.3	83.5	80.4	82.4	84.2	83.9
Mobile Sources	13.8	14.6	15.7	16.5	17.1	17.4	17.5	17.3	17.2
Nitric Acid	4.9	4.9	5.0	5.1	5.3	5.4	5.6	5.8	5.8
Stationary Sources	3.8	3.8	3.9	3.9	4.0	4.0	4.2	4.2	4.3
Manure Management	3.4	3.6	3.5	3.7	3.8	3.7	3.8	3.9	4.0
Human Sewage	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2
Adipic Acid	5.0	5.2	4.8	5.2	5.5	5.5	5.7	4.7	2.0
International Bunker Fuels*	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total*	**108.2**	**110.5**	**113.3**	**113.8**	**121.5**	**118.8**	**121.5**	**122.4**	**119.4**

* Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.

Adipic Acid Production

The majority of the adipic acid produced in the United States is used to manufacture nylon 6,6. Adipic acid is also used to produce some low-temperature lubricants, and to add a “tangy” flavor to foods. Nitrous oxide is emitted as a by-product of the chemical synthesis of adipic acid.

In 1998, U.S. adipic acid plants emitted 2.0 MMTCE of N_2O, or 2 percent of U.S. N_2O emissions. Since 1990, even though adipic acid production increased, by 1998, all of the three major adipic acid plants in the United States had voluntarily implemented N_2O abatement technology. As a result, emissions in 1998 decreased by 58 percent relative to the previous year.

Nitric Acid Production

Nitric acid production is another industrial source of N_2O emissions. Used primarily to make synthetic commercial fertilizer, this raw material is also a major component in the production of adipic acid and explosives.

Virtually all of the nitric acid manufactured in the United States is produced by the oxidation of ammonia, during which N_2O is formed and emitted to the atmosphere. In 1998, N_2O emissions from nitric acid production were 5.8 MMTCE, or 5 percent of U.S. N_2O emissions. From 1990 to 1998, emissions from this source increased by 18 percent as nitric acid production grew.

Manure Management

Nitrous oxide is produced as part of microbial nitrification and denitrification processes in managed and unmanaged manure, the latter of which is addressed under agricultural soil management. Total N_2O emissions from managed manure systems in 1998 were 4.0 MMTCE, accounting for 3 percent of U.S. N_2O emissions. Emissions increased by 19 percent from 1990 to 1998.

Other Sources

Other sources of N_2O included agricultural residue burning, waste combustion, and human sewage in wastewater treatment systems. In 1998, agricultural residue burning and municipal solid waste combustion each emitted approximately 0.1 MMTCE of N_2O. Although N_2O emissions from wastewater treatment were not fully estimated because of insufficient data availability, the human sewage component of domestic wastewater resulted in emissions of 2.2 MMTCE in 1998.

HFCs, PFCs and SF_6 Emissions

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are categories of synthetic chemicals that are being used as alternatives to the ozone depleting substances (ODSs), which are being phased out under the *Montreal Protocol* and Clean Air Act Amendments of 1990. Because HFCs and PFCs do not directly deplete the stratospheric ozone layer, they are not controlled by the *Montreal Protocol*.

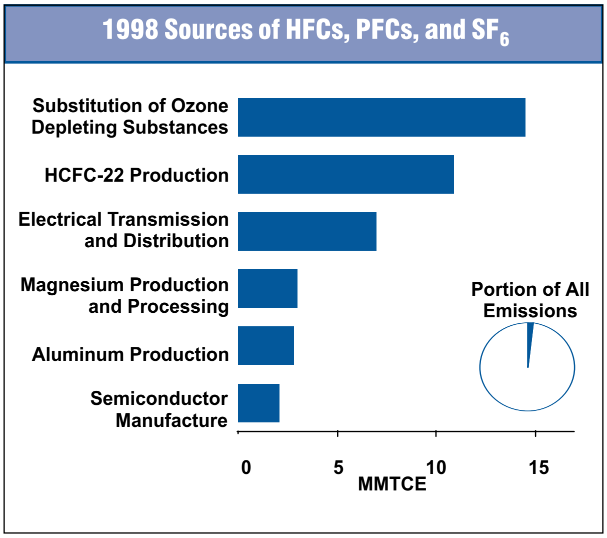
These compounds, however, along with sulfur hexafluoride (SF_6), are potent greenhouse gases. In addition to having high global warming potentials, SF_6 and many HFCs and PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere. Sulfur hexafluoride, itself, is the most potent greenhouse gas the IPCC has evaluated.

In addition to their use as substitutes for ozone depleting substances, the other emissive sources of these gases are aluminum production, HCFC-22 production, semiconductor manufacturing, electrical transmission and distribution, and magnesium production and processing. Figure ES-13 and Table ES-11 present emission estimates for HFCs, PFCs, and SF_6, which totaled 40.3 MMTCE in 1998.

Substitution of Ozone Depleting Substances

The use and subsequent emissions of HFCs and PFCs as ODS substitutes increased dramatically from small amounts in 1990 to 14.5 MMTCE in 1998. This increase was the result of efforts to phase-out CFCs and other ODSs in the United States, especially the introduction of HFC-134a as a CFC substitute in refrigeration

Figure ES-13


1998 Sources of HFCs, PFCs, and SF_6

applications. This trend is expected to continue for many years, and will accelerate in the early part of the next century as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*.

Other Industrial Sources

HFCs, PFCs, and SF_6 are also emitted from a number of other industrial processes. During the production of primary aluminum, two PFCs—CF_4 and C_2F_6—are emitted as intermittent by-products of the smelting process. Emissions from aluminum production were estimated to have decreased by 48 percent between 1990 and 1998 due to voluntary emission reduction efforts by the industry and falling domestic aluminum production.

HFC-23 is a by-product emitted during the production of HCFC-22. Emissions from this source were 10.9 MMTCE in 1998, and have increased by 15 percent since 1990. This increase is attributable to the 30 percent increase in HCFC-22 production that has occurred since 1990; one third of this increase occurred between 1997 and 1998. The intensity of HFC-23 emissions (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured), however, has declined significantly since 1990.

The semiconductor industry uses combinations of HFCs, PFCs, $SF_{6,}$ and other gases for plasma etching and chemical vapor deposition processes. For 1998, it was estimated that the U.S. semiconductor industry emitted a total of 2.1 MMTCE. Emissions from this source category have increased with the growth in the semiconductor industry and the rising intricacy of chip designs.

The primary use of SF_6 is as a dielectric in electrical transmission and distribution systems. Fugitive emissions of SF_6 occur from leaks in and servicing of substations and circuit breakers, especially from older equipment. Estimated emissions from this source increased by 25 percent from 1990, to 7.0 MMTCE in 1998.

Table ES-11: Emissions of HFCs, PFCs, and SF_6 (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
Substitution of Ozone Depleting Substances	0.3	0.2	0.4	1.4	2.7	7.0	9.9	12.3	14.5
Aluminum Production	5.4	4.7	4.4	3.8	3.2	3.1	3.2	3.0	2.8
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2	10.9
Semiconductor Manufacture	0.8	0.8	0.8	1.0	1.1	1.5	1.9	1.9	2.1
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	3.0	3.0	3.0
Total	**23.3**	**22.0**	**23.5**	**23.8**	**25.1**	**29.0**	**33.5**	**35.3**	**40.3**

Note: Totals may not sum due to independent rounding.

Box ES-4: Emissions of Ozone Depleting Substances

Chlorofluorocarbons (CFCs) and other halogenated compounds were first emitted into the atmosphere this century. This family of man-made compounds includes CFCs, halons, methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs). These substances have been used in a variety of industrial applications, including refrigeration, air conditioning, foam blowing, solvent cleaning, sterilization, fire extinguishing, coatings, paints, and aerosols.

Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases.

Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase-out ODSs by signing and ratifying the Copenhagen Amendments to the *Montreal Protocol* in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996.

The IPCC Guidelines do not include reporting instructions for estimating emissions of ODSs because their use is being phased-out under the *Montreal Protocol*. The United States believes, however, that a greenhouse gas emissions inventory is incomplete without these emissions; therefore, estimates for several Class I and Class II ODSs are provided in Table ES-12. Compounds are grouped by class according to their ozone depleting potential. Class I compounds are the primary ODSs; Class II compounds include partially halogenated chlorine compounds (i.e., HCFCs), some of which were developed as interim replacements for CFCs. Because these HCFC compounds are only partially halogenated, their hydrogen-carbon bonds are more vulnerable to oxidation in the troposphere and, therefore, pose only one-tenth to one-hundredth the threat to stratospheric ozone compared to CFCs.

It should be noted that the effects of these compounds on radiative forcing are not provided. Although many ODSs have relatively high direct GWPs, their indirect effects from ozone also a greenhouse gas destruction are believed to have negative radiative forcing effects, and therefore could significantly reduce the overall magnitude of their radiative forcing effects. Given the uncertainties surrounding the net effect of these gases, emissions are reported on an unweighted basis.

Table ES-12: Emissions of Ozone Depleting Substances (Gg)

Compound	1990	1991	1992	1993	1994	1995	1996	1997	1998
Class I									
CFC-11	53.5	48.3	45.1	45.4	36.6	36.2	26.6	25.1	24.9
CFC-12	112.6	103.5	80.5	79.3	57.6	51.8	35.5	23.1	21.0
CFC-113	26.4	20.6	17.1	17.1	8.6	8.6	+	+	+
CFC-114	4.7	3.6	3.0	3.0	1.6	1.6	0.3	0.1	0.1
CFC-115	4.2	4.0	3.8	3.6	3.3	3.0	3.2	2.9	2.7
Carbon Tetrachloride	32.3	31.0	21.7	18.6	15.5	4.7	+	+	+
Methyl Chloroform	158.3	154.7	108.3	92.9	77.4	46.4	+	+	+
Halon-1211	1.0	1.1	1.0	1.1	1.0	1.1	1.1	1.1	1.1
Halon-1301	1.8	1.8	1.7	1.7	1.7	1.8	1.9	1.9	1.9
Class II									
HCFC-22	79.8	79.5	79.5	71.2	71.4	72.3	73.2	74.2	75.1
HCFC-123	+	+	0.3	0.3	0.5	0.6	0.7	0.8	0.9
HCFC-124	+	+	0.4	2.6	4.8	5.2	5.6	5.9	6.1
HCFC-141b	+	+	+	5.0	12.4	20.6	25.4	25.1	26.7
HCFC-142b	+	+	0.7	1.7	4.6	7.3	8.3	8.7	9.0
HCFC-225ca/cb	+	+	+	+	+	+	+	+	+

Source: EPA
\+ Does not exceed 0.05 Gg

Lastly, SF_6 is also used as a protective covergas for the casting of molten magnesium. Estimated emissions from primary magnesium production and magnesium casting were 3.0 MMTCE in 1998, an increase of 76 percent since 1990.

Criteria Pollutant Emissions

In the United States, carbon monoxide (CO), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2) are commonly referred to as "criteria pollutants," as termed in the Clean Air Act. Criteria pollutants do not have a direct global warming effect, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Carbon monoxide is produced when carbon-containing fuels are combusted incompletely. Nitrogen oxides (i.e., NO and NO_2) are created by lightning, fires, fossil fuel combustion, and in the stratosphere from nitrous oxide (N_2O). NMVOCs which include such compounds as propane, butane, and ethane are emitted primarily from transportation, industrial processes, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from the combustion of fossil fuels and by the metals industry.

In part because of their contribution to the formation of urban smog—and acid rain in the case of SO_2 and NO_x—criteria pollutants are regulated under the Clean Air Act. These gases also indirectly affect the global climate by reacting with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Unlike other criteria pollutants, SO_2 emitted into the atmosphere is believed to affect the Earth's radiative budget negatively; therefore, it is discussed separately.

One of the most important indirect climate change effects of criteria pollutants is their role as precursors for tropospheric ozone formation. They can also alter the atmospheric lifetimes of other greenhouse gases. For example, CO interacts with the hydroxyl radical the major atmospheric sink for methane emissions to form CO_2. Therefore, increased atmospheric concentrations of CO limit the number of hydroxyl molecules (OH) available to destroy methane.

Since 1970, the United States has published estimates of annual emissions of criteria pollutants (EPA 1999).[9] Table ES-13 shows that fuel combustion accounts for the majority of emissions of these gases. Industrial processes such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents are also significant sources of CO, NO_x, and NMVOCs.

Box ES-5: Sources and Effects of Sulfur Dioxide

Sulfur dioxide (SO_2) emitted into the atmosphere through natural and anthropogenic processes affects the Earth's radiative budget through its photochemical transformation into sulfate aerosols that can (1) scatter sunlight back to space, thereby reducing the radiation reaching the Earth's surface; (2) affect cloud formation; and (3) affect atmospheric chemical composition (e.g., stratospheric ozone, by providing surfaces for heterogeneous chemical reactions). The overall effect of SO_2 derived aerosols on radiative forcing is believed to be negative (IPCC 1996). However, because SO_2 is short-lived and unevenly distributed in the atmosphere, its radiative forcing impacts are highly uncertain.

Sulfur dioxide is also a major contributor to the formation of urban smog, which can cause significant increases in acute and chronic respiratory diseases. Once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to the Earth as the primary source of acid rain. Because of these harmful effects, the United States has regulated SO_2 emissions in the Clean Air Act.

Electric utilities are the largest source of SO_2 emissions in the United States, accounting for 62 percent in 1998. Coal combustion contributes nearly all of those emissions (approximately 96 percent). Sulfur dioxide emissions have decreased in recent years, primarily as a result of electric utilities switching from high sulfur to low sulfur coal.

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[9] NO_x and CO emission estimates from agricultural residue burning were estimated separately, and therefore not taken from EPA (1999).

Table ES-13: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
NO_x	**21,798**	**21,936**	**22,176**	**22,398**	**22,683**	**22,177**	**22,034**	**22,153**	**22,066**
Stationary Combustion	9,884	9,779	9,914	10,080	9,993	9,822	9,553	9,728	9,719
Mobile Combustion	10,744	11,132	11,224	11,294	11,508	11,294	11,261	11,289	11,184
Oil and Gas Activities	139	110	134	111	106	100	121	121	122
Industrial Processes	921	802	785	774	939	842	979	890	915
Solvent Use	1	2	2	2	2	3	3	3	2
Agricultural Residue Burning	26	26	29	23	32	27	30	32	34
Waste	83	86	87	112	103	89	87	89	90
CO	**85,394**	**87,485**	**84,589**	**84,716**	**88,911**	**80,093**	**82,028**	**79,284**	**78,082**
Stationary Combustion	4,999	5,313	5,583	5,068	5,007	5,383	5,405	4,455	4,491
Mobile Combustion	68,985	73,177	71,543	72,210	74,057	67,433	66,674	65,301	63,780
Oil and Gas Activities	302	313	337	337	307	316	287	292	296
Industrial Processes	9,502	7,088	5,401	5,421	7,708	5,291	7,899	7,432	7,669
Solvent Use	4	4	5	4	5	5	5	5	5
Agricultural Residue Burning	623	578	688	544	717	590	675	704	733
Waste	979	1,012	1,032	1,133	1,111	1,075	1,083	1,095	1,107
NMVOCs	**18,795**	**18,929**	**18,527**	**18,708**	**19,290**	**18,613**	**17,624**	**17,469**	**17,011**
Stationary Combustion	912	975	1,011	901	898	973	951	770	776
Mobile Combustion	8,037	8,239	7,862	7,919	8,223	7,621	7,398	7,169	7,065
Oil and Gas Activities	555	581	574	588	587	582	459	461	464
Industrial Processes	3,179	2,983	2,811	2,893	3,043	2,859	2,859	3,002	3,066
Solvent Use	5,217	5,245	5,353	5,458	5,590	5,609	5,569	5,672	5,239
Agricultural Residue Burning	NA	NA	NA	NA	NA	NA	NA	NA	NA
Waste	895	907	916	949	949	968	388	394	400
SO_2	**21,465**	**20,903**	**20,689**	**20,381**	**19,840**	**17,401**	**18,695**	**19,216**	**19,441**
Stationary Combustion	18,407	17,959	17,684	17,459	17,134	14,724	15,981	16,458	16,635
Mobile Combustion	1,322	1,373	1,402	1,351	1,172	1,183	1,208	1,235	1,261
Oil and Gas Activities	390	343	377	347	344	334	300	301	303
Industrial Processes	1,306	1,187	1,186	1,159	1,135	1,117	1,167	1,184	1,204
Solvent Use	+	+	+	1	1	1	+	1	1
Agricultural Residue Burning	NA	NA	NA	NA	NA	NA	NA	NA	NA
Waste	38	40	40	65	54	43	37	37	38

Source: (EPA 1999) except for estimates from agricultural residue burning.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

1. Introduction

This report presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 1998. A summary of these estimates is provided in Table 1-4 and Table 1-5 by gas and source category. The emission estimates in these tables are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis in order to show the relative contribution of each gas to global average radiative forcing.[1,2] This report also discusses the methods and data used to calculate these emission estimates.

In June of 1992, the United States signed the United Nations Framework Convention on Climate Change (UNFCCC). The objective of the UNFCCC is "to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." [3,4]

Parties to the Convention, by signing, make commitments "to develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"[5] The United States views this report as an opportunity to fulfill this commitment under UNFCCC.

In 1988, preceding the creation of the UNFCCC, the Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The charter of the IPCC is to assess available scientific information on climate change, assess the environmental and socio-economic impacts of climate change, and formulate response strategies (IPCC 1996). Under Working Group 1 of the IPCC, nearly 140 scientists and national experts from more than thirty countries corroborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) to ensure that the emission inventories submitted to the UNFCCC are consistent and comparable between nations. The *Revised 1996 IPCC Guidelines* were accepted by the IPCC at its Twelfth Session (Mexico City, 11-13 September 1996). The information provided in this inventory is presented in accordance with these guidelines.

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[1] See the section below entitled *Global Warming Potentials* for an explanation of GWP values.

[2] See the section below entitled *What is Climate Change?* for an explanation of radiative forcing.

[3] The term "anthropogenic", in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC/UNEP/OECD/IEA 1997).

[4] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <http://www.unfccc.de>.

[5] Article 4 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (also identified in Article 12). See <http://www.unfccc.de>.

Additionally, in order to fully comply with the *Revised 1996 IPCC Guidelines*, the United States has provided estimates of carbon dioxide emissions from fossil fuel combustion using the IPCC Reference Approach in Annex O.

Overall, the purpose of an inventory of anthropogenic greenhouse gas emissions is (1) to provide a basis for the ongoing development of methodologies for estimating sources and sinks of greenhouse gases; (2) to provide a common and consistent mechanism through which Parties to the UNFCCC can estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change; and (3) as a prerequisite for accounting for reductions and evaluating possible mitigation strategies.

What is Climate Change?

Climate change refers to long-term fluctuations in temperature, precipitation, wind, and other elements of the Earth's climate system.[6] Natural processes such as solar-irradiance variations, variations in the Earth's orbital parameters,[7] and volcanic activity can produce variations in climate. The climate system can also be influenced by changes in the concentration of various gases in the atmosphere, which affect the Earth's absorption of radiation.

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation, though, is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 34°C lower (IPCC 1996).

Under the UNFCCC, the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."[8] Given that definition, in its 1995 assessment of the science of climate change, the IPCC concluded that:

> *Human activities are changing the atmospheric concentrations and distributions of greenhouse gases and aerosols. These changes can produce a radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation (IPCC 1996).*

The IPCC went on to report in its assessment that the "[g]lobal mean surface temperature [of the Earth] has increased by between about 0.3 and 0.6 °C since the late 19th century…" (IPCC 1996) and finally concluded with the following statement:

> *Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long term natural variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of the evidence suggests that there is a discernable human influence on global climate (IPCC 1996).*

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide, and other trace gases in the atmosphere that absorb the terrestrial radiation leav-

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[6] The Earth's climate system comprises the atmosphere, oceans, biosphere, cryosphere, and geosphere.

[7] For example, eccentricity, precession, and inclination.

[8] Article 1 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change.

ing the surface of the Earth (IPCC 1996). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC 1996). Holding everything else constant, increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth).

> *Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases (IPCC 1996).*

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, emitted solely by human activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as halons. Other fluorine containing halogenated substances include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). There are also several gases that, although they do not have a direct radiative forcing effect, do influence the formation and destruction of ozone, which does have such a terrestrial radiation absorbing effect. These gases referred to here as ozone precursors include carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane volatile organic compounds (NMVOCs).[9] Aerosols extremely small particles or liquid droplets often produced by emissions of sulfur dioxide (SO_2) can also affect the absorptive characteristics of the atmosphere.

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes except when directly or indirectly perturbed out of equilibrium by anthropogenic activities generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems.

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of Global Warming Potentials (GWPs), which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to directly affect the average global concentration of water vapor; however, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. A warmer atmosphere has an increased water holding capacity; yet, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and

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[9] Also referred to in the U.S. Clean Air Act as "criteria pollutants."

between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric carbon dioxide is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere, as of 1994, increased from approximately 280 parts per million by volume (ppmv) in pre-industrial[10] times to 358 ppmv, a 28 percent increase (IPCC 1996).[11] The IPCC has stated that "[t]here is no doubt that this increase is largely due to human activities, in particular fossil fuel combustion…" (IPCC 1996). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

In its latest scientific assessment, the IPCC also stated that "[t]he increased amount of carbon dioxide [in the atmosphere] is leading to climate change and will produce, on average, a global warming of the Earth's surface because of its enhanced greenhouse effect although the magnitude and significance of the effects are not fully resolved" (IPCC 1996).

Methane (CH_4). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. The average global concentration of methane in the atmosphere was 1,720 parts per billion by volume (ppbv) in 1994, a 145 percent increase from the pre-industrial concentration of 700 ppbv (IPCC 1996). It is estimated that 60 to 80 percent of current CH_4 emissions are the result of anthropogenic activities. Carbon isotope measurements indicate that roughly 20 percent of methane emissions are from fossil fuel consumption, and an equal percentage is produced by natural wetlands, which will likely increase with rising temperatures and rising microbial action (IPCC 1996).

Methane is removed from the atmosphere by reacting with the hydroxyl radical (OH) and is ultimately converted to CO_2. Increasing emissions of methane, though, reduces the concentration of OH, and thereby the rate of further methane removal (IPCC 1996).

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially the use of synthetic and manure fertilizers; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste combustion; and biomass burning. The atmospheric concentration of nitrous oxide (N_2O) in 1994 was about 312 parts per billion by volume (ppbv), while pre-industrial concentrations were roughly 275 ppbv. The majority of this 13 percent increase has occurred after the pre-industrial period and is most likely due to anthropogenic activities (IPCC 1996). Nitrous oxide is removed from the atmosphere primarily by the photolytic action of sunlight in the stratosphere.

Ozone (O_3). Ozone is present in both the upper stratosphere,[12] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[13] where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as chlorofluorocarbons (CFCs), have depleted stratospheric ozone concentrations. This loss of ozone in the strato-

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[10] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 1996).

[11] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750-1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 1996).

[12] The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

[13] The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

sphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 1996).

Tropospheric ozone, which is also a greenhouse gas, is produced from the oxidation of methane and from reactions with precursor gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs). This latter group of ozone precursors is included in the category referred to as "criteria pollutants" in the United States under the Clean Air Act[14] and its subsequent amendments. The tropospheric concentrations of both ozone and these precursor gases are short-lived and, therefore, spatially variable.

Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride (SF_6). Halocarbons are, for the most part, man-made chemicals that have both direct and indirect radiative forcing effects. Halocarbons that contain chlorine chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform, and carbon tetrachloride and bromine halons, methyl bromide, and hydrobromofluorocarbons (HBFCs) result in stratospheric ozone depletion and are therefore controlled under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which is itself an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation. Under the *Montreal Protocol*, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the *Protocol*, a cap was placed on the production and importation of HCFCs by non-Article 5[15] countries beginning in 1996, and then followed by a complete phase-out by the year 2030. The ozone depleting gases covered under the *Montreal Protocol* and its Amendments are not covered by the UNFCCC; however, they are reported in this inventory under Annex L.

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are not ozone depleting substances, and therefore are not covered under the *Montreal Protocol*. They are, however, powerful greenhouse gases. HFCs primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process currently have a small aggregate radiative forcing impact; however, it is anticipated that their contribution to overall radiative forcing will increase (IPCC 1996). PFCs and SF_6 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, and SF_6 is also small; however, because they have extremely long atmospheric lifetimes, their concentrations tend to irreversibly accumulate in the atmosphere.

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect and result from their role in promoting the formation of ozone in the troposphere and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects. (NO_x emissions injected higher in the stratosphere[16] can lead to stratospheric ozone deple-

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[14] [42 U.S.C §7408, CAA §108]

[15] Article 5 of the *Montreal Protocol* covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

[16] Primarily from fuel combustion emissions from high altitude supersonic aircraft.

tion.) Additionally, NO_x emissions from aircraft are expected to decrease methane concentrations, thus having a negative radiative forcing effect (IPCC 1999). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning—both natural and anthropogenic fires—fuel combustion, and, in the stratosphere, from nitrous oxide (N_2O). Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Nonmethane Volatile Organic Compounds (NMVOCs). Nonmethane volatile organic compounds include compounds such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere. They can be produced by natural events such as dust storms and volcanic activity or by anthropogenic processes such as fuel combustion. Their effect upon radiative forcing is to both absorb radiation and to alter cloud formation, thereby affecting the reflectivity (i.e., albedo) of the Earth. Aerosols are removed from the atmosphere primarily by precipitation, and generally have short atmospheric lifetimes. Like ozone precursors, aerosol concentrations and composition vary by region (IPCC 1996).

Anthropogenic aerosols in the troposphere are primarily the result of sulfur dioxide (SO_2)[17] emissions from fossil fuel and biomass burning. Overall, aerosols tend to produce a negative radiative forcing effect (i.e., net cooling effect on the climate), although because they are short-lived in the atmosphere lasting days to weeks their concentrations respond rapidly to changes in emissions.[18] Locally, the negative radiative forcing effects of aerosols can offset the positive forcing of greenhouse gases (IPCC 1996). “However, the aerosol effects do not cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result” (IPCC 1996). Emission estimates for sulfur dioxide are provided in Annex M of this report.

Global Warming Potentials

A Global Warming Potential (GWP) is intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas (see Table 1-1). It is defined as the cumulative radiative forcing both direct and indirect effects over a specified time horizon resulting from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP weighted emissions are measured in million metric tons of carbon equivalents (MMTCE). Carbon comprises 12/44$^{\text{ths}}$ of carbon dioxide by weight. The relationship between gigagrams (Gg) of a gas and MMTCE can be expressed as follows:

$$\text{MMTCE} = (\text{Gg of gas}) \times \left(\frac{\text{MMT}}{1{,}000\ \text{Gg}}\right) \times (\text{GWP}) \times \left(\frac{12}{44}\right)$$

where,

MMTCE = Million Metric Tons of Carbon Equivalents

Gg = Gigagrams (equivalent to a thousand metric tons)

GWP = Global Warming Potential

$\left(\frac{12}{44}\right)$ = Carbon to carbon dioxide molecular weight ratio.

MMT = Million Metric Tons

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases.

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[17] Sulfur dioxide is a primary anthropogenic contributor to the formation of “acid rain” and other forms of atmospheric acid deposition.

[18] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer negative forcing effect (i.e., a few years) (IPCC 1996).

According to the IPCC, GWPs typically have an uncertainty of ±35 percent. The parties to the UNFCCC have also agreed to use GWPs based upon a 100 year time horizon although other time horizon values are available.

> *In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons.*[19]

Greenhouse gases with long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, tropospheric ozone, ozone precursors (e.g., NO_x, CO, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. No GWP values are attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere. Other greenhouse gases not yet listed by the Intergovernmental Panel on Climate Change (IPCC), but are already or soon will be in commercial use include: HFC-245fa, hydrofluoroethers (HFEs), and nitrogen trifluoride (NF_3).

Recent Trends in U.S. Greenhouse Gas Emissions

Total U.S. greenhouse gas emissions rose in 1998 to 1,834.6million metric tons of carbon equivalents (MMTCE)[20] (11.2 percent above 1990 baseline levels).

Table 1-1: Global Warming Potentials and Atmospheric Lifetimes (Years)

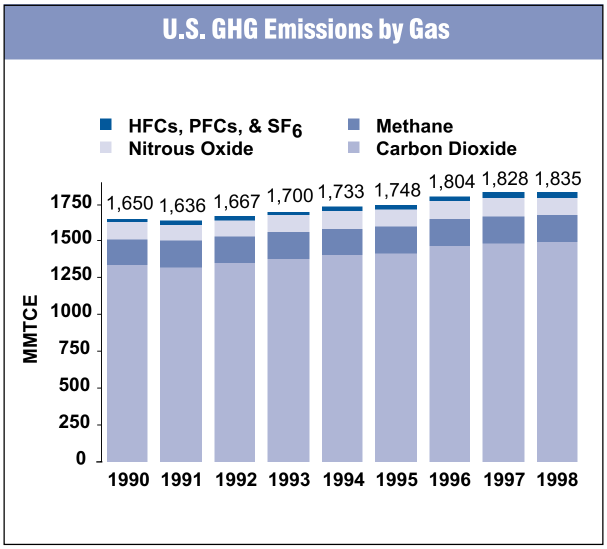
Gas	Atmospheric Lifetime	GWP[a]
Carbon dioxide (CO_2)	50-200	1
Methane (CH_4)[b]	12±3	21
Nitrous oxide (N_2O)	120	310
HFC-23	264	11,700
HFC-125	32.6	2,800
HFC-134a	14.6	1,300
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-227ea	36.5	2,900
HFC-236fa	209	6,300
HFC-4310mee	17.1	1,300
CF_4	50,000	6,500
C_2F_6	10,000	9,200
C_4F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

Source: (IPCC 1996)

[a] 100 year time horizon

[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Figure 1-1


U.S. GHG Emissions by Gas

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[19] Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties at its second session; held at Geneva from 8 to 19 July 1996; Addendum; Part Two: Action taken by the Conference of the Parties at its second session; Decision 9/CP.2; Communications from Parties included in Annex I to the Convention: guidelines, schedule and process for consideration; Annex: Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention; p. 18.

[20] Estimates are presented in units of millions of metric tons of carbon equivalents (MMTCE), which weights each gas by its GWP value, or Global Warming Potential (see previous section).

Figure 1-2

Annual Percent Change in U.S. GHG Emissions

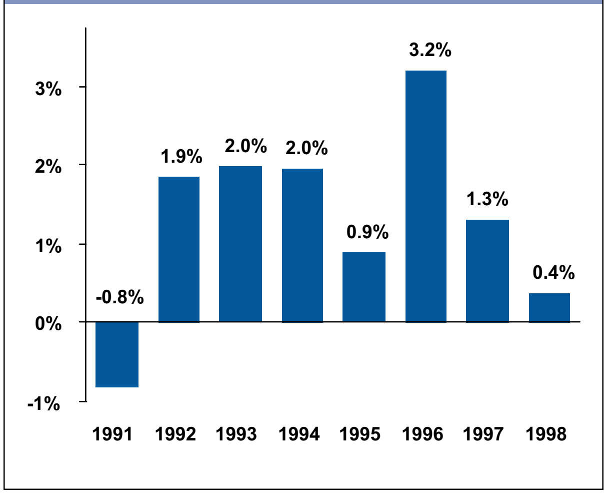
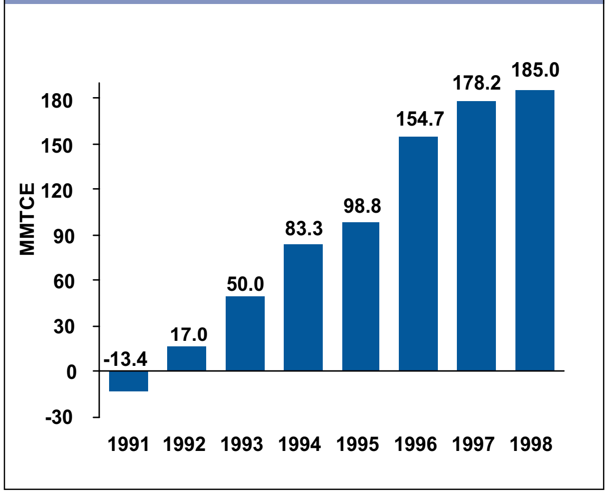


Figure 1-3

Absolute Change in U.S. GHG Emissions Since 1990



The single year increase in emissions from 1997 to 1998 was 0.4 percent (6.8 MMTCE), less than the 1.3 percent average annual rate of increase for the 1990s. Figure 1-1 through Figure 1-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute changes since 1990.

As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion, accounted for 80 percent of weighted emissions in 1998. Emissions from this source grew by 11 percent (148.1 MMTCE) from 1990 to 1998 and were also responsible for over 80 percent of the increase in national emissions during this period. The annual increase in CO_2 emissions from this source was only 0.5 percent in 1998 lower than the source's average annual rate of 1.3 percent during the 1990s despite a strong 3.9 percent increase in U.S. gross domestic product.

In addition to economic growth, changes in CO_2 emission from fossil fuel combustion are also correlated with energy prices and seasonal temperatures. Exceptionally mild winter conditions in 1998 moderated growth in CO_2 emissions from fossil fuel combustion below what would have been expected given the strength of the economy and continued low fuel prices. Table 1-2 shows annual changes in emissions during the last few years of the 1990s for particular fuel types and sectors.

Carbon dioxide emissions from fossil fuel combustion increased dramatically in 1996, due primarily to two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as to colder winter conditions and the associated rise in demand for natural gas from residential, commercial and industrial customers for heating caused gas prices to rise sharply; and 2) higher consumption of petroleum fuels for transportation. Milder weather conditions in summer and winter moderated the growth in emissions in 1997; however, the shut-down of several nuclear power plants lead electric utilities to increase their consumption of coal to offset the lost capacity. In 1998, weather conditions were a dominant factor in slowing the growth in emissions. Warm winter temperatures resulted in a significant drop in residential, commercial, and industrial natural gas consumption. This drop in emissions from natural gas used for heating was primarily offset by two factors: 1) electric utility emissions, which increased in part due to a hot summer and its associated air conditioning demand; and 2) increased motor gasoline consumption for transportation.

Other significant trends in emissions from additional source categories over the nine year period from 1990 through 1998 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 14.2 MMTCE. This increase was partly offset, however, by reductions in PFC emissions from aluminum production by 2.6 MMTCE (48 percent), which were the result of both

Table 1-2: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMTCE and Percent)

Sector	Fuel Type	1995-1996		1996-1997		1997-1998	
Electric Utility	Coal	24.5	5.7%	14.3	3.1%	5.5	1.2%
Electric Utility	Petroleum	1.4	10.0%	2.2	14.4%	7.3	41.6%
Electric Utility	Natural Gas	(6.9)	(14.6%)	3.3	8.1%	4.2	9.8%
Transportation[a]	Petroleum	13.8	3.3%	1.1	0.2%	7.2	1.7%
Residential	Natural Gas	5.8	8.1%	(3.8)	(4.9%)	(7.4)	(10.0%)
Commercial	Natural Gas	1.9	4.2%	0.9	1.9%	(2.7)	(5.7%)
Industrial	Natural Gas	4.7	3.4%	(1.4)	(1.0%)	(2.9)	(2.0%)
All Sectors[b]	All Fuels[b]	49.4	3.5%	19.4	1.3%	7.5	0.5%

[a] Excludes emissions from International Bunker Fuels.
[b] Includes fuels and sectors not shown in table.

voluntary industry emission reduction efforts and lower domestic aluminum production.

- Combined N_2O and CH_4 emissions from mobile combustion rose by 3.3 MMTCE (22 percent), primarily due to increased rates of N_2O generation in highway vehicles.
- Methane emissions from the manure management activities have increased by 7.9 MMTCE (53 percent) as the composition of the swine and dairy industries shift toward larger facilities. An increased number of large facilities leads to an increased use of liquid systems, which translates into increased methane production.
- Methane emissions from coal mining dropped by 6.2 MMTCE (26 percent) as a result of the mining of less gassy coal from underground mines and the increased use of methane from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 8.5 MMTCE (11 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.
- By 1998, all of the three major adipic acid producing plants had voluntarily implemented N_2O abatement technology; as a result, emissions fell by 3.0 MMTCE (60 percent). The majority of this decline occurred from 1997 to 1998, despite increased production.

Overall, from 1990 to 1998, total emissions of CO_2, CH_4, and N_2O increased by 153.7 (11 percent), 3.1 (2 percent), and 11.1 MMTCE (10 percent), respectively. During the same period, weighted emissions of HFCs, PFCs, and SF_6 rose by 17.0 MMTCE (73 percent). Despite being emitted in smaller quantities relative to the other principle greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because of their extremely high Global Warming Potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests and in landfilled carbon, which were estimated to be 12 percent of total emissions in 1998.

As an alternative, emissions can be aggregated across gases by the IPCC defined sectors, referred to here as chapters. Over the nine year period of 1990 to 1998, total emissions in the Energy, Industrial Processes, Agriculture, and Waste chapters climbed by 146.5 (10 percent), 18.5 (39 percent), 18.5 (14 percent), and 1.5 MMTCE (2 percent), respectively. Estimates of the quantity of carbon sequestered in the Land-Use Change and Forestry chapter, although based on projections, declined by 105.5 MMTCE (33 percent).

Table 1-4 summarizes emissions and sinks from all U.S. anthropogenic sources in weighted units of MMTCE, while unweighted gas emissions and sinks in gigagrams (Gg) are provided in Table 1-5. Alternatively, emissions and sinks are aggregated by chapter in Table

Box 1-1: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

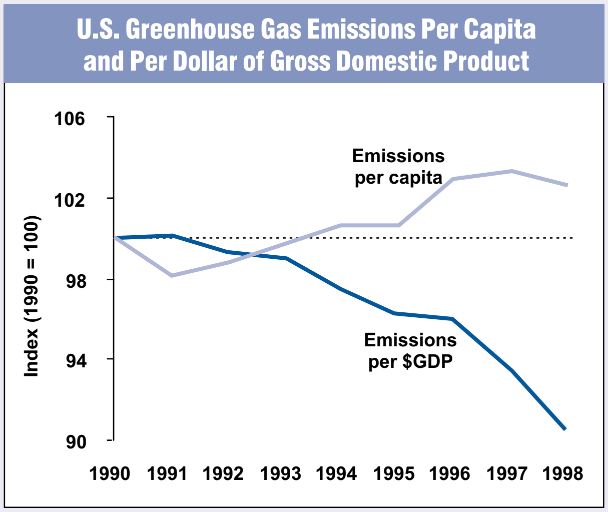
There are several ways to assess a nation's greenhouse gas emitting intensity. These measures of intensity could be based on aggregate energy consumption because energy-related activities[21] are the largest sources of emissions, on fossil fuel consumption only because almost all energy-related emissions involve the combustion of fossil fuels, on electricity consumption because electric utilities were the largest sources of U.S. greenhouse gas emissions in 1998, on total gross domestic product as a measure of national economic activity, or on a per capita basis. Depending upon which of these measures is used, the United States could appear to have reduced or increased its national greenhouse gas intensity. Table 1-3 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.3 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption thereby indicating an improved or lower greenhouse gas emitting intensity and much slower than that for either electricity consumption or overall gross domestic product. Emissions, however, are growing faster than national population, thereby indicating a worsening or higher greenhouse gas emitting intensity on a per capita basis (see Figure 1-4). Overall, atmospheric CO_2 concentrations a function of many complex anthropogenic and natural processes are increasing at 0.4 percent per year.

Table 1-3: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable Rate[g]	1991	1992	1993	1994	1995	1996	1997	1998	Growth
GHG Emissions[a]	99	101	103	105	106	109	111	111	1.3%
Energy Consumption[b]	100	101	104	106	108	112	112	112	1.4%
Fossil Fuel Consumption[c]	99	101	103	105	106	110	111	111	1.4%
Electricity Consumption[c]	102	102	105	108	111	114	116	119	2.2%
GDP[d]	99	102	104	108	110	114	118	123	2.6%
Population[e]	101	102	103	104	105	106	107	108	1.0%
Atmospheric CO_2 Concentration[f]	100	101	101	101	102	102	103	104	0.4%

[a] GWP weighted values
[b] Energy content weighted values. (DOE/EIA)
[c] (DOE/EIA)
[d] Gross Domestic Product in chained 1992 dollars (BEA 1999)
[e] (U.S. Census Bureau 1999)
[f] Mauna Loa Observatory, Hawaii (Keeling and Whorf 1999)
[g] Average annual growth rate

Figure 1-4



U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product

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[21] Energy-related activities are those that involve fossil fuel combustion (industrial, transportation, residential, and commercial end-use sectors), and the production, transmission, storage, and distribution of fossil fuels.

Table 1-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**1,340.3**	**1,326.1**	**1,350.4**	**1,383.3**	**1,404.8**	**1,416.5**	**1,466.2**	**1,486.4**	**1,494.0**
Fossil Fuel Combustion	1,320.1	1,305.8	1,330.1	1,361.5	1,382.0	1,392.0	1,441.3	1,460.7	1,468.2
Cement Manufacture	9.1	8.9	8.9	9.4	9.8	10.0	10.1	10.5	10.7
Natural Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.2	3.9
Lime Manufacture	3.0	3.0	3.1	3.1	3.2	3.4	3.6	3.7	3.7
Waste Combustion	2.8	3.0	3.0	3.1	3.1	3.0	3.1	3.4	3.5
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.9	2.0	2.3	2.4
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2
Carbon Dioxide Consumption	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4
Land-Use Change and Forestry (Sink)[a]	(316.4)	(316.3)	(316.2)	(212.7)	(212.3)	(211.8)	(211.3)	(211.1)	(210.8)
International Bunker Fuels[b]	32.2	32.7	30.0	27.2	26.7	27.5	27.9	29.9	31.3
CH_4	**177.9**	**177.7**	**179.4**	**178.7**	**181.6**	**184.1**	**183.1**	**183.8**	**180.9**
Landfills	58.2	58.1	59.1	59.6	59.9	60.5	60.2	60.2	58.8
Enteric Fermentation	32.7	32.8	33.2	33.7	34.5	34.9	34.5	34.2	33.7
Natural Gas Systems	33.0	33.4	33.9	34.6	34.3	34.0	34.6	34.1	33.6
Manure Management	15.0	15.5	16.0	17.1	18.8	19.7	20.4	22.1	22.9
Coal Mining	24.0	22.8	22.0	19.2	19.4	20.3	18.9	18.8	17.8
Petroleum Systems	7.4	7.5	7.2	6.9	6.7	6.7	6.5	6.5	6.3
Rice Cultivation	2.4	2.3	2.6	2.4	2.7	2.6	2.4	2.6	2.7
Stationary Sources	2.3	2.4	2.4	2.4	2.4	2.5	2.6	2.3	2.3
Mobile Sources	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.3
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Petrochemical Production	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Agricultural Residue Burning	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Silicon Carbide Production	+	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	+	+	+	+	+	+	+	+	+
N_2O	**108.2**	**110.5**	**113.3**	**113.8**	**121.5**	**118.8**	**121.5**	**122.4**	**119.4**
Agricultural Soil Management	75.3	76.3	78.2	77.3	83.5	80.4	82.4	84.2	83.9
Mobile Sources	13.8	14.6	15.7	16.5	17.1	17.4	17.5	17.3	17.2
Nitric Acid	4.9	4.9	5.0	5.1	5.3	5.4	5.6	5.8	5.8
Stationary Sources	3.8	3.8	3.9	3.9	4.0	4.0	4.2	4.2	4.3
Manure Management	3.4	3.6	3.5	3.7	3.8	3.7	3.8	3.9	4.0
Human Sewage	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2
Adipic Acid	5.0	5.2	4.8	5.2	5.5	5.5	5.7	4.7	2.0
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[b]	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
HFCs, PFCs, and SF_6	**23.3**	**22.0**	**23.5**	**23.8**	**25.1**	**29.0**	**33.5**	**35.3**	**40.3**
Substitution of Ozone Depleting Substances	0.3	0.2	0.4	1.4	2.7	7.0	9.9	12.3	14.5
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2	10.9
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	3.0	3.0	3.0
Aluminum Production	5.4	4.7	4.4	3.8	3.2	3.1	3.2	3.0	2.8
Semiconductor Manufacture	0.8	0.8	0.8	1.0	1.1	1.5	1.9	1.9	2.1
Total Emissions	**1,649.7**	**1,636.2**	**1,666.6**	**1,699.7**	**1,733.0**	**1,748.5**	**1,804.4**	**1,827.9**	**1,834.6**
Net Emission (Sources and Sinks)	**1,333.3**	**1,320.0**	**1,350.5**	**1,487.0**	**1,520.7**	**1,536.6**	**1,593.1**	**1,616.8**	**1,623.8**

\+ Does not exceed 0.05 MMTCE

[a] Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

[b] Emissions from International Bunker Fuels are not included in totals.

Note: Totals may not sum due to independent rounding.

Table 1-5: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**4,914,351**	**4,862,349**	**4,951,561**	**5,072,271**	**5,150,787**	**5,193,841**	**5,376,081**	**5,449,974**	**5,478,051**
Fossil Fuel Combustion	4,840,483	4,787,926	4,876,887	4,992,123	5,067,248	5,103,838	5,284,901	5,355,900	5,383,502
Cement Manufacture	33,278	32,535	32,792	34,624	36,087	36,847	37,079	38,323	39,227
Natural Gas Flaring	9,097	10,295	10,169	13,716	13,800	17,164	16,506	15,521	14,214
Lime Manufacture	11,092	10,891	11,245	11,496	11,895	12,624	13,179	13,434	13,627
Waste Combustion	10,345	10,931	10,993	11,295	11,308	11,104	11,504	12,532	12,889
Limestone and Dolomite Use	5,113	4,896	4,502	4,058	5,541	6,987	7,499	8,537	8,854
Soda Ash Manufacture and Consumption	4,144	4,035	4,091	4,048	4,012	4,309	4,273	4,434	4,325
Carbon Dioxide Consumption	800	840	882	912	898	968	1,140	1,294	1,413
Land-Use Change and Forestry (Sink)[a]	(1,159,994)	(1,159,646)	(1,159,299)	(779,935)	(778,285)	(776,659)	(774,725)	(774,083)	(773,019)
International Bunker Fuels[b]	117,965	120,019	109,965	99,886	98,017	101,014	102,197	109,788	114,700
CH_4	**31,054**	**31,020**	**31,329**	**31,203**	**31,711**	**32,147**	**31,972**	**32,084**	**31,593**
Landfills	10,171	10,152	10,321	10,402	10,452	10,566	10,508	10,510	10,268
Enteric Fermentation	5,712	5,732	5,804	5,876	6,016	6,094	6,032	5,973	5,885
Natural Gas Systems	5,770	5,840	5,923	6,042	5,987	5,931	6,041	5,961	5,860
Manure Management	2,613	2,708	2,801	2,990	3,283	3,447	3,567	3,861	3,990
Coal Mining	4,184	3,975	3,835	3,356	3,390	3,550	3,301	3,274	3,104
Petroleum Systems	1,294	1,307	1,262	1,206	1,175	1,168	1,143	1,142	1,108
Rice Cultivation	414	404	453	414	476	445	420	453	476
Stationary Sources	404	410	425	415	416	437	446	399	395
Mobile Sources	257	255	257	255	253	251	246	239	232
Wastewater Treatment	150	152	154	155	157	158	160	161	163
Petrochemical Production	56	57	60	66	70	72	75	77	77
Agricultural Residue Burning	30	28	33	26	34	28	32	34	35
Silicon Carbide Production	1	1	1	1	1	1	1	1	1
International Bunker Fuels[b]	2	2	2	2	2	2	2	2	2
N_2O	**1,280**	**1,307**	**1,340**	**1,346**	**1,437**	**1,406**	**1,437**	**1,448**	**1,412**
Agricultural Soil Management	891	903	925	914	988	951	975	996	992
Mobile Sources	163	172	185	195	202	206	207	205	203
Nitric Acid	58	58	59	60	63	64	67	68	68
Stationary Source	45	45	46	46	47	48	49	50	50
Manure Management	40	42	42	43	44	44	45	46	47
Human Sewage	23	24	24	24	25	25	25	25	25
Adipic Acid	59	62	57	61	65	66	67	55	23
Agricultural Residue Burning	1	1	1	1	1	1	1	1	1
Waste Combustion	1	1	1	1	1	1	1	1	1
International Bunker Fuels[b]	3	3	3	3	3	3	3	3	3
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M	M
HCFC-22 Production[c]	3	3	3	3	3	2	3	3	3
Semiconductor Manufacture	M	M	M	M	M	M	M	M	M
Electrical Transmission and Distribution[d]	1	1	1	1	1	1	1	1	1
Magnesium Production and Processing[d]	+	+	+	+	+	+	+	+	+
NO_x	**21,798**	**21,936**	**22,176**	**22,398**	**22,683**	**22,177**	**22,034**	**22,153**	**22,066**
CO	**85,394**	**87,485**	**84,589**	**84,716**	**88,911**	**80,093**	**82,028**	**79,284**	**78,082**
NMVOCs	**18,795**	**18,929**	**18,527**	**18,708**	**19,290**	**18,613**	**17,624**	**17,469**	**17,011**

\+ Does not exceed 0.5 Gg

M Mixture of multiple gases

NA Not Available

[a] Sinks are not included in CO_2 emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

[b] Emissions from International Bunker Fuels are not included in totals.

[c] HFC-23 emitted

[d] SF_6 emitted

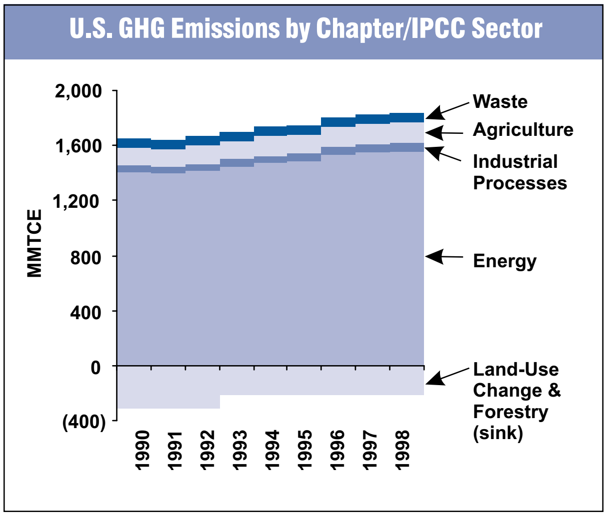
Note: Totals may not sum due to independent rounding.

1-6 and Figure 1-5.

Methodology and Data Sources

Emissions of greenhouse gases from various sources have been estimated using methodologies that are consistent with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). To the extent possible, the present U.S. Inventory relies on published activity and emission factor data. Depending on the emission source category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, etc.; emission factors are factors that relate quantities of emissions to an activity. For some sources, IPCC default methodologies and emission factors have been employed. However, for most emission sources, the IPCC default methodologies were expanded and more comprehensive methods were applied.

Figure 1-5


U.S. GHG Emissions by Chapter/IPCC Sector

Inventory emission estimates from energy consumption and production activities are based primarily on the latest official fuel consumption data from the Energy Information Administration (EIA) of the U.S. Department of Energy. Emission estimates for NO_x, CO, and NMVOCs were taken directly, except where noted, from the United States Environmental Protection Agency's (EPA) report, *National Air Pollutant Emission Trends 1900 - 1998* (EPA 1999), which is an annual EPA publication that provides the latest estimates of regional and national emissions of criteria pollutants. Emissions of these pollutants are estimated by the EPA based on statistical information about each source category, emission factors, and control efficiencies. While the EPA's estimation methodologies for criteria pollutants are conceptually similar to the IPCC recommended methodologies, the large number of sources EPA used in developing its criteria pollutant estimates makes it difficult to reproduce the methodologies from EPA (1999) in this inventory document. In these instances, the references containing detailed documentation of the methods used are identified for the interested reader. For agricultural sources, the EPA criteria pollutant emission estimates were supplemented using activity data from other agencies. Complete documentation of the methodologies and data sources used is provided in conjunction with the discussion of each source and in the various annexes.

Emissions from fossil fuels combusted in ships and aircraft engaged in the international transport of passengers and cargo are not included in U.S. totals, but are

Table 1-6: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMTCE)

Chapter/IPCC Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Energy	1,408.4	1,394.5	1,419.4	1,450.2	1,471.1	1,483.0	1,531.5	1,549.5	1,554.8
Industrial Processes	48.3	46.9	48.3	49.5	52.3	57.2	62.5	64.2	66.9
Agriculture	129.0	130.8	133.9	134.3	143.5	141.6	143.9	147.4	147.5
Land-Use Change and Forestry (Sink)*	(316.4)	(316.3)	(316.2)	(212.7)	(212.3)	(211.8)	(211.3)	(211.1)	(210.8)
Waste	64.0	64.1	65.1	65.7	66.0	66.6	66.4	66.7	65.5
Total Emissions	**1,649.7**	**1,636.2**	**1,666.6**	**1,699.7**	**1,733.0**	**1,748.5**	**1,804.4**	**1,827.9**	**1,834.6**
Net Emissions (Sources and Sinks)	**1,333.3**	**1,320.0**	**1,350.5**	**1,487.0**	**1,520.7**	**1,536.6**	**1,593.1**	**1,616.8**	**1,623.8**

* Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

Note: Totals may not sum due to independent rounding.

reported separately as international bunkers in accordance with IPCC reporting guidelines (IPCC/UNEP/OECD/IEA 1997). Carbon dioxide emissions from fuel combusted within U.S. territories, however, are included in U.S. totals.

Uncertainty in and Limitations of Emission Estimates

While the current U.S. emissions inventory provides a solid foundation for the development of a more detailed and comprehensive national inventory, it has several strengths and weaknesses.

First, this inventory by itself does not provide a complete picture of past or future emissions in the United States; it only provides an inventory of U.S. emissions for the years 1990 through 1998. However, the United States believes that common and consistent inventories taken over a period of time can and will contribute to understanding future emission trends. The United States produced its first comprehensive inventory of greenhouse gas emissions and sinks in 1993, and intends to update it annually, in conjunction with its commitments under the UNFCCC. The methodologies used to estimate emissions will also be updated periodically as methods and information improve and as further guidance is received from the IPCC and UNFCCC.

Secondly, there are uncertainties associated with the emission estimates. Some of the current estimates, such as those for CO_2 emissions from energy-related activities and cement processing, are considered to be fairly accurate. For other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated limits the scope or accuracy of the estimates presented. Despite these uncertainties, the *Revised 1996 IPCC Guidelines for National Greenhouse*

Box 1-2: Greenhouse Gas Emissions from Transportation Activities

Motor vehicle usage is increasing all over the world, including in the United States. Since the 1970s, the number of highway vehicles registered in the United States has increased faster than the overall population, according to the Federal Highway Administration. Likewise, the number of miles driven up 21 percent from 1990 to 1998 and gallons of gasoline consumed each year in the United States have increased relatively steadily since the 1980s, according to the Energy Information Administration. These increases in motor vehicle usage are the result of a confluence of factors including population growth, economic growth, increasing urban sprawl, and low fuel prices.

One of the unintended consequences of these changes is a slowing of progress toward cleaner air in both urban and rural parts of the country. Passenger cars, trucks, motorcycles, and buses emit significant quantities of air pollutants with local, regional, and global effects. Motor vehicles are major sources of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nonmethane volatile organic compounds (NMVOCs), nitrogen oxides (NO_x), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). Motor vehicles are also important contributors to many serious air pollution problems, including ground-level ozone (i.e., smog), acid rain, fine particulate matter, and global warming. Within the United States and abroad, government agencies have taken strong actions to reduce these emissions. Since the 1970s, the EPA has reduced lead in gasoline, developed strict emission standards for new passenger cars and trucks, directed states to enact comprehensive motor vehicle emission control programs, required inspection and maintenance programs, and more recently, introduced the use of reformulated gasoline to mitigate the air pollution impacts from motor vehicles. New vehicles are now equipped with advanced emissions controls, which are designed to reduce emissions of nitrogen oxides, hydrocarbons, and carbon monoxide.

Table 1-7 summarizes greenhouse gas emissions from all transportation-related activities. Overall, transportation activities excluding international bunker fuels accounted for an almost constant 26 percent of total U.S. greenhouse gas emissions from 1990 to 1998. These emissions were primarily CO_2 from fuel combustion, which increased by 11 percent from 1990 to 1998. However, because of larger increases in N_2O and HFC emissions during this period, overall emissions from transportation activities actually increased by 12 percent.

Table 1-7: Transportation-Related Greenhouse Gas Emissions (MMTCE)

Gas/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**399.6**	**391.5**	**401.1**	**409.1**	**422.3**	**427.7**	**441.7**	**443.4**	**450.2**
Passenger Cars	169.1	167.6	171.7	173.3	172.2	175.0	178.5	180.0	185.1
Light-Duty Trucks	77.4	77.1	77.1	80.4	87.1	88.9	91.1	92.1	94.6
Other Trucks	56.3	54.2	55.9	59.1	62.1	63.6	67.7	70.1	70.3
Buses	2.7	2.8	2.9	3.0	3.3	3.5	3.0	3.2	3.2
Aircraft[a]	48.2	46.1	45.5	45.8	48.0	46.8	49.1	48.8	49.4
Boats and Vessels	15.1	14.4	18.5	17.3	17.0	17.0	18.1	13.7	12.5
Locomotives	7.3	6.8	7.3	6.7	7.9	8.1	8.7	9.0	9.0
Other[b]	23.6	22.3	22.3	23.6	24.8	24.8	25.4	26.5	26.3
International Bunker Fuels[c]	32.2	32.7	30.0	27.2	26.7	27.5	27.9	29.9	31.3
CH_4	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.4**	**1.4**	**1.4**	**1.3**
Passenger Cars	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5
Light-Duty Trucks	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.5
Other Trucks and Buses	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Aircraft	+	+	+	+	+	+	+	+	+
Boats and Vessels	+	+	+	+	+	+	+	+	+
Locomotives	+	+	+	+	+	+	+	+	+
Other[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[c]	+	+	+	+	+	+	+	+	+
N_2O	**13.8**	**14.6**	**15.7**	**16.5**	**17.1**	**17.4**	**17.5**	**17.3**	**17.2**
Passenger Cars	8.1	8.0	8.4	8.6	8.8	8.9	8.9	8.7	8.6
Light-Duty Trucks	4.2	5.1	5.8	6.4	6.6	6.8	6.8	6.8	6.8
Other Trucks and Buses	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.9	1.0
Aircraft[d]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Boats and Vessels	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other[d]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
International Bunker Fuels[c]	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
HFCs	**+**	**+**	**0.2**	**0.7**	**1.8**	**2.6**	**3.7**	**4.7**	**4.7**
Mobile Air Conditioners[e]	+	+	0.2	0.7	1.8	2.6	3.7	4.7	4.7
Total[c]	**414.8**	**407.5**	**418.5**	**427.8**	**442.7**	**449.2**	**464.3**	**466.8**	**473.5**

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

[a] Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.

[b] "Other" CO_2 emissions include motorcycles, construction equipment, agricultural machinery, pipelines, and lubricants.

[c] Emissions from International Bunker Fuels include emissions from both civilian and military activities, but are not included in totals.

[d] "Other" CH_4 and N_2O emissions include motorcycles, construction equipment, agricultural machinery, gasoline-powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel-powered recreational, industrial, lawn and garden, light construction, airport service.

[e] Includes primarily HFC-134a

Box 1-3: Greenhouse Gas Emissions from Electric Utilities

Like transportation, activities related to the generation, transmission, and distribution of electricity in the United States result in significant greenhouse gas emissions. Table 1-8 presents greenhouse gas emissions from electric utility-related activities. Aggregate emissions from electric utilities of all greenhouse gases increased by 15 percent from 1990 to 1998, and accounted for a relatively constant 29 percent of U.S. greenhouse emissions during the same period.[22] The majority of these emissions resulted from the combustion of coal in boilers to produce steam that is passed through a turbine to generate electricity. Overall, the generation of electricity results in a larger portion of total U.S. greenhouse gas emissions than any other activity.

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[22] Emissions from nonutility generators are not included in these estimates. Nonutilties were estimated to produce about 10 percent of the electricity generated in the United States in 1998 (DOE and EPA 1999).

Table 1-8: Electric Utility-Related Greenhouse Gas Emissions (MMTCE)

Gas/Fuel Type or Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**476.6**	**473.2**	**472.7**	**490.5**	**493.9**	**494.0**	**513.0**	**532.8**	**549.9**
Coal	409.0	407.2	411.8	428.7	429.5	433.0	457.5	471.8	477.3
Natural Gas	41.2	41.1	40.7	39.5	44.0	47.2	40.3	43.6	47.8
Petroleum	26.4	24.9	20.2	22.3	20.5	13.9	15.3	17.5	24.8
Geothermal	0.1	0.1	0.1	0.1	+	+	+	+	+
CH_4	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Stationary Combustion (Utilities)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**	**2.1**	**2.2**	**2.3**	**2.3**
Stationary Combustion (Utilities)	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.3	2.3
SF_6	**5.6**	**5.9**	**6.2**	**6.4**	**6.7**	**7.0**	**7.0**	**7.0**	**7.0**
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0	7.0
Total	**484.3**	**481.2**	**481.0**	**499.1**	**502.9**	**503.2**	**522.4**	**542.2**	**559.3**

\+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding. Values do not include emissions from nonutility generators.

Gas Inventories (IPCC/UNEP/OECD/IEA 1997) require that countries provide single point estimates for each gas and emission or removal source category. Within the discussion of each emission source, specific factors affecting the accuracy of the estimates are discussed.

Finally, while the IPCC methodologies provided in the *Revised 1996 IPCC Guidelines* represent baseline methodologies for a variety of source categories, many of these methodologies continue to be improved and refined as new research and data becomes available. The current U.S. inventory uses the IPCC methodologies when applicable, and supplements them with other available methodologies and data where possible. The United States realizes that additional efforts are still needed to improve methodologies and data collection procedures. Specific areas requiring further research include:

Incorporating excluded emission sources. Quantitative estimates of some of the sources and sinks of greenhouse gas emissions are not available at this time. In particular, emissions from some land-use activities and industrial processes are not included in the inventory either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex P for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report.

Improving the accuracy of emission factors. Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to methane and nitrous oxide emissions from stationary and mobile combustion is highly uncertain.

Collecting detailed activity data. Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied. For example, the ability to estimate emissions of methane and nitrous oxide from jet aircraft is limited due to a lack of activity data by aircraft type and number of landing and take-off cycles.

Applying Global Warming Potentials. GWP values have several limitations including that they are not applicable to unevenly distributed gases and aerosols such as tropospheric ozone and its precursors. They are also intended to reflect global averages and, therefore, do not account for regional effects. Overall, the main uncertainties in developing GWP values are the estimation of atmospheric lifetimes, assessing indirect effects, choosing the appropriate integration time horizon, and assessing instantaneous radiative forcing effects which are dependent upon existing atmospheric concentrations. According to the IPCC, GWPs typically have an uncertainty of ±35 percent (IPCC 1996).

Emissions calculated for the U.S. inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies, assumptions, and incomplete data. As new information becomes available in the future, the United States will continue to improve and revise its emission estimates.

Organization of Report

In accordance with the IPCC guidelines for reporting contained in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), this U.S. inventory of greenhouse gas emissions and sinks is segregated into six sector-specific chapters, listed below in Table 1-9.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/IPCC Sector: Overview of emission trends for each IPCC defined sector

Source: Description of source pathway and emission trends from 1990 through 1998

- — **Methodology:** Description of analytical methods employed to produce emission estimates
- — **Data Sources:** Identification of data references, primarily for activity data and emission factors
- — **Uncertainty:** Discussion of relevant issues related to the uncertainty in the emission estimates presented

Special attention is given to carbon dioxide from fossil fuel combustion relative to other sources because of its share of emissions relative to other sources and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electric utility sector, are treated individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-10.

Changes in This Year's U.S. Greenhouse Gas Inventory Report

Each year the EPA not only recalculates and revises the emission estimates for all years that are presented in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* but also attempts to improve the analyses themselves through the use of better methods or data. A summary of this year's changes is presented in the following three sections and includes updates to historical data, changes in methodology, and other changes. The magnitude of each change is also described.

Changes to historical data are generally due to statistical data supplied by other agencies. Data sources are provided for further reference.

For methodological changes, differences between

Table 1-9: IPCC Sector Descriptions

Chapter/IPCC Sector	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions.
Industrial Processes	By-product or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion.
Solvent Use	Emissions, of primarily non-methane volatile organic compounds (NMVOCs), resulting from the use of solvents.
Agriculture	Anthropogenic emissions from agricultural activities except fuel combustion and sewage emissions, which are addressed under Energy and Waste, respectively.
Land-Use Change and Forestry	Emissions and removals from forest and land-use change activities, primarily carbon dioxide.
Waste	Emissions from waste management activities.

Source: (IPCC/UNEP/OECD/IEA 1997)

Table 1-10: List of Annexes

ANNEX A	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
ANNEX B	Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Stationary Combustion
ANNEX C	Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Mobile Combustion
ANNEX D	Methodology for Estimating Methane Emissions from Coal Mining
ANNEX E	Methodology for Estimating Methane Emissions from Natural Gas Systems
ANNEX F	Methodology for Estimating Methane Emissions from Petroleum Systems
ANNEX G	Methodology for Estimating Emissions from International Bunker Fuels Used by the U.S. Military
ANNEX H	Methodology for Estimating Methane Emissions from Enteric Fermentation
ANNEX I	Methodology for Estimating Methane Emissions from Manure Management
ANNEX J	Methodology for Estimating Methane Emissions from Landfills
ANNEX K	Global Warming Potential Values
ANNEX L	Ozone Depleting Substance Emissions
ANNEX M	Sulfur Dioxide Emissions
ANNEX N	Complete List of Sources
ANNEX O	IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion
ANNEX P	Sources of Greenhouse Gas Emissions Excluded
ANNEX Q	Constants, Units, and Conversions
ANNEX R	Abbreviations
ANNEX S	Chemical Symbols
ANNEX T	Glossary

the previous Inventory and this Inventory are explained. Many of the changes in methodology are due to a recent series of IPCC good practice workshops held to assist in the preparation of greenhouse gas inventories and in the implementation of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Unless otherwise noted, the methodological changes incorporated into this year's Inventory reflect the recommendations of experts at these IPCC good practice workshops. In general, when methodological changes have been implemented, the entire time series (1990 through 1998) has been recalculated to reflect the change.

Changes in Historical Data

- In the CO_2 Emissions from Fossil Fuel Combustion section of the Energy chapter, most differences, as compared to previous emission estimates, are due to revised energy consumption data from the Energy Information Administration (EIA 1999a, 1999c, 1999d) for selected years (see below for detail on an additional small methodological change). In addition, a small error in estimates of CO_2 emissions from combustion of petroleum used for transportation has been corrected in this Inventory. Previously, the combustion efficiency had been inadvertently applied to bunker fuel emissions prior to removing them from the calculation of CO_2 emissions from petroleum used for transportation. In the current Inventory, the combustion efficiency is correctly applied once to all emissions after the subtraction of bunker fuels. The combined data and methodological changes resulted in an average decrease of 4.3 MMTCE (0.3 percent) in annual CO_2 emissions from fossil fuel combustion for 1990 through 1997.
- In the Stationary Combustion (excluding CO_2) section of the Energy Chapter, differences from previous emission estimates are due to revised energy consumption data from the EIA (1999a, 1999d) for selected years. This revision resulted in an increase of less than 0.1 MMTCE (0.6 percent) in annual CH_4 emissions and an average increase of less than 0.1 MMTCE (0.7 percent) in annual N_2O emissions from stationary combustion for 1990 through 1997.
- In the Mobile Combustion (excluding CO_2) section of the Energy Chapter, differences with previous emission estimates for highway sources are due to revised estimates of historical vehicle-miles-traveled by the Federal Highway Administration (FHWA 1999). Extremely small differences exist in the non-highway estimates due to revised historical fuel consumption data from EIA (1999a, 1999c) and FHWA (1999). These revisions caused an average increase of less than 0.1 MMTCE (3.0 percent) in annual CH_4 emissions and an increase of 0.3 MMTCE (1.9 percent) in annual N_2O emissions from mobile combustion for 1990 through 1997.
- In the Natural Gas Systems section of the Energy

Chapter, historical estimates of methane emissions are revised based on the transmission pipeline mileage reported by the Office of Pipeline Safety (OPS). Inventories in previous years relied on the American Gas Association (AGA) for transmission pipeline mileage data. AGA aggregates pipeline mileage data as reported in FERC Form 2 "Annual Report of Natural Gas Pipeline Companies"; however, only interstate pipeline companies regulated by FERC submit Form 2. In contrast, OPS data is for all companies with more than one mile of transmission pipeline and includes both intra- and interstate pipelines. Accordingly, OPS reports pipeline mileage that is higher than that reported by AGA. Using the new data, EPA recalculated historical emission estimates, which resulted in increases for most years. The historical emission estimates have increased an average of 0.7 MMTCE (1.5 percent) in annual CH_4 emissions for 1990 through 1997.

- In the Natural Gas Flaring and Criteria Pollutant Emissions in the Oil and Gas Activities section of the Energy chapter, changes in emission estimates for natural gas flaring are due to revisions in data from the EIA (1999e). These revisions caused an average increase of 0.2 MMTCE (5.8 percent) in CO_2 annual emissions for 1990 through 1997. The EPA (1999b) has also revised estimates for criteria pollutants from oil and gas activities for 1996 and 1997. These revisions resulted in average increases of 3.5 percent in annual NOx emissions, and 3.9 percent in CO annual emissions from 1990 through 1997, and 1.0 percent in annual NMVOCs emissions from1990 through 1997.
- In the International Bunker Fuels section of the Energy chapter, a small error in the 1990-1997 Inventory is corrected in this volume. Emissions from combustion of distillate fuel in marine bunkers were misreported by two years in that edition, presenting 1988 estimates for 1990, 1989 estimates for 1991, and so forth. In addition, the activity data for foreign airlines at U.S. airports in 1997 have been adjusted slightly (BEA 1999). The combined data and methodological changes resulted in an average decreases of 2.0 MMTCE (7.4 percent) in annual CO_2 emissions, less than 0.1 MMTCE (10.9 percent) in annual CH_4 emissions and less than 0.1 MMTCE (8.3 percent) in annual N_2O emissions from international bunker fuels for 1990 through 1997.
- In the Limestone and Dolomite Use section of the Industrial Processes chapter, the 1997 value for limestone and dolomite consumption was revised by the United States Geological Survey (USGS 1999). This data change resulted in an increase of 0.2 MMTCE, or 9.3 percent, of CO_2 emissions from limestone and dolomite use in 1997.
- In the Carbon Dioxide Consumption section of the Industrial Processes chapter, the 1997 value was revised. The reference (Freedonia 1999) does not provide data for 1997, so it has been extrapolated using annual growth rates from confirmed 1993 through 1996 values. Previously, the growth in CO_2 production was also applied to calculate CO_2 used in EOR applications. However, this year's data shows that Freedonia holds EOR constant for 1996-1998. This revision in data resulted in an average increase of less than 0.1 MMTCE, or 5.3 percent, of CO_2 emissions from CO_2 consumption for 1997.
- In the Petrochemical Production section of the Industrial Processes chapter, the differences between the 1990-1997 Inventory and this volume reflect updated production data for ethylene, ethylene dichloride, and methanol from the Chemical Manufacturers Association (CMA 1999). These updates caused an average increase of less than 0.1 MMTCE (1.5 percent) in annual CH_4 emissions from petrochemical production for 1994 through 1997.
- In the Substitution of Ozone Depleting Substances section of the Industrial Processes chapter, a review of the current chemical substitution trends with input from industry representatives resulted in updated assumptions for the Vintaging Model, particularly in the stationary refrigeration and foams sectors. These updates resulted in an average decrease of 2.0 MMTCE (22.7 percent) in aggregate HFC, PFC, and SF_6 emissions from substitution of ozone depleting substances for 1994 through 1997.
- In the Enteric Fermentation section of the Agriculture chapter, the emission estimates for the 1990-

1998 Inventory have been recalculated using updated animal population data. Specifically, animal population data for 1994 through 1997 were updated to reflect the recent publication of final livestock population estimates by USDA (1999a-h, n). Also, horse population data for 1990 through 1998 were updated to reflect revised data from the Food and Agriculture Organization (FAO 1999). The dairy cow emission factors were also updated to reflect revised milk production data. These data modifications caused an average increase of less than 0.1 MMTCE (less than 0.1 percent) in annual CH_4 emissions from enteric fermentation for 1990 through 1997.

Methodological Changes

Carbon Dioxide Emissions from Fossil Fuel Combustion

The emission factor used to calculate emissions from the combustion of residual fuel at electric utilities was updated to 21.29 MMTCE/QBtu, based on new data that EIA received from electric utilities (EIA 1999b). The emission factor for residual fuel for all other sectors remains at 21.49 MMTCE/QBtu.

Additionally, non-bunker jet fuel emissions from military vehicles for 1990-1998, which are accounted for under the transportation end-use sector, have been estimated for the first time in this inventory. Data on jet fuel expenditures by the U.S. military was supplied by the Office of the Under Secretary of Defense (Environmental Security), U.S. Department of Defense (DoD). Data on fuel delivered to the military within the U.S. was provided from unpublished data by the Defense Energy Support Center, under DoD's Defense Logistics Agency. The quantity of fuel used was estimated using these data sources. Jet fuel densities for each fuel type were obtained from the Air Force (1998). The combined data and methodological changes resulted in an average decrease of 4.3 MMTCE (0.3 percent) of CO_2 annual emissions from fossil fuel combustion for 1990 through 1997.

Petroleum Systems

EPA has restated the emissions of methane from petroleum systems for 1998 and previous years, resulting in a substantial, 5.4 MMTCE, almost four-fold increase in the estimate in CH_4 from 1990 through 1997. The new, higher estimate of methane emissions from petroleum systems is based on work sponsored by EPA and presented in *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999a). Where the previous estimates of methane emissions from the petroleum industry used emission and activity factors based on top-down, broad categories of activities, the revised approach is based on a more detailed, bottom-up analysis of 70 different crude oil handling and processing activities from the wellhead to refining.

The overall approach to these new petroleum sector estimates is now consistent with the detailed, bottom-up analysis that has been used for several years to estimate methane emissions from the natural gas industry. As with natural gas, the new approach to estimating methane emissions from petroleum systems is based on a detailed characterization of the petroleum sector, which describe the emissions producing sources within the sector. Under this approach, EPA has developed emissions factors for each emission producing activity that describes the rate of annual emissions per activity. The emissions factors derive largely from Radian International LLC (Radian 1996e). Other sources of emissions factors include data from various reports and documents of the American Petroleum Institute, EPA, Minerals Management Service (MMS) reports, Gas Research Institute (GRI), Canadian Association of Petroleum Producers (CAPP), and various industry peer review panels. Activity factors are used to generalize the emissions to the entire industry and are multiplied by the emission factors to generate the total emissions estimates. The major sources of activity factors include various reports from the Energy Information Administration (EIA), API, Radian, EPA, MMS, the *Oil &Gas Journal*, and peer review panels.

International Bunker Fuels

International bunker fuel emissions resulting from military aviation and marine activities for 1990-1998 have been estimated for the first time in this inventory. Data on jet fuel expenditures by the U.S. military was supplied by the Office of the Under Secretary of Defense (Environmental Security), U.S. Department of Defense (DoD). Estimates of the percentage of each services' total operations that are international operations were developed by DoD. Military aviation bunkers include international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Data on fuel delivered to the military within the U.S. was provided from unpublished data by the Defense Energy Support Center, under DoD's Defense Logistics Agency. Together, the data allow the quantity of fuel used in military international operations to be estimated. Jet fuel densities for each fuel type were obtained (Air Force 1998). The combined data and methodological changes resulted in an average decreases of 2.0 MMTCE (7.4 percent) in annual CO_2 emissions, less than 0.1 MMTCE (10.9 percent) in annual CH_4 emissions and less than 0.1 MMTCE (8.3 percent) in annual N_2O emissions from international bunker fuels for 1990 through 1997.

Cement Manufacture

During clinker production some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust. The emissions attributable to the calcinated portion of the cement kiln dust are not accounted for by the clinker emission factor. These additional CO_2 emissions were estimated as 2 percent of the CO_2 emissions calculated from clinker production. The previous inventory did not include cement kiln dust emissions estimates. These additional emissions from cement kiln dust were combined with the emissions from clinker production to calculate total cement production emissions. This methodological change resulted in an average increase of 0.2 MMTCE (2.0 percent) in annual CO_2 emissions from cement manufacture for 1990 through 1997.

Lime Manufacture

During the calcination stage of lime manufacture, CO_2 is driven off as a gas and normally exits the system with the stack gas. Carbon dioxide emissions were estimated by applying a CO_2 emission factor to the total amount of lime produced. The emission factor used in this analysis is the product of the mass of CO_2 released per unit of lime, and the average calcium plus magnesium oxide (CaO + MgO) content of lime. In previous inventories the average calcium plus magnesium oxide content of lime was not factored into the emissions factor. The inclusion of the CaO or CaO + MgO content of lime in the current inventory, was recommended by the National Lime Association (Males 1999). Lime industry experts believe that approximately 93 percent is a representative value for lime's average calcium plus magnesium oxide content (ASTM 1996; Schwarzkopf 1995). The remainder is composed of silica, aluminum, and iron oxides (3.83 percent) and $CaCO_3$ (3.41 percent). These other compounds are present because limestone feed is not 100 percent pure, nor is the conversion process 100 percent efficient (Males 1999). This yields an emission factor of 0.73 tons of CO_2 per ton of lime produced. In the previous Inventory, CaO was considered to be 100 percent of limestone, thus yielding an emission factor of 0.785 tons of CO_2 per ton of lime produced. This methodological change resulted in an average decrease of 0.2 MMTCE (6.8 percent) in annual CO_2 emissions from lime manufacture for 1990 through 1997.

Adipic Acid Production

The equation used to estimate N_2O emissions from adipic acid production was changed from the previous Inventory to include both a destruction factor and an abatement system utilization factor. The N_2O destruction factor represents the amount of N_2O expressed as a percentage of N_2O emissions that are destroyed by the currently installed abatement technology. The abatement system utilization factor represents the percent of time that the abatement equipment operates. This methodological change resulted in an average increase of 0.3 MMTCE (7.5 percent) in annual N_2O emissions from adipic acid production for 1990 through 1997.

Nitric Acid Production

An estimated 20 percent of nitric acid plants in the United States are equipped with Non-Selective Catalytic Reduction (NSCR) technology (Choe, et al. 1993). In the process of destroying NOx, NSCR systems also destroy 80 to 90 percent of the N_2O. Hence, the emission factor is equal to (9.5 × 0.80) + (2 × 0.20) = 8 kg N_2O per metric ton HNO_3. In previous Inventories the emission factor was calculated without weighting the percent of plants using NSCR and Selective Catalytic reduction (SCR) technologies, thus the previous emission factor was 5.5 kg N_2O per metric ton HNO_3. This methodological change resulted in an average increase of 1.7 MMTCE (46.2 percent) in annual N_2O emissions from nitric acid production for 1990 through 1997.

Aluminum Production

PFC emissions from aluminum production were estimated by multiplying an emission factor by the annual production. In the previous Inventory, PFC emissions were estimated using a single per unit emission factor for 1990, and emissions for 1991 through 1996 were estimated with emission factors that incorporated data on reductions in anode effects provided by aluminum companies through the Voluntary Aluminum Industry Partnership (VAIP). The current inventory combines data on smelter operating parameters (anode effect frequency and anode effect duration) with slope coefficients that relate the operating parameters to emissions of CF_4 and C_2F_6. The operating parameter data has been reported by smelters and the slope coefficients are based upon measurements taken at the individual smelters. In cases where data reports or smelter specific coefficients are unavailable, technology-specific defaults have been used. These revisions in methodology resulted in an average increase of 0.3 MMTCE (8.3 percent) in annual PFC emissions from aluminum production for 1990 through 1997.

Semiconductor Manufacture

HFC, PFC, and SF_6 emissions from semiconductor manufacture were estimated using silicon chip manufacturing characteristics and data provided through the Emission Reduction Partnership for the Semiconductor Industry. For previous Inventories, emissions were estimated based on gas sales data from 1994, emission factors for the most commonly used gases, and projections regarding the growth of semiconductor sales and the effectiveness of emission reduction efforts. For the 1998 Inventory, emissions have been recalculated using an improved estimation method that uses two sets of data. For 1990 through 1994, emissions were estimated based on the historical consumption of silicon (square centimeters), the estimated average number of interconnecting layers in the chips produced, and an estimated per-layer emission factor. The average number of layers per chip was based on industry estimates of silicon consumption by line-width and of the number of layers per line-width. The per-layer emission factor was based on the total annual emissions reported by the participants in the EPA's Emission Reduction Partnership for the Semiconductor Industry. For the three years for which gas sales data were available (1992 through 1994), the estimates derived using the new method are within 10 percent of the estimates derived using gas sales data and average values for emission factors and GWP values.

For 1995 through 1998, emissions were estimated based on the total annual emissions reported by the participants in the EPA's Emission Reduction Partnership for the Semiconductor Industry. Partners estimate their emissions using a range of methods; the partners with relatively high emissions typically multiply estimates of their PFC consumption by process-specific emission factors that they have either measured or obtained from suppliers manufacturing equipment and based tools. To estimate total U.S. emissions from semiconductor manufacturing based on reported partner emissions, a per-plant emissions factor was estimated for the partners. This per-plant emission factor was then applied to plants operated by semiconductor manufacturers who were not partners, considering the varying characteristics of the plants operated by partners and non-partners (e.g., typical plant size and type of device produced). The resulting estimate of non-partner emissions was added to the emissions reported by the partners to obtain total U.S. emissions. These revisions in methodology resulted in an average increase of 0.4 MMTCE (72.4 percent) in annual HFC, PFC, and SF_6 emissions from semiconductor manufacture for 1990 through 1997.

Manure Management

The methodology for estimating N2O emissions from manure management no longer assumes that 20 percent of the manure nitrogen volatilizes before N2O production and therefore is not available for N2O production. This assumption was used in previous Inventories to correct for what appeared to be an inconsistency with the Agricultural Soil Management emission estimate methodologies, which account for indirect N2O emissions from nitrogen volatilized from managed manure systems, as well as from nitrogen in applied animal manure. However, as a result of efforts carried out by the IPCC in their work on inventory "good practice," the determination was made that there is not an inconsistency. Through this process, it became clear that the total amount of manure nitrogen in managed systems is available for both N2O production (accounted for in the Manure Management calculations) and nitrogen volatilization (accounted for in the Agricultural Soil Management calculations). Therefore, this step has been removed so that the methodology corresponds with the guidance described in IPCC/UNEP/OECD/IEA (1997). This results in a larger amount of nitrogen available for N2O production.

Additionally, all animal population data, except horses, for 1994 through 1997 were updated to reflect the recent publication of final livestock population estimates for 1994 through 1997 from USDA (USDA 1999a-f, i-o). Horse population data for 1990 through 1998 were updated to reflect updated data from the Food and Agriculture Organization (FAO 1999). These methodological and data changes together cause an average increase of 1.9 MMTCE (11.2 percent) in annual CH_4 emissions and 0.8 MMTCE (28.3 percent) in annual N_2O emissions from manure management for 1990 through 1997.

Rice Cultivation

The climatic conditions of Arkansas (in 1998), southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop to be grown each year. This second rice crop is produced from re-growth on the stubble after the first crop has been harvested. For the 1990-1998 U.S. Inventory, the approach used to estimate emissions from rice cultivation was modified to account for emissions from ratooned and primary areas separately. In this Inventory, data was collected on the flooding season length, area cultivated, and emissions rate range for both the primary and ratoon crops. In previous Inventories, emissions from the primary and ratoon seasons were not estimated separately. Instead, flooding season lengths and a daily emission factor range that are representative of the primary crop were used to estimate emissions from both the primary and ratooned areas. This approach was assumed to result in a reasonable first approximation for the ratooned areas because the higher daily average emissions from ratooned areas are at least somewhat canceled out by a shorter ratoon flooding season (compared to the primary crop). For the current Inventory, information on ratoon flooding season lengths was collected from agricultural extension agents in the states that practice ratooning, and emission factors for both the primary season and the ratoon season were derived from published results of field experiments in the United States. This change caused an average decrease of 0.2 MMTCE (6.3 percent) in annual CH_4 emissions from rice cultivation for 1990 through 1997.

Agricultural Soil Management

The current Inventory includes two new sources of nitrogen that were not accounted for in previous inventories: land application of sewage sludge and production of non-alfalfa forage legumes. The current Inventory also includes several data and methodological changes relative to the previous Inventory. Three changes to the data have been made. First, an error was found in a conversion factor used to calculate organic fertilizer nitrogen consumption; correcting this factor has resulted in higher organic fertilizer consumption statistics and lower synthetic fertilizer consumption statistics. Second, crop production statistics for some crops have changed due to the use of updated statistics from the U.S. Department of Agriculture (USDA 1994a, 1998). Third, a more recent data source has been used to estimate the annual areas under histosol cultivation, resulting in higher area estimates for the entire time series (USDA 1994b).

Two methodological changes have also been made. First, the emission factor for histosol cultivation has been revised upward as a result of new guidance proposed by the IPCC in their work on inventory "good practice." Second, in the indirect calculations for leaching and runoff, the total amount of applied nitrogen has been assumed to be subject to leaching and runoff, rather than just the unvolatilized portion. This change was also a result of work carried out under the "good practice" inventory effort. Through this process, it became clear that the methodology assumes all of the volatilized nitrogen redeposits. Therefore, in order to simplify the methodology, rather than including a volatilization and subsequent redeposition step, the leaching and runoff fraction is just applied to all the applied nitrogen in a single calculation. This change to the leaching and runoff calculation has resulted in an increase in the emission estimates for this process. All the changes taken together (i.e., the inclusion of the two additional sources of applied nitrogen, combined with the data changes and the methodological changes) resulted in an average increase in the annual emissions from agricultural soil management of 10.2 MMTCE (14.7 percent) relative to the estimates in the previous Inventory.

Agriculture Residue Burning

This inventory includes three methodological changes as compared to previous Inventories. Previous calculations on rice production in Florida were based on the assumption that the Sem-Chi Rice Co. accounted for all of Florida's rice production. However, this Inventory uses revised production data to include acreage from additional producers. Average production per acre for Florida for all years was assumed to be the same as 1998 productivity of Sem-Chi Rice. Total production in Florida for 1990 through 1998 was estimated using this average productivity and the revised annual acreage.

The methodology for estimating the percentage of rice crop residue burned from rice was also revised. In the previous Inventory, the percentage of rice burned was assumed to be 3 percent in all states except California. To obtain a more accurate estimate for this Inventory, estimates of the percentage of rice area burned per year for 1990 through 1998 in each of the seven rice burning states were obtained from agricultural extension agents. A weighted (by area) national average percent area burned was calculated for each year.

Additionally, production numbers for corn were changed to include only corn from grain. Corn for silage was included in the previous Inventory, but is now excluded because there is no resulting residue. Historical crop production data, which previously had been taken from annual USDA summary reports, was revised using two USDA reports of final crop estimates (USDA 1994a, 1998). These methodological changes cause an average decrease of less than 0.1 MMTCE (17.1 percent) in annual CH_4 emissions and less than 0.1 MMTCE (12.9 percent) in annual N_2O emissions from agriculture residue burning for 1990 through 1997.

Landfills

The methodology used to estimate recovered landfill gas was altered from the previous Inventory. Previous landfill gas recovery estimates (1990-1997) were based on 1990 and 1992 data obtained from Governmental Advisory Associates (GAA 1994). The 1998 Inventory reflects estimates of landfill gas recovered per year based on site-specific data collected from vendors of flaring equipment, and a database on landfill gas-to-energy (LFGTE) projects compiled by the EPA's Landfill Methane Outreach Program (LMOP). Based on the information provided by vendors, the EPA estimated total methane recovered due to the use of 235 flares for 1990 through 1998. This estimate likely underestimates emissions because the EPA believes that more than 700 flares are in use at landfills in the United States. The

EPA is currently working with the Solid Waste Association of North America (SWANA) to better characterize the emissions reduced by flaring and expects to present a revised estimate in the next Inventory. Additionally, the LMOP database provided data on landfill gas flow and energy generation for 237 out of approximately 260 operational LFGTE projects. From this data, the EPA was able to estimate the methane emissions avoided due to LFGTE projects.

The EPA assumes that emissions from industrial landfills are equal to seven percent of the total methane emissions from municipal landfills. The amount of methane oxidized is assumed to be ten percent of the methane generated (Liptay et al. 1998). To calculate net methane emissions, methane recovered and oxidized is subtracted from methane generated at municipal and industrial landfills. The 1990 through 1997 emission estimates were updated for this Inventory according to the revised recovery estimates. This change resulted in an average decrease in the annual estimates of total CH_4 emissions from landfills of 1.6 MMTCE (2.3 percent) relative to the estimates in the previous Inventory.

Human Sewage

The assumptions used to estimate N_2O emissions from human sewage changed slightly from those used for the previous Inventory. The total estimate of nitrogen in human sewage was decreased by the amount of nitrogen added to soils via sewage sludge applications which are accounted for under the Agricultural Soil Management source category.

Annually variable population and per capita protein consumption factors were obtained from the U.S. Census Bureau and the United Nations Food and Agriculture Organization (FAO), respectively. Protein consumption estimates are updated by the FAO annually. However, data for protein intake was unavailable for 1998 and therefore, the value of per capita protein consumption for the previous year was used. In addition, the protein intake estimate for 1997 was unavailable for the 1997 Inventory. Thus, this Inventory reflects an updated 1997 protein intake estimate published in 1998. These methodological changes for the 1990 through 1997 estimates resulted in an average annual decrease in N_2O emissions from Human Sewage of 0.2 MMTCE (6.8 percent) relative to the estimates in the previous Inventory.

Other Changes

Two source categories have been added in the current Inventory. First, CO_2 emissions from the combustion of plastics in municipal solid waste are now reported in the Waste Combustion section. Previously, only N_2O emissions had been estimated. The second, an addition in Land-Use Change and Forestry, addresses the storage of carbon resulting from the disposal of yard trimmings in landfills. Yard trimmings, a sizeable portion of municipal solid waste, are a significant carbon sink when landfilled.

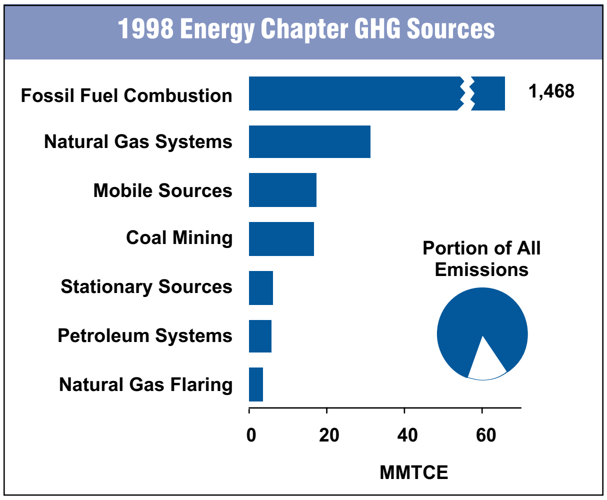
The IPCC Reporting Tables, presented in Annex N of the 1990-1997 Inventory, have been removed from this Inventory. A new, more detailed, common reporting format has been developed by the UNFCCC as a substitute for those tables. The United States intends to submit information to the UNFCCC Secretariat using this common reporting format in a separate report.

2. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 85 percent of total emissions on a carbon equivalent basis in 1998. This included 99, 34, and 18 percent of the nation's carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 80 percent of national emissions from all sources on a carbon equivalent basis, while the non-CO_2 emissions from energy represented a much smaller portion of total national emissions (4 percent collectively).

Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 2-1). Due to the relative importance of fossil fuel combustion-related CO_2 emissions, they are considered separately from other emissions. Fossil fuel combustion also emits CH_4 and N_2O, as well as criteria pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs). Mobile fossil fuel combustion was the second largest source of N_2O emissions in the United States, and overall energy-related activities were collectively the largest source of criteria pollutant emissions.

Figure 2-1



Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of CH_4 from natural gas systems, petroleum systems, and coal mining. Smaller quantities of CO_2, CO, NMVOCs, and NO_x are also emitted.

The combustion of biomass and biomass-based fuels also emits greenhouse gases. Carbon dioxide emissions from these activities, however, are not included in national emissions totals in the Energy chapter because biomass fuels are of biogenic origin. It is assumed that the carbon released when biomass is consumed is recycled as U.S. forests and crops regenerate, causing no net addition of CO_2 to the atmosphere. The net impacts of land-use and forestry activities on the carbon cycle are accounted for in the Land-use change and Forestry chapter. Emissions of other greenhouse gases from the combustion of biomass and biomass based fuels are included in national totals under stationary and mobile combustion.

Overall, emissions from energy-related activities have increased from 1990 to 1998 due, in part, to the strong performance of the U.S. economy. Over this period, the U.S. Gross Domestic Product (GDP) grew approximately 23

Table 2-1: Emissions from Energy (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**1,322.6**	**1,308.6**	**1,332.8**	**1,365.2**	**1,385.7**	**1,396.6**	**1,445.8**	**1,464.9**	**1,472.1**
Fossil Fuel Combustion	1,320.1	1,305.8	1,330.1	1,361.5	1,382.0	1,392.0	1,441.3	1,460.7	1,468.2
Natural Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.2	3.9
Biomass-Wood*	55.6	56.2	59.0	58.8	61.4	64.2	66.1	62.9	64.2
International Bunker Fuels*	32.2	32.7	30.0	27.2	26.7	27.5	27.9	29.9	31.3
Biomass-Ethanol*	1.6	1.2	1.5	1.7	1.8	2.0	1.4	1.8	2.0
Fossil Fuel Carbon in Products*	(69.4)	(69.0)	(70.7)	(73.5)	(78.4)	(79.2)	(80.7)	(84.3)	(85.6)
CH_4	**68.2**	**67.5**	**67.0**	**64.6**	**64.3**	**64.9**	**64.0**	**63.1**	**61.3**
Natural Gas Systems	33.0	33.4	33.9	34.6	34.3	34.0	34.6	34.1	33.6
Coal Mining	24.0	22.8	22.0	19.2	19.4	20.3	18.9	18.8	17.8
Petroleum Systems	7.4	7.5	7.2	6.9	6.7	6.7	6.5	6.5	6.3
Stationary Combustion	2.3	2.4	2.4	2.4	2.4	2.5	2.6	2.3	2.3
Mobile Combustion	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.3
International Bunker Fuels*	+	+	+	+	+	+	+	+	+
N_2O	**17.6**	**18.3**	**19.5**	**20.4**	**21.1**	**21.4**	**21.7**	**21.5**	**21.5**
Mobile Combustion	13.8	14.6	15.7	16.5	17.1	17.4	17.5	17.3	17.2
Stationary Combustion	3.8	3.8	3.9	3.9	4.0	4.0	4.2	4.2	4.3
International Bunker Fuels*	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3
Total	**1,408.4**	**1,394.5**	**1,419.4**	**1,450.2**	**1,471.1**	**1,483.0**	**1,531.5**	**1,549.5**	**1,554.8**

\+ Does not exceed 0.05 MMTCE
* These values are presented for informational purposes only and are not included or are already accounted for in totals.
Note: Totals may not sum due to independent rounding.

Table 2-2: Emissions from Energy (Tg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**4,849.6**	**4,798.2**	**4,887.1**	**5,005.8**	**5,081.0**	**5,121.0**	**5,301.4**	**5,371.4**	**5,397.7**
Fossil Fuel Combustion	4,840.5	4,787.9	4,876.9	4,992.1	5,067.2	5,103.8	5,284.9	5,355.9	5,383.5
Natural Gas Flaring	9.1	10.3	10.2	13.7	13.8	17.2	16.5	15.5	14.2
Biomass-Wood*	203.8	205.9	216.5	215.4	225.3	235.2	162.5	230.5	235.6
International Bunker Fuels*	118.0	120.0	110.0	99.9	98.0	101.0	102.2	109.8	114.7
Biomass-Ethanol*	5.7	4.5	5.5	6.1	6.7	7.2	5.1	6.7	7.3
Fossil Fuel Carbon in Products*	(254.5)	(253.2)	(259.1)	(269.4)	(287.4)	(290.6)	(295.9)	(309.0)	(313.8)
CH_4	**11.9**	**11.8**	**11.7**	**11.3**	**11.2**	**11.3**	**11.2**	**11.0**	**10.7**
Natural Gas Systems	5.8	5.8	5.9	6.0	6.0	5.9	6.0	6.0	5.9
Coal Mining	4.2	4.0	3.8	3.4	3.4	3.6	3.3	3.3	3.1
Stationary Combustion	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Petroleum Systems	1.3	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1
Mobile Combustion	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2
International Bunker Fuels*	+	+	+	+	+	+	+	+	+
N_2O	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**
Mobile Combustion	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Stationary Combustion	+	+	+	+	+	+	+	+	+
International Bunker Fuels*	+	+	+	+	+	+	+	+	+

\+ Does not exceed 0.05 Tg
* These values are presented for informational purposes only and are not included or are already accounted for in totals.
Note: Totals may not sum due to independent rounding.

percent, or at an average annual rate of 3.1 percent. This robust economic activity increased the demand for fossil fuels, with an associated increase in greenhouse gas emissions. Table 2-1 summarizes emissions for the Energy chapter in units of million metric tons of carbon equivalents (MMTCE), while unweighted gas emissions in Teragrams (Tg) are provided in Table 2-2. Overall, emissions due to energy-related activities were 1,554.8 MMTCE in 1998, an increase of 10 percent since 1990.

Carbon Dioxide Emissions from Fossil Fuel Combustion

Carbon dioxide emissions from fossil fuel combustion grew by 0.5 percent from 1997 to 1998. Exceptionally mild winter conditions in 1998 moderated growth in CO_2 emissions from fossil fuel combustion below what would have been expected given the strength of the economy and continued low fuel prices. Overall, CO_2 emissions from fossil fuel combustion have increased by 11.2 percent since 1990.

Eighty-five percent of the energy consumed in the United States was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure 2-2 and Figure 2-3). Of the remaining portion, 8 percent was supplied by nuclear electric power and 7 percent by renewable energy (EIA 1999a).

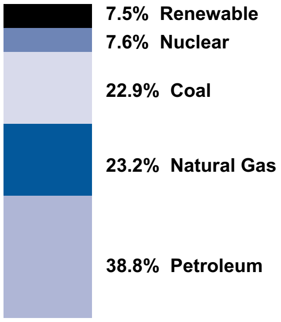
As fossil fuels are combusted, the carbon stored in the fuels is emitted as CO_2 and smaller amounts of other gases, including methane (CH_4), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs). These other gases are emitted as a by-product of incomplete fuel combustion.[1]

The amount of carbon in fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about 55 percent.[2] Petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent of total energy consumption over the period of 1990 through 1998. Natural gas and coal followed in order of importance, accounting for an average of 24 and 22 percent of total consumption, respectively. Most petroleum was consumed in the transportation end-use sector, while the vast majority of coal was used by electric utilities, with natural gas consumed largely in the industrial and residential end-use sectors (see Figure 2-4) (EIA 1999a).

Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.3 percent from

Figure 2-2

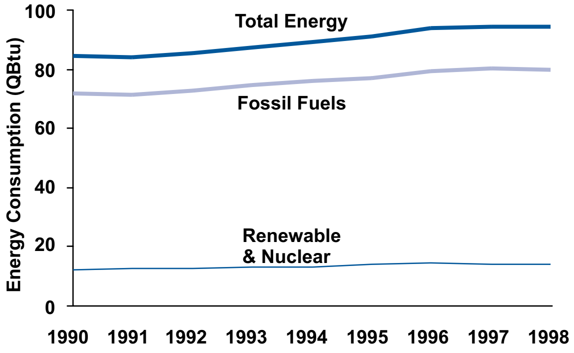
1998 U.S. Energy Consumption by Energy Source



Source: DOE/EIA-0384(99), Annual Energy Review 1998, Table 1.3, July 1999

Figure 2-3

U.S. Energy Consumption (Quadrillion Btu)



Source: DOE/EIA-0384(99), Annual Energy Review 1998, Table 1.3, July 1999

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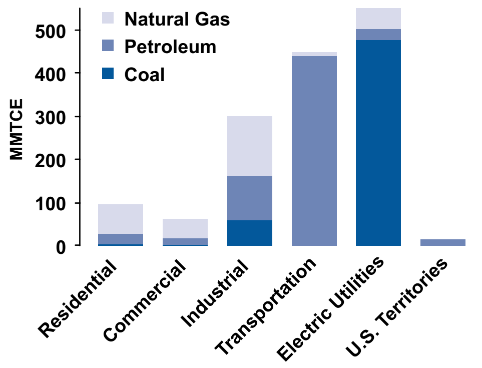
[1] See the sections entitled Stationary Combustion and Mobile Combustion for information on non-CO_2 gas emissions from fossil fuel combustion.

[2] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States.

1990 to 1998. The major factor behind this trend was a robust domestic economy, combined with relatively low energy prices (see Figure 2-5). For example, petroleum prices reached historic lows in 1998, with prices in many cases less than those seen in the 1970s before the oil crisis. After 1990, when CO_2 emissions from fossil fuel combustion were 1,320.1 MMTCE (4,840.5 Tg), there was a slight decline of emissions in 1991 due to a national economic downturn, followed by an increase to 1,468.2 MMTCE (5,383.5 Tg) in 1998 (see Figure 2-5, Table 2-3, and Table 2-4).

Figure 2-4

1998 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Note: Utilities also include emissions of 0.04 MMTCE from geothermal based eletricity generation

Since 1990, overall fossil fuel consumption increased significantly. Higher coal consumption during the period accounted for about 36 percent of the change in total CO_2 emissions from fossil fuel combustion, petroleum accounted for 42 percent, and natural gas for 21 percent.

In regard to annual changes from 1997 to 1998, absolute emissions from petroleum and coal increased by 11.5 and 5.1 MMTCE, respectively. Increased demand for transportation fuels and by electric utilities were the primary causes of the growth in emissions from petroleum combustion, while record electricity demand drove most of the increase in emissions from coal combustion. Emissions from natural gas combustion, however, decreased

Table 2-3: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMTCE)

Fuel/Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Coal	**480.9**	**475.2**	**477.5**	**493.9**	**495.2**	**498.1**	**520.5**	**534.5**	**539.6**
Residential	1.6	1.4	1.5	1.5	1.4	1.4	1.4	1.5	1.5
Commercial	2.4	2.2	2.2	2.2	2.1	2.1	2.1	2.2	2.2
Industrial	67.7	64.1	61.8	61.4	61.9	61.4	59.2	58.7	58.4
Transportation	+	+	+	+	+	+	+	+	+
Electric Utilities	409.0	407.2	411.8	428.7	429.5	433.0	457.5	471.8	477.3
U.S. Territories	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Natural Gas	**272.8**	**277.7**	**286.0**	**296.4**	**301.4**	**313.6**	**319.2**	**318.8**	**309.7**
Residential	65.1	67.5	69.4	73.4	71.7	71.7	77.5	73.7	66.3
Commercial	38.8	40.4	41.5	43.1	42.9	44.8	46.7	47.6	44.9
Industrial	117.9	119.7	125.6	131.1	132.6	139.5	144.2	142.8	139.9
Transportation	9.8	8.9	8.8	9.3	10.2	10.4	10.6	11.2	10.8
Electric Utilities	41.2	41.1	40.7	39.5	44.0	47.2	40.3	43.6	47.8
U.S. Territories	-	-	-	-	-	-	-	-	-
Petroleum	**566.4**	**552.9**	**566.5**	**571.1**	**585.4**	**580.3**	**601.7**	**607.3**	**618.9**
Residential	23.9	24.4	24.8	26.2	25.3	25.7	27.2	27.0	27.0
Commercial	18.0	17.1	16.1	14.9	14.9	15.0	14.6	13.8	13.8
Industrial	100.0	94.2	104.2	98.0	102.0	97.5	103.3	105.8	101.8
Transportation	389.1	381.9	391.6	399.2	411.5	416.7	430.5	431.6	438.8
Electric Utilities	26.4	24.9	20.2	22.3	20.5	13.9	15.3	17.5	24.8
U.S. Territories	9.0	10.5	9.6	10.5	11.2	11.5	10.8	11.7	12.8
Geothermal*	**0.1**	**0.1**	**0.1**	**0.1**	**+**	**+**	**+**	**+**	**+**
Total	**1,320.1**	**1,305.8**	**1,330.1**	**1,361.5**	**1,382.0**	**1,392.0**	**1,441.3**	**1,460.7**	**1,468.2**

- Not applicable

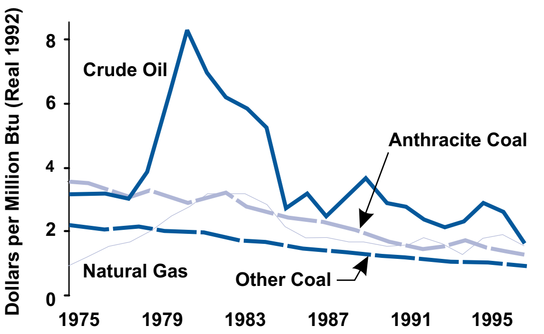
+ Does not exceed 0.05 MMTCE

* Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes.

Note: Totals may not sum due to independent rounding.

Figure 2-5

Fossil Fuel Production Prices



Source: DOE/EIA-0384(97), Annual Energy Review 1999, Table 3.1, July 1999

by 9.1 MMTCE (2.9 percent), again due in large part to the mild winter conditions and lower heating demands.

An analysis was performed by the EIA (1999c) to examine the effects of weather conditions on U.S. fuel consumption patterns. The analysis—using the EIA's Short-Term Forecasting System—found that if normal weather conditions had existed in 1998, overall CO_2 emissions from fossil fuel combustion would have increased by about 1.2 percent above weather-adjusted emissions in 1997, instead of the actual 0.5 percent increase.[3] See also Box 2-1 and Table 2-11 for additional discussion on overall emission trends and Figure 2-9 for data on heating degree days.[4]

Table 2-4: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (Tg)

Fuel/Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Coal	**1,763.3**	**1,742.3**	**1,750.9**	**1,811.1**	**1,815.7**	**1,826.2**	**1,908.3**	**1,959.9**	**1,978.7**
Residential	5.8	5.3	5.4	5.3	5.2	5.1	5.2	5.5	5.4
Commercial	8.7	8.0	8.1	8.1	7.8	7.6	7.8	8.2	8.1
Industrial	248.4	235.0	226.6	225.1	227.1	225.0	217.0	215.3	214.0
Transportation	+	+	+	+	+	+	+	+	+
Electric Utilities	1,499.7	1,493.2	1,510.0	1,571.7	1,574.7	1,587.5	1,677.4	1,730.0	1,750.2
U.S. Territories	0.6	0.7	0.8	0.9	0.9	0.9	0.9	1.0	1.0
Natural Gas	**1,000.3**	**1,018.1**	**1,048.6**	**1,086.7**	**1,105.0**	**1,149.7**	**1,170.4**	**1,168.9**	**1,135.4**
Residential	238.5	247.3	254.5	269.1	262.9	263.0	284.2	270.2	243.1
Commercial	142.4	148.2	152.3	158.2	157.2	164.3	171.2	174.5	164.5
Industrial	432.2	439.0	460.4	480.6	486.3	511.4	528.6	523.6	512.9
Transportation	36.0	32.8	32.1	33.9	37.2	38.1	38.7	41.0	39.6
Electric Utilities	151.1	150.6	149.3	144.9	161.4	173.0	147.7	159.7	175.3
U.S. Territories	-	-	-	-	-	-	-	-	-
Petroleum	**2,076.7**	**2,027.4**	**2,077.2**	**2,094.1**	**2,146.4**	**2,127.8**	**2,206.1**	**2,226.9**	**2,269.2**
Residential	87.7	89.4	90.9	96.1	92.8	94.4	99.7	98.9	99.1
Commercial	66.1	62.6	59.1	54.7	54.7	54.9	53.6	50.8	50.5
Industrial	366.5	345.5	382.1	359.5	373.8	357.4	378.9	387.8	373.2
Transportation	1,426.5	1,400.2	1,436.0	1,463.7	1,508.9	1,527.8	1,578.4	1,582.4	1,608.9
Electric Utilities	96.8	91.2	73.9	81.8	75.0	51.0	56.0	64.1	90.8
U.S. Territories	33.1	38.6	35.2	38.3	41.1	42.3	39.5	42.9	46.9
Geothermal*	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.1**	**+**	**0.1**	**0.1**
Total	**4,840.5**	**4,787.9**	**4,876.9**	**4,992.1**	**5,067.2**	**5,103.8**	**5,284.9**	**5,355.9**	**5,383.5**

- Not applicable

+ Does not exceed 0.05 Tg

* Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes.

Note: Totals may not sum due to independent rounding.

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[3] The 1.2 percent growth rate in EIA's weather adjusted model is actually the average annual growth rate between 1990 and 1998. The EIA goes on to state that given the high rate of economic growth in 1998, the increase in weather adjusted emissions between 1997 and 1998 would likely have been even greater.

[4] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F, while cooling degree days are deviations of the mean daily temperature above 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990.

For the purpose of international reporting the IPCC (IPCC/UNEP/OECD/IEA 1997) requires that particular adjustments be made to national fuel consumption statistics. Certain fossil fuel-based products are used for manufacturing plastics, asphalt, or lubricants. A portion of the carbon consumed for these non-energy products can be sequestered for long periods of time. To account for the fact that the carbon in these fuels ends up in products instead of being combusted (i.e., oxidized and released into the atmosphere), the fraction of fossil fuel-based carbon in manufactured products is subtracted from emission estimates. The IPCC (1997) also requires that CO_2 emissions from the consumption of fossil fuels for aviation and marine international transport activities (i.e., international bunker fuels) be reported separately, and not included in national emission totals. Both estimates of carbon in products and international bunker fuel emissions for the United States are provided in Table 2-5 and Table 2-6.

End-Use Sector Consumption

When analyzing CO_2 emissions from fossil fuel combustion, four end-use sectors were defined: industrial, transportation, residential, and commercial. Electric utilities also emit CO_2; however, these emissions occur as they combust fossil fuels to provide electricity to one of the four end-use sectors. For the discussion below, electric utility emissions have been distributed to each end-use sector based upon their share of national electricity consumption. This method of distributing emissions assumes that each sector consumes electricity from an equally carbon-intensive electricity source. In reality, sources of electricity vary widely in carbon intensity. By giving equal carbon-intensity weight to each sector's electricity consumption, for example, emissions attributed to the industrial end-use sector may be overestimated, while emissions attributed to the residential end-use sector may be underestimated. After the end-use sectors are discussed, emissions from electric utilities are addressed separately. Emissions from U.S. territories

Table 2-5: Fossil Fuel Carbon in Products and CO_2 Emissions from International Bunker Fuel Combustion (MMTCE)

Category/Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Fossil Fuel Carbon in Products	**69.4**	**69.0**	**70.7**	**73.5**	**78.4**	**79.2**	**80.7**	**84.3**	**85.6**
Industrial	67.5	67.2	68.9	71.6	76.5	77.4	78.7	82.2	83.3
Transportation	1.8	1.6	1.6	1.7	1.7	1.7	1.6	1.7	1.8
Territories	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.4	0.4
International Bunker Fuels*	**32.2**	**32.7**	**30.0**	**27.2**	**26.7**	**27.5**	**27.9**	**29.9**	**31.3**
Aviation*	12.7	12.7	12.9	13.0	13.2	13.9	14.2	15.2	15.5
Marine*	19.4	20.0	17.1	14.3	13.6	13.6	13.7	14.7	15.8

* See International Bunker Fuels for additional detail.
Note: Totals may not sum due to independent rounding.

Table 2-6: Fossil Fuel Carbon in Products and CO_2 Emissions from International Bunker Fuel Combustion (Tg CO_2)

Category/Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Fossil Fuel Carbon in Products	**254.5**	**253.2**	**259.1**	**269.4**	**287.4**	**290.6**	**295.9**	**309.0**	**313.8**
Industrial	247.3	246.4	252.6	262.6	280.4	283.6	288.6	301.3	305.5
Transportation	6.5	5.8	6.0	6.1	6.3	6.2	6.0	6.4	6.7
Territories	0.7	0.9	0.5	0.7	0.6	0.7	1.2	1.4	1.6
International Bunker Fuels*	**118.0**	**120.0**	**110.0**	**99.9**	**98.0**	**101.0**	**102.2**	**109.8**	**114.7**
Aviation*	46.7	46.7	47.1	47.6	48.3	51.1	52.1	55.9	56.9
Marine*	71.2	73.3	62.8	52.3	49.7	49.9	50.1	53.9	57.8

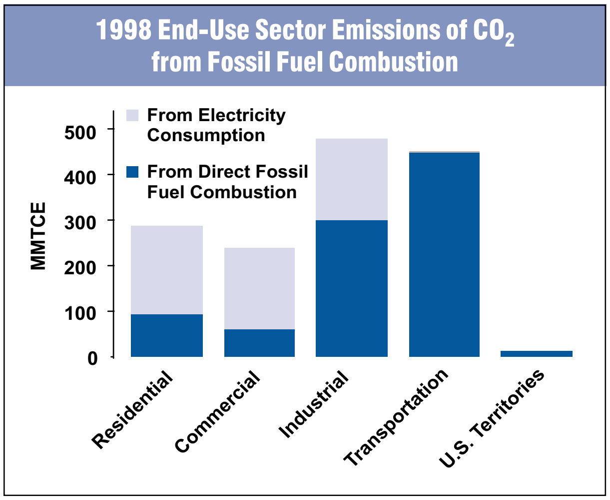
* See International Bunker Fuels for additional detail.
Note: Totals may not sum due to independent rounding.

Table 2-7: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMTCE)*

End-Use Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Industrial	**451.7**	**440.3**	**458.0**	**458.0**	**466.2**	**464.4**	**477.3**	**482.5**	**478.9**
Combustion	285.6	278.1	291.6	290.5	296.5	298.3	306.7	307.3	300.0
Electricity	166.2	162.2	166.4	167.5	169.7	166.0	170.6	175.3	178.9
Transportation	**399.6**	**391.5**	**401.1**	**409.1**	**422.3**	**427.7**	**441.7**	**443.4**	**450.3**
Combustion	398.9	390.8	400.4	408.5	421.7	427.1	441.1	442.7	449.6
Electricity	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Residential	**252.9**	**257.0**	**255.8**	**271.6**	**268.2**	**269.8**	**285.4**	**284.7**	**286.8**
Combustion	90.6	93.3	95.7	101.0	98.4	98.8	106.1	102.2	94.8
Electricity	162.4	163.7	160.1	170.5	169.8	170.9	179.3	182.6	192.0
Commercial	**206.7**	**206.3**	**205.4**	**212.0**	**213.8**	**218.3**	**225.9**	**238.0**	**239.3**
Combustion	59.2	59.7	59.9	60.2	59.9	61.9	63.4	63.7	60.9
Electricity	147.4	146.7	145.5	151.8	153.9	156.4	162.5	174.4	178.4
U.S. Territories	**9.2**	**10.7**	**9.8**	**10.7**	**11.5**	**11.8**	**11.0**	**12.0**	**13.0**
Total	**1,320.1**	**1,305.8**	**1,330.1**	**1,361.5**	**1,382.0**	**1,392.0**	**1,441.3**	**1,460.7**	**1,468.2**

* Emissions from fossil fuel combustion by electric utilities are allocated based on electricity consumption by each end-use sector.
Note: Totals may not sum due to independent rounding.

Figure 2-6



1998 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

are also calculated separately due to a lack of end-use-specific consumption data. Table 2-7 and Figure 2-6 summarize CO_2 emissions from direct fossil fuel combustion and pro-rated emissions from electricity consumption by end-use sector.

The overall demand for energy in the United States and other countries fluctuates in response to general economic conditions, energy prices, and weather. For example, a year with strong economic growth, low energy prices, and severe summer and winter weather conditions would be expected to have proportionally greater emissions from fossil fuel combustion than a year with poor economic performance, high energy prices, and mild average temperatures. Except for 1991, economic growth in the United States during the 1990s has fluctuated but overall been robust, and energy prices have been low and declining. Average U.S. temperatures, however have fluctuated more significantly, with hotter summer temperatures in 1998 stimulating electricity demand and warmer winter temperatures reducing demand for heating fuels.

Longer-term changes in energy consumption patterns are a function of variables that affect the scale of consumption (e.g., population, number of cars, and size of houses) and the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs) and consumer behavior (e.g., bicycling or tele-commuting to work instead of driving).

Carbon dioxide emissions, however, are also a function of the type fuel combusted and its carbon intensity. Producing heat or electricity using natural gas or wind energy instead of coal, for example, can reduce or even eliminate the CO_2 emissions associated with energy consumption (see Box 2-1).

Industrial End-Use Sector

The industrial end-use sector accounted for approximately one-third of CO_2 emissions from fossil fuel combustion. On average, nearly 63 percent of these emissions resulted from the direct consumption of fossil fuels in order to meet industrial demand for steam and process heat. The remaining 37 percent resulted from their consumption of electricity for uses such as motors, electric furnaces, ovens, and lighting.

The industrial end-use sector includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy consumption is manufacturing, which was estimated in 1994 to have accounted for 80 percent of industrial energy consumption (EIA 1997). Therefore, in general emissions from the industrial end-use are fairly correlated with economic growth, however, certain activities within the sector, such as heating of industrial buildings and agriculture, are also affected by weather conditions.

According to current EIA sectoral definitions, the industrial sector also includes emissions from nonutility generators (e.g., independent power producers) who produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market. The number and quantity of electricity generated by nonutilities has increased significantly as many states have begun deregulating their electricity markets. In future inventories, these nonutility generators will be removed from the industrial sector and incorporated into a single sector with electric utilities.

Although the largest share of emissions was attributed to the industrial end-use sector, from 1990 to 1998, its emissions grew the least in percentage terms (6 percent). From 1997 to 1998, emissions actually declined slightly (1 percent), likely due in part to lower output by some energy intensive industries—such as primary metals—and weather-related changes in agricultural activities.

The industry was also the largest user of fossil fuels for non-energy applications. Fossil fuels can be used for producing products such as fertilizers, plastics, asphalt, or lubricants that can sequester or store carbon for long periods of time. Asphalt used in road construction, for example, stores carbon essentially indefinitely. Similarly, fossil fuels used in the manufacture of materials like plastics can also store carbon, if the material is not burned. The amount of carbon contained in industrial products made from fossil fuels rose 24 percent between 1990 and 1998, to 85.6 MMTCE (313.8 Tg CO_2).

Transportation End-Use Sector

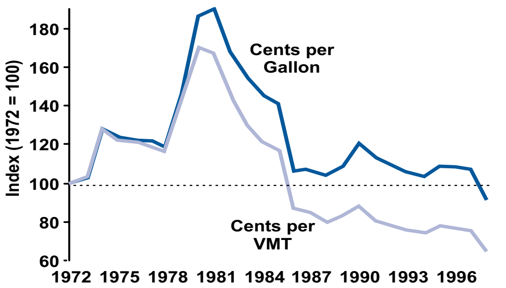
Transportation was second to the industrial end-use sector in terms of U.S. CO_2 emissions from fossil fuel combustion, accounting for slightly over 30 percent—excluding international bunker fuels. Almost all of the energy consumed in this end-use sector came from petroleum-based products, with nearly two-thirds due to gasoline consumption in automobiles and other highway vehicles. Other uses, including diesel fuel for the trucking industry and jet fuel for aircraft, accounted for the remainder.

Following the overall trend in U.S. energy consumption, fossil fuel combustion for transportation grew steadily after declining in 1991, resulting in an increase in CO_2 emissions of 33 percent from 1990 to 454.9 MMTCE (1,668.0 Tg) in 1998. This increase was primarily the result of greater motor gasoline and jet fuel consumption. It was slightly offset by decreases in the consumption of residual fuel.

Overall, motor vehicle fuel efficiency stabilized in the 1990s after increasing steadily since 1977 (EIA 1999a). This trend was due, in part, to a decline in gasoline prices and new motor vehicle sales being increasingly dominated by less fuel-efficient light-duty trucks and sport-utility vehicles (see Figure 2-7 and Figure 2-8). Moreover, declining petroleum prices during the 1990s, combined with a strong economy and a growing population, were largely responsible for an overall increase in vehicle miles traveled (EIA 1999a).

Figure 2-7

Motor Gasoline Retail Prices (Real)



Source for gasoline prices: DOE/EIA-0384(97), Annual Energy Review 1997, July, 1998, Table 5.22
Source for motor vehicle fuel efficiency: DOT/FHWA, Highway Statistics Summary to 1995, Highway Statistic 1996, 1997, 1998.

Table 2-8 provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. Fifty-eight percent of the emissions from this end-use sector were the result of the combustion of motor gasoline in passenger cars and light-duty trucks. Diesel highway vehicles and jet aircraft were also significant contributors, each accounting for 14 percent of CO_2 emissions from the transportation end-use sector.

Residential and Commercial End-Use Sectors

From 1990 to 1998, the residential and commercial end-use sectors, on average, accounted for 20 and 16 percent, respectively, of CO_2 emissions from fossil fuel combustion. Both end-use sectors were heavily reliant on electricity for meeting energy needs, with about two-thirds of their emissions attributable to electricity consumption for lighting, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Coal consumption was a minor component of energy use in both the residential and commercial end-use sectors.

Unlike in other major end-use sectors, emissions from residences and commercial buildings did not decline during the economic downturn in 1991, but instead decreased in 1994, then grew steadily through 1998. This difference in overall trends compared to other end-use sectors is because energy consumption in residences and commercial buildings is affected proportionately more by the weather than by prevailing economic conditions. Both end-use sectors are also affected by population and regional migration trends.

In 1998, winter conditions in the United States were extremely warm, with heating degree days 12 percent below normal (see Figure 2-9). Due primarily to these warm winter conditions, emissions from natural gas consumption in residences and commercial establishments declined by an impressive 10 and 6 percent, respectively.

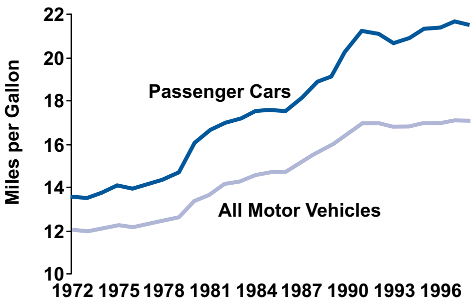
In 1998, electricity consumption in the residential and commercial end-use sectors increased by 4.5 and 1.7 percent, respectively. These increases were partly the result of air conditioning related demand and the hotter than normal summer in 1998, with cooling degree days 12 percent above normal (see Figure 2-10). U.S. temperatures during June, July, and August of 1998 were on average 10 percent higher than normal levels.[6] In the month of June, alone, residential customers increased their consumption of electricity by 17 percent above that for the same period the previous year (EIA 1999b).

Electric Utilities

The United States relied on electricity to meet a significant portion of its energy requirements. Electric-

Figure 2-8

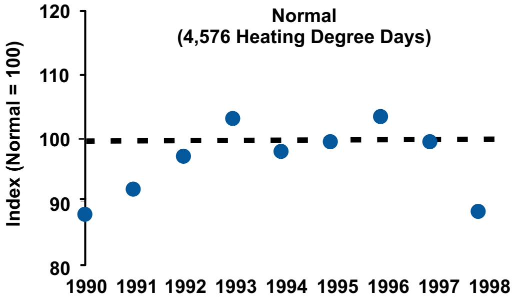
Motor Vehicle Fuel Efficiency



Source: DOT/FHWA, Highway Statistics Summary to 1995, Highway Statistics 1996, Highway Statistics 1997, 1998.

Figure 2-9

Heating Degree Days[5]



Note: Excludes Alaska and Hawaii

Source: DOE/EIA-0384(97), Annual Energy Review 1998, July, 1999, Table 1.7 and 1.8.

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[5] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990.

[6] Measured in terms of cooling degree days. Normals defined by the average between 1961 and 1990.

Table 2-8: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMTCE)

Fuel/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Motor Gasoline	**260.6**	**259.2**	**263.1**	**269.0**	**273.3**	**278.9**	**284.1**	**286.5**	**294.6**
Passenger Cars	167.1	165.8	169.8	171.2	170.2	172.9	176.4	177.9	182.9
Light-Duty Trucks	74.8	74.6	74.5	77.7	84.1	85.7	87.4	88.1	90.6
Other Trucks	11.3	11.2	11.2	11.7	10.4	10.9	11.1	11.0	11.4
Motorcycles	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
Buses	0.6	0.6	0.6	0.7	0.9	0.8	0.6	0.6	0.6
Construction Equipment	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7
Agricultural Machinery	1.2	1.2	1.2	2.0	2.1	2.2	2.1	2.2	2.3
Boats (Recreational)	4.6	4.7	4.7	4.6	4.5	5.3	5.4	5.5	5.6
Distillate Fuel Oil (Diesel)	**75.7**	**72.6**	**75.3**	**77.3**	**82.5**	**83.8**	**89.8**	**93.5**	**94.0**
Passenger Cars	1.9	1.9	2.0	2.0	2.0	2.0	2.1	2.2	2.1
Light-Duty Trucks	2.4	2.4	2.4	2.6	2.8	3.0	3.6	3.9	3.9
Other Trucks	44.8	42.9	44.5	47.2	51.4	52.4	56.5	58.9	58.8
Buses	2.1	2.2	2.2	2.3	2.3	2.7	2.4	2.5	2.5
Construction Equipment	2.9	2.8	2.9	2.9	2.9	2.8	3.0	3.0	3.0
Agricultural Machinery	6.3	6.2	6.3	6.3	6.3	6.2	6.5	6.7	6.7
Boats (Freight)	4.9	4.8	5.0	4.6	4.5	4.3	5.0	5.0	5.0
Locomotives	7.2	6.6	7.2	6.5	7.8	7.9	8.6	8.8	8.8
Marine Bunkers	3.1	2.9	2.9	2.9	2.4	2.5	2.2	2.5	3.1
Jet Fuel	**60.1**	**58.1**	**57.6**	**58.1**	**60.4**	**60.0**	**62.7**	**63.3**	**64.2**
General Aviation	1.7	1.5	1.3	1.1	1.2	1.4	1.6	1.7	1.7
Commercial Air Carriers	32.2	29.8	30.6	31.3	32.0	33.1	34.1	35.3	35.8
Military Vehicles	9.8	9.7	7.5	7.2	6.2	5.8	5.4	4.8	5.0
Aviation Bunkers	12.7	12.7	12.9	13.0	13.2	13.9	14.2	15.2	15.5
Other*	3.6	4.3	5.3	5.5	7.8	5.6	7.4	6.3	6.2
Aviation Gasoline	**0.8**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
General Aviation	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7
Residual Fuel Oil	**21.9**	**22.0**	**23.0**	**19.4**	**19.1**	**18.5**	**19.2**	**15.5**	**14.5**
Boats (Freight)	5.6	4.9	8.8	8.1	7.9	7.4	7.7	3.2	1.9
Marine Bunkers	16.4	17.1	14.3	11.4	11.2	11.1	11.4	12.2	12.7
Natural Gas	**9.8**	**8.9**	**8.8**	**9.3**	**10.2**	**10.4**	**10.6**	**11.2**	**10.8**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Buses	+	+	+	+	+	+	+	+	+
Pipeline	9.8	8.9	8.8	9.2	10.1	10.4	10.5	11.1	10.7
LPG	**0.4**	**0.3**	**0.3**	**0.3**	**0.5**	**0.5**	**0.3**	**0.2**	**0.2**
Light-Duty Trucks	0.1	0.1	0.1	0.1	0.2	0.3	0.1	0.1	0.1
Other Trucks	0.2	0.2	0.2	0.2	0.3	0.3	0.1	0.1	0.1
Buses	+	+	+	+	+	+	+	+	+
Electricity	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Buses	+	+	+	+	+	+	+	+	+
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Pipeline	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lubricants	1.8	1.6	1.6	1.6	1.7	1.7	1.6	1.7	1.8
Total (including bunkers)	**431.8**	**424.2**	**431.1**	**436.4**	**449.1**	**455.3**	**469.6**	**473.4**	**481.5**

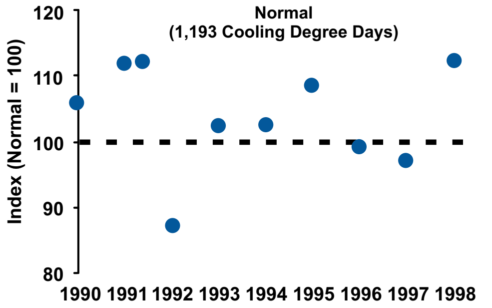
Note: Totals may not sum due to independent rounding. Estimates include emissions from the combustion of both aviation and marine international bunker fuels.

* Including but not limited to fuel blended with heating oils and fuel used for chartered aircraft flights.

\+ Does not exceed 0.05 MMTCE

Figure 2-10

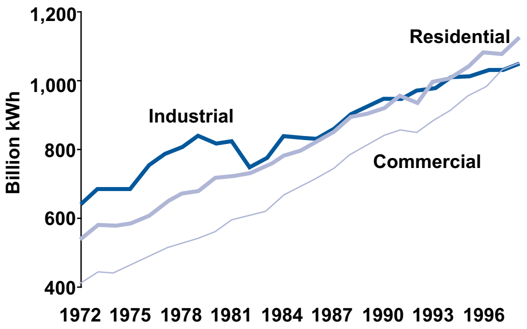
Cooling Degree Days



Note: Excludes Alaska and Hawaii
Source: DOE/EIA-0384(97), Annual Energy Review 1998, July, 1999, Table 1.7 and 1.8.

Figure 2-11

Electric Utility Retail Sales by End-Use Sector



Note: The transportation end-use sector consumes minor quantities of electricty.

ity was consumed primarily in the residential, commercial, and industrial end-use sectors for uses such as lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 2-11).

In 1998, retail sales by electric utilities increased in all end-use sectors due largely to robust economic growth and the year's summer weather conditions. The summer of 1998 for the United States was exceptionally warm, with cooling degree days 14 percent above normal (see Figure 2-10).[7] As a result, in part, of increased demand for electricity, especially for air conditioning, emissions from electric utilities rose by 3.2 percent from 1997 to 1998.

To generate the majority of this electricity, utilities combusted fossil fuels, especially coal. In 1998, electric utilities were the largest producers of CO_2 emissions from fossil fuel combustion, accounting for 37 percent. Electric utilities were responsible for such a large share of emissions partly because they rely on more carbon intensive coal for a majority of their primary energy. Some of the electricity consumed in the United States was generated using low or zero CO_2 emitting technologies such as hydroelectric or nuclear energy. In 1998, however, coal, natural gas, and petroleum were used to produce the majority—52, 15, and 4 percent, respectively—of the electricity generated by utilities in the United States (EIA 1999b).

Electric utilities were the dominant consumer of coal in the United States, accounting for 88 percent in 1998. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions. In fact, electric utilities consumed record amounts of coal (18,717 TBtu) in 1998. Overall, emissions from coal burned at electric utilities increased by 17 percent from 1990 to 1998. This increase in coal-related emissions from was alone responsible for 46 percent of the overall rise in CO_2 emissions from fossil fuel combustion.

In addition to this rise in consumption of coal, consumption of both natural gas and petroleum also rose in 1998 by 10 and 42 percent, respectively (EIA 1999f). This dramatic change in petroleum consumption was due mainly to a drop in petroleum prices (26 percent or the lowest price in 20 years) and the increased electricity demand which required the use of idle or underutilized petroleum units (EIA 1999b).

Demand for fossil fuels by electric utilities is also affected by the supply of electricity from other energy sources. In 1998, there was a significant decline in hydroelectric generation (8.5 percent) due mainly to reduced snowfall in the Northwest (EIA 1999b). This de-

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[7] Cooling degree days in 1998 were approximately 3 standard deviations above the normal value (i.e., average of 1961 to 1990).

Box 2-1: Sectoral Carbon Intensity Trends Related to Fossil Fuel and Overall Energy Consumption

Fossil fuels are the predominant source of energy in the United States, and carbon dioxide (CO_2) is emitted as a product from their complete combustion. Useful energy, however, can be generated from many other sources that do not emit CO_2 in the energy conversion process.[8] In the United States, useful energy is also produced from renewable (i.e., hydropower, biofuels, geothermal, solar, and wind) and nuclear sources.

Energy-related CO_2 emissions can be reduced by not only lowering total energy consumption (e.g., through conservation measures) but also by lowering the carbon intensity of the energy sources employed (e.g., fuel switching from coal to natural gas). The amount of carbon emitted—in the form of CO_2—from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that carbon that is oxidized. Fossil fuels vary in their average carbon content, ranging from about 13.7 MMTCE/EJ for natural gas to 26.4 MMTCE/EJ for coal and petroleum coke.[9] In general, the carbon intensity of fossil fuels is the highest for coal products, followed by petroleum and then natural gas. Other sources of energy, however, may be directly or indirectly carbon neutral (i.e., 0 MMTCE/EJ). Energy generated from nuclear and many renewable sources do not result in direct emissions of CO_2. Biofuels such as wood and ethanol are also considered to be carbon neutral, as the CO_2 emitted during combustion is assumed to be offset by the carbon sequestered in the growth of new biomass.[10] The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 2-9 provides a time series of the carbon intensity for each sector of the U.S. economy. The time series incorporates only the energy consumed from the direct combustion of fossil fuels in each sector. For example, the carbon intensity for the residential sector does not include the energy from or emissions related to the consumption of electricity for lighting or wood for heat. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest carbon intensity, which was related to the large percentage of energy derived from natural gas for heating. The carbon intensity of the commercial sector was greater than the residential sector for the period from 1990 to 1996, but then declined to an equivalent level as commercial businesses shifted away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher carbon intensities over this period. The carbon intensity of the transportation sector was closely related to the carbon content of petroleum products (e.g., motor gasoline and jet fuel), which were the primary sources of energy. Lastly, the electric utility sector had the highest carbon intensity due to its heavy reliance on coal for generating electricity.

Table 2-9: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMTCE/EJ)

Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Residential[a]	14.7	14.7	14.6	14.6	14.6	14.6	14.6	14.7	14.7
Commercial[a]	15.2	15.1	15.0	14.9	14.9	14.8	14.8	14.7	14.8
Industrial[a]	16.9	16.8	16.7	16.6	16.6	16.5	16.4	16.4	16.4
Transportation[a]	18.3	18.3	18.3	18.3	18.3	18.2	18.2	18.2	18.2
Electric Utilities[b]	22.4	22.4	22.4	22.5	22.4	22.4	22.6	22.6	22.5
All Sectors[c]	**18.7**	**18.7**	**18.6**	**18.7**	**18.6**	**18.6**	**18.6**	**18.6**	**18.7**

[a] Does not include electricity or renewable energy consumption.
[b] Does not include electricity produced using nuclear or renewable energy.
[c] Does not include nuclear or renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption. Exajoule (EJ) = 10^{18} joules = 0.9479 QBtu.

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[8] CO_2 emissions, however, may be generated from upstream activities (e.g., manufacture of the equipment).

[9] One exajoule (EJ) is equal to 10^{18} joules or 0.9478 QBtu.

[10] This statement assumes that there is no net loss of biomass-based carbon associated with the land use practices used to produce these biomass fuels.

In contrast to Table 2-9, Table 2-10 presents carbon intensity values that incorporate energy consumed from all sources (i.e., fossil fuels, renewables, and nuclear). In addition, the emissions related to the generation of electricity have been attributed to both electric utilities and the sector in which that electricity was eventually consumed.[11] This table, therefore, provides a more complete picture of the actual carbon intensity of each sector per unit of energy consumed. The transportation sector in Table 2-10 emerges as the most carbon intensive when all sources of energy are included, due to its almost complete reliance on petroleum products and relatively minor amount of biomass based fuels such as ethanol. The "other end-use sectors" (i.e. the residential, commercial, and industrial sectors) use significant quantities of biofuels such as wood, thereby lowering the overall carbon intensity. The carbon intensity of electric utilities differs greatly from the scenario in Table 2-9 where only the energy consumed from the direct combustion of fossil fuels was included. This difference is due almost entirely to the inclusion of electricity generation from nuclear and hydropower sources, which do not emit carbon dioxide.

Table 2-10: Carbon Intensity from Energy Consumption by Sector (MMTCE/EJ)

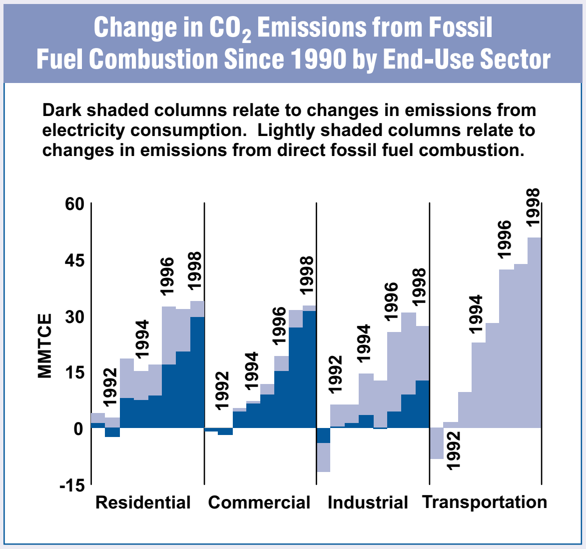
Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Transportation[a]	18.2	18.2	18.2	18.2	18.2	18.1	18.1	18.1	18.1
Other End-Use Sectors[a,b]	14.9	14.7	14.7	14.8	14.7	14.4	14.5	14.7	14.7
Electric Utilities[c]	15.3	15.0	15.2	15.3	15.2	14.8	14.9	15.4	15.4
All Sectors[d]	**15.8**	**15.6**	**15.7**	**15.7**	**15.7**	**15.5**	**15.5**	**15.7**	**15.7**

[a] Includes electricity (from fossil fuel, nuclear, and renewable sources) and direct renewable energy consumption.
[b] Other End-Use Sectors include the residential, commercial, and industrial sectors.
[c] Includes electricity generation from nuclear and renewable sources.
[d] Includes nuclear and renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption. Assumed that residential consumed all of the biofuel-based energy and 50 percent of the solar energy in the combined EIA residential/commercial sector category. Exajoule (EJ) = 10^{18} joules = 0.9479 QBtu.

By comparing the values in Table 2-9 and Table 2-10, a couple of observations can be made. The usage of renewable and nuclear energy sources has resulted in a significantly lower carbon intensity of the U.S. economy. However, over the nine year period of 1990 through 1998, the carbon intensity of U.S. fossil fuel consumption has been fairly constant, as the proportion of renewable and nuclear energy technologies has not changed significantly.

Figure 2-12 and Table 2-11 present the detailed CO_2 emission trends underlying the carbon intensity differences and changes described in Table 2-9. In Figure 2-12, changes over time in both overall end-use sector-related emissions and electricity-related emissions for each year since 1990 are highlighted. In Table 2-11 changes in emissions since 1990 are presented by sector and fuel type to provide more detail on these changes.

Figure 2-12



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[11] In other words, the emissions from the generation of electricity are intentionally double counted by attributing them both to utilities and the sector in which electricity consumption occurred.

Table 2-11: Change in CO_2 Emissions from Direct Fossil Fuel Combustion Since 1990 (MMTCE)

Sector/Fuel Type	1991	1992	1993	1994	1995	1996	1997	1998
Residential	**2.7**	**5.1**	**10.5**	**7.9**	**8.3**	**15.5**	**11.6**	**4.2**
Coal	(0.1)	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)
Natural Gas	2.4	4.4	8.3	6.6	6.7	12.4	8.6	1.2
Petroleum	0.5	0.9	2.3	1.4	1.8	3.3	3.1	3.1
Commercial	**0.4**	**0.6**	**1.0**	**0.7**	**2.6**	**4.2**	**4.4**	**1.6**
Coal	(0.2)	(0.2)	(0.2)	(0.3)	(0.3)	(0.3)	(0.1)	(0.2)
Natural Gas	1.6	2.7	4.3	4.0	6.0	7.9	8.7	6.0
Petroleum	(0.9)	(1.9)	(3.1)	(3.1)	(3.0)	(3.4)	(4.2)	(4.3)
Industrial	**(7.5)**	**6.0**	**4.9**	**10.9**	**12.7**	**21.1**	**21.7**	**14.5**
Coal	(3.6)	(5.9)	(6.3)	(5.8)	(6.4)	(8.6)	(9.0)	(9.4)
Natural Gas	1.9	7.7	13.2	14.7	21.6	26.3	24.9	22.0
Petroleum	(5.7)	4.2	(1.9)	2.0	(2.5)	3.4	5.8	1.8
Transportation	**(8.1)**	**1.5**	**9.6**	**22.8**	**28.2**	**42.1**	**43.9**	**50.7**
Coal	-	-	-	-	-	-	-	-
Natural Gas	(0.9)	(1.1)	(0.6)	0.3	0.6	0.7	1.4	1.0
Petroleum	(7.2)	2.6	10.1	22.5	27.3	41.4	42.5	49.7
Electric Utility	**(3.4)**	**(3.9)**	**13.9**	**17.3**	**17.4**	**36.4**	**56.2**	**73.3**
Coal	(1.8)	2.8	19.7	20.5	24.0	48.5	62.8	68.3
Natural Gas	(0.1)	(0.5)	(1.7)	2.8	6.0	(0.9)	2.4	6.6
Petroleum	(1.5)	(6.2)	(4.1)	(6.0)	(12.5)	(11.1)	(8.9)	(1.6)
U.S. Territories	**1.5**	**0.6**	**1.5**	**2.3**	**2.6**	**1.8**	**2.8**	**3.9**
Coal	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	-	-	-	-	-	-	-	-
Petroleum	1.5	0.6	1.4	2.2	2.5	1.8	2.7	3.8
All Sectors	**(14.3)**	**9.9**	**41.4**	**61.8**	**71.8**	**121.2**	**140.6**	**148.1**

+ Does not exceed 0.05 MMTCE
- Not applicable
Note: Totals may not sum due to independent rounding.

cline, however, offset by a slightly larger increase in electricity generation at nuclear power plants (7 percent) after seven generating units, that had previously been idle, were brought back into service (EIA 1999b).

It is important to note that the electric utility sector includes only regulated utilities. According to current EIA sectoral definitions, nonutility generators of electricity (e.g., independent power producers, qualifying cogenerators, and other small power producers) are included in the industrial sector. These nonutility generators produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market. The number and quantity of electricity generated by nonutilities has increased significantly as many states have begun deregulating their electricity markets.

A recent report by the U.S. Department of Energy and the EPA (DOE and EPA 1999) estimated emissions from the entire electric power industry, including regulated utilities and nonutilities. According to this report CO_2 emissions from nonutilities in 1998 were 56 MMTCE, bringing combined emissions from electricity generation up to 41 percent (605.5 MMTCE) of total U.S. CO_2 emissions from fossil fuel combustion, versus 37 percent from utilities alone. In other words, nonutilities were responsible for 10 percent of emissions from electricity generation. The growth in nonutility emissions from 1997 to 1998 was 9 percent. In future inventories, these nonutility generators will be removed from the industrial sector and incorporated into a single sector with electric utilities.

Methodology

The methodology used by the United States for estimating CO_2 emissions from fossil fuel combustion is conceptually similar to the approach recommended by the IPCC for countries that intend to develop detailed, sectoral-based emission estimates (IPCC/UNEP/OECD/IEA 1997). A detailed description of the U.S. methodology is presented in Annex A, and is characterized by the following steps:

1. Determine fuel consumption by fuel type and sector. By aggregating consumption data by sector (e.g., commercial, industrial, etc.), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil, etc.), estimates of total U.S. fossil fuel consumption for a particular year were made. The United States does not include territories in its national energy statistics; therefore, fuel consumption data for territories was collected separately. [12]

2. Determine the total carbon content of fuels consumed. Total carbon was estimated by multiplying the amount of fuel consumed by the amount of carbon in each fuel. This total carbon estimate defines the maximum amount of carbon that could potentially be released to the atmosphere if all of the carbon in each fuel were converted to CO_2. The carbon content coefficients used by the United States are presented in Annex A.

3. Subtract the amount of carbon stored in products. Non-energy uses of fossil fuels can result in storage of some or all of the carbon contained in the fuel for some period of time, depending on the end-use. For example, asphalt made from petroleum can sequester up to 100 percent of the carbon for extended periods of time, while other fossil fuel products, such as lubricants or plastics, lose or emit some carbon when they are used and/or burned as waste. Aggregate U.S. energy statistics include consumption of fossil fuels for non-energy uses; therefore, the portion of carbon that remains in products after they are manufactured was subtracted from potential carbon emission estimates. The amount of carbon remaining in products was based on the best available data on the end-uses and fossil fuel products. These non-energy uses occurred in the industrial and transportation sectors and U.S. territories.[13]

4. Adjust for carbon that does not oxidize during combustion. Because combustion processes are not 100 percent efficient, some of the carbon contained in fuels is not emitted to the atmosphere. Rather, it remains behind as soot and ash. The estimated amount of carbon not oxidized due to inefficiencies during the combustion process was assumed to be 1 percent for petroleum and coal and 0.5 percent for natural gas (see Annex A).

5. Subtract emissions from international bunker fuels. According to the IPCC guidelines (IPCC/UNEP/OECD/IEA 1997) emissions from international transport activities, or bunker fuels, should not be included in national totals. Because U.S. energy consumption statistics include these bunker fuels—distillate fuel oil, residual fuel oil, and jet fuel—as part of consumption by the transportation sector, emissions from international transport activities were calculated separately and subtracted from emission estimates for the transportation sector. The calculations for emissions from bunker fuels follow the same procedures used for emissions from consumption of all fossil fuels (i.e., estimation of consumption, determination of carbon content, and adjustment for the fraction of carbon not oxidized).

*6. Allocate transportation emissions by vehicle type. B*ecause the transportation end-use sector was the largest direct consumer of fossil fuels in the United States,[14] a more detailed accounting of carbon dioxide emissions is provided. For fuel types other than jet fuel, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Specific data by vehicle type were not available for 1998; therefore, the 1997 percentage allocations were applied to 1998 fuel consumption data in order to estimate emissions in 1998. Military vehicle jet fuel consumption was provided by the Defense Energy Support Center, under Department of Defense's (DoD) Defense Logistics Agency and the Office of the Undersecretary of Defense (Envi-

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[12] Fuel consumption by U.S. territories (i.e. American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed emissions of13 MMTCE in 1998.

[13] See Waste Combustion section of Waste chapter for discussion of emissions from the combustion of plastics in the municipal solid waste steam.

[14] Electric utilities are not considered a final end-use sector, because they consume energy solely to provide electricity to the other sectors.

ronmental Security). The difference between total U.S. jet fuel consumption (as reported by DOE/EIA) and civilian air carrier consumption for both domestic and international flights (as reported by DOT/BTS and BEA) plus military jet fuel consumption is reported as "other" under the jet fuel category in Table 2-8, and includes such fuel uses as blending with heating oils and fuel used for chartered aircraft flights.

Data Sources

Data on fuel consumption for the United States and its territories, carbon content of fuels, and percent of carbon sequestered in non-energy uses were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE). Fuel consumption data were obtained primarily from the *Monthly Energy Review* (EIA 1999f) and various EIA databases. Data on military jet fuel use was supplied by the Office of the Under Secretary of Defense (Environmental Security) and the Defense Energy Support Center (Defense Logistics Agency) of the U.S. Department of Defense (DoD). Estimates of international bunker fuel emissions are discussed in the section entitled International Bunker Fuels.

IPCC (IPCC/UNEP/OECD/IEA 1997) provided combustion efficiency rates for petroleum and natural gas. Bechtel (1993) provided the fraction oxidation values for coal. Vehicle type fuel consumption data for the allocation of transportation sector emissions were primarily taken from the Transportation Energy Databook prepared by the Center for Transportation Analysis at Oak Ridge National Laboratory (DOE 1993, 1994, 1995, 1996, 1997, 1998). All jet fuel and aviation gasoline was assumed to have been consumed in aircraft. Densities for each military jet fuel type were obtained from the Air Force (1998).

Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (1998a) and fossil fuel consumption data as discussed above and presented in Annex A.

For consistency of reporting, the IPCC has recommended that national inventories report energy data (and emissions from energy) using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA, and used in this inventory, are, instead, "bottom up" in nature. In other words, they are collected through surveys at the point of delivery or use and aggregated to determine national totals.

It is also important to note that EIA uses gross calorific values (GCV) (i.e., higher heating values) as its reporting standard for energy statistics. Fuel consumption activity data presented here have not been adjusted to correspond to international standard, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).

Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted, in principle is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and consumption of products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

There are uncertainties, however, concerning the consumption data sources, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., petroleum), the amount of carbon contained in the fuel per unit of useful energy can vary. Non-energy uses of the fuel can also create situations where the carbon is not emitted to the atmosphere (e.g., plastics, asphalt, etc.) or is emitted at a delayed rate. The proportions of fuels used in these non-energy production processes that result in the sequestration of carbon have been assumed. Additionally, inefficiencies in the combustion process, which can result in ash or soot remaining unoxidized for long periods, were also assumed. These factors all contribute to the uncertainty in the CO_2 estimates.

Other sources of uncertainty are fuel consumption by U.S. territories and bunker fuels consumed by the military. The United States does not collect as detailed energy statistics for its territories as for the fifty states and the District of Columbia. Therefore estimating both emissions and bunker fuel consumption by these territories is difficult.

For Table 2-8, uncertainties also exist as to the data used to allocate CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom up estimates of fuel consumption by vehicle type do not match top down estimates from EIA. Further research is planned to better allocate detailed transportation end-use sector emissions.

For the United States, however, these uncertainties impact on overall CO_2 emission estimates are believed to be relatively small. For the United States, CO_2 emission estimates from fossil fuel combustion are considered accurate within one or two percent. See, for example, Marland and Pippin (1990).

Stationary Combustion (excluding CO_2)

Stationary combustion encompasses all fuel combustion activities except those related to transportation (i.e., mobile combustion). Other than carbon dioxide (CO_2), which was addressed in the previous section, gases from stationary combustion include the greenhouse gases methane (CH_4) and nitrous oxide (N_2O) and the criteria pollutants nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[15] Emissions of these gases from stationary sources depend upon fuel characteristics, technology type, usage of pollution control equipment, and ambient environmental conditions. Emissions also vary with the size and vintage of the combustion technology as well as maintenance and operational practices.

Nitrous oxide and NO_x emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. Carbon monoxide emissions from stationary combustion are generally a function of the efficiency of combustion and the use of emission controls; they are highest when less oxygen is present in the air-fuel mixture than is necessary for complete combustion. These conditions are most likely to occur during start-up and shut-down and during fuel switching (e.g., the switching of coal grades at a coal-burning electric utility plant). Methane and NMVOC emissions from stationary combustion are primarily a function of the CH_4 content of the fuel, combustion efficiency, and post-combustion controls.

Emissions of CH_4 increased slightly from 1990 to 1996, but fell to just below the 1990 level in 1998 to 2.3 MMTCE (395 Gg). This decrease in emissions was primarily due to lower wood consumption in the residential sector. Nitrous oxide emissions rose 12 percent since 1990 to 4.3 MMTCE (50 Gg) in 1998. The largest source of N_2O emissions was coal combustion by electric utilities, which alone accounted for 54 percent of total N_2O emissions from stationary combustion in 1998. Overall, though, stationary combustion is a small source of CH_4 and N_2O in the United States.

In contrast, stationary combustion was a significant source of NO_x emissions, but a smaller source of CO and NMVOCs. In 1998, emissions of NO_x from stationary combustion represented 44 percent of national NO_x emissions, while CO and NMVOC emissions from stationary combustion contributed approximately 6 and 5 percent, respectively, to the national totals. From 1990 to 1998, emissions of NO_x were fairly constant, while emissions of CO and NMVOCs decreased by 10 and 15 percent, respectively.

The decrease in CO and NMVOC emissions from 1990 to 1998 can largely be attributed to decreased residential wood consumption, which is the most significant source of these pollutants from stationary combustion. Overall, NO_x emissions from energy varied due to fluctuations in emissions from electric utilities. Table 2-12 through Table 2-15 provide CH_4 and N_2O emission

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[15] Sulfur dioxide (SO_2) emissions from stationary combustion are addressed in Annex M.

Table 2-12: CH_4 Emissions from Stationary Combustion (MMTCE)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Electric Utilities	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	+	+	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+	+
Industrial	**0.8**	**0.8**	**0.8**	**0.8**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Coal	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Wood	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Commercial/Institutional	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	0.1	+	+	+	+	+	+	+	+
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood[*]	NA	NA	NA	NA	NA	NA	NA	NA	NA
Residential	**1.3**	**1.3**	**1.4**	**1.3**	**1.3**	**1.4**	**1.4**	**1.1**	**1.1**
Coal	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.9	1.0	1.1	1.0	0.9	1.0	1.1	0.8	0.8
Total	**2.3**	**2.4**	**2.4**	**2.4**	**2.4**	**2.5**	**2.6**	**2.3**	**2.3**

+ Does not exceed 0.05 MMTCE

NA (Not Available)

[*] Commercial/institutional emissions from the combustion of wood are included under the residential sector.

Note: Totals may not sum due to independent rounding.

Table 2-13: N_2O Emissions from Stationary Combustion (MMTCE)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Electric Utilities	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**	**2.1**	**2.2**	**2.3**	**2.3**
Coal	1.9	1.9	1.9	2.0	2.0	2.0	2.1	2.2	2.2
Fuel Oil	0.1	0.1	+	0.1	+	+	+	+	0.1
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+	+
Industrial	**1.4**	**1.4**	**1.5**	**1.5**	**1.5**	**1.5**	**1.6**	**1.6**	**1.6**
Coal	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel Oil	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.5	0.5
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8
Commercial/Institutional	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	+	+	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+	+
Wood[*]	NA	NA	NA	NA	NA	NA	NA	NA	NA
Residential	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**3.8**	**3.8**	**3.9**	**3.9**	**4.0**	**4.0**	**4.2**	**4.2**	**4.3**

+ Does not exceed 0.05 MMTCE

NA (Not Available)

[*] Commercial/institutional emissions from the combustion of wood are included under the residential sector.

Note: Totals may not sum due to independent rounding.

Table 2-14: CH_4 Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Electric Utilities	**23**	**23**	**22**	**23**	**23**	**23**	**23**	**24**	**26**
Coal	16	16	16	17	17	17	18	19	19
Fuel Oil	4	4	3	3	3	2	2	2	4
Natural Gas	3	3	3	3	3	3	3	3	3
Wood	1	1	1	1	1	+	1	1	1
Industrial	**140**	**138**	**143**	**145**	**151**	**155**	**159**	**159**	**160**
Coal	27	26	25	25	25	24	24	23	23
Fuel Oil	17	16	17	17	18	17	18	19	18
Natural Gas	40	41	43	45	45	48	49	49	48
Wood	55	55	58	59	63	65	68	68	70
Commercial/Institutional	**23**	**23**	**23**	**23**	**23**	**23**	**24**	**24**	**23**
Coal	1	1	1	1	1	1	1	1	1
Fuel Oil	9	9	8	8	8	8	7	7	7
Natural Gas	13	13	14	14	14	15	15	16	15
Wood*	NA	NA	NA	NA	NA	NA	NA	NA	NA
Residential	**218**	**227**	**237**	**224**	**219**	**236**	**240**	**191**	**187**
Coal	19	17	17	17	17	16	17	17	17
Fuel Oil	13	13	13	14	13	14	14	14	14
Natural Gas	21	22	23	24	24	24	26	24	22
Wood	166	175	184	169	166	183	183	135	133
Total	**404**	**410**	**425**	**415**	**416**	**437**	**446**	**399**	**395**

+ Does not exceed 0.5 Gg

NA (Not Available)

* Commercial/institutional emissions from the combustion of wood are included under the residential sector.

Note: Totals may not sum due to independent rounding.

Table 2-15: N_2O Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Electric Utilities	**24**	**24**	**24**	**25**	**25**	**25**	**26**	**27**	**27**
Coal	23	22	23	24	24	24	25	26	26
Fuel Oil	1	1	1	1	1	+	+	+	1
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+	+
Industrial	**17**	**17**	**17**	**17**	**18**	**18**	**19**	**19**	**19**
Coal	4	4	3	3	3	3	3	3	3
Fuel Oil	5	5	5	5	5	5	5	6	6
Natural Gas	1	1	1	1	1	1	1	1	1
Wood	7	7	8	8	8	9	9	9	9
Commercial/Institutional	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	1	1	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+	+
Wood*	NA	NA	NA	NA	NA	NA	NA	NA	NA
Residential	**3**	**4**	**4**	**4**	**4**	**4**	**4**	**3**	**3**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	1	1	1	1	1	1	1	1	1
Natural Gas	+	+	+	+	+	+	1	+	+
Wood	2	2	2	2	2	2	2	2	2
Total	**45**	**45**	**46**	**46**	**47**	**48**	**49**	**50**	**50**

+ Does not exceed 0.5 Gg

NA (Not Available)

* Commercial/institutional emissions from the combustion of wood are included under the residential sector.

Note: Totals may not sum due to independent rounding.

Table 2-16: NO_x, CO, and NMVOC Emissions from Stationary Combustion in 1998 (Gg)

Sector/Fuel Type	NO_x	CO	NMVOC
Electric Utilities	**5,535**	**377**	**48**
Coal	4,894	231	26
Fuel Oil	189	16	4
Natural Gas	310	78	8
Wood	NA	NA	NA
Internal Combustion	141	53	9
Industrial	**2,997**	**1,090**	**166**
Coal	613	91	5
Fuel Oil	209	52	6
Natural Gas	1,141	314	46
Wood	NA	NA	NA
Other Fuels[a]	115	314	40
Internal Combustion	918	319	69
Commercial/Institutional	**364**	**134**	**23**
Coal	33	12	1
Fuel Oil	85	17	3
Natural Gas	219	55	12
Wood	NA	NA	NA
Other Fuels[a]	27	50	8
Residential	**823**	**2,891**	**539**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	32	2,636	500
Other Fuels[c]	791	255	39
Total	**9,719**	**4,491**	**776**

NA (Not Available)

Note: Totals may not sum due to independent rounding. See Annex B for emissions in 1990 through 1998.

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1999).

[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1999).

[c] "Other Fuels" include LPG, waste oil, coke oven gas, and coke (EPA 1999).

estimates from stationary sources by sector and fuel type. Estimates of NO_x, CO, and NMVOC emissions in 1998 are given in Table 2-16.[16]

Methodology

Methane and nitrous oxide emissions were estimated by multiplying emission factors (by sector and fuel type) by fossil fuel and wood consumption data. National coal, natural gas, fuel oil, and wood consumption data were grouped into four sectors—industrial, commercial/institutional, residential, and electric utilities.

For NO_x, CO, and NMVOCs, the major source categories included in this section are those used in EPA (1999): coal, fuel oil, natural gas, wood, other fuels (including LPG, coke, coke oven gas, and others), and stationary internal combustion. The EPA estimates emissions of NO_x, CO, and NMVOCs by sector and fuel source using a "bottom-up" estimating procedure. In other words, emissions were calculated either for individual sources (e.g., industrial boilers) or for multiple sources combined, using basic activity data as indicators of emissions. Depending on the source category, these basic activity data may include fuel consumption, fuel deliveries, tons of refuse burned, raw material processed, etc.

The EPA derived the overall emission control efficiency of a source category from published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of NO_x, CO, and NMVOCs from stationary source combustion, as described above, is consistent with the methodology recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

More detailed information on the methodology for calculating emissions from stationary sources, including emission factors and activity data, is provided in Annex B.

Data Sources

Emissions estimates for NO_x, CO, and NMVOCs in this section were taken directly from the EPA's *National Air Pollutant Emissions Trends: 1900 - 1998* (EPA 1999). Fuel consumption data were provided by the U.S. Energy Information Administration's *Annual Energy Review* (EIA 1999a) and *Monthly Energy Review* (EIA 1999b). Emission factors were provided by the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997).

Uncertainty

Methane emission estimates from stationary sources are highly uncertain, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and

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[16] See Annex B for a complete time series of criteria pollutant emission estimates for 1990 through 1998.

N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control). The uncertainties associated with the emission estimates of these gases are greater than with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the criteria pollutants, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

Mobile Combustion (excluding CO_2)

Mobile combustion emits greenhouse gases other than CO_2, including methane (CH_4), nitrous oxide (N_2O), and the criteria pollutants carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs).

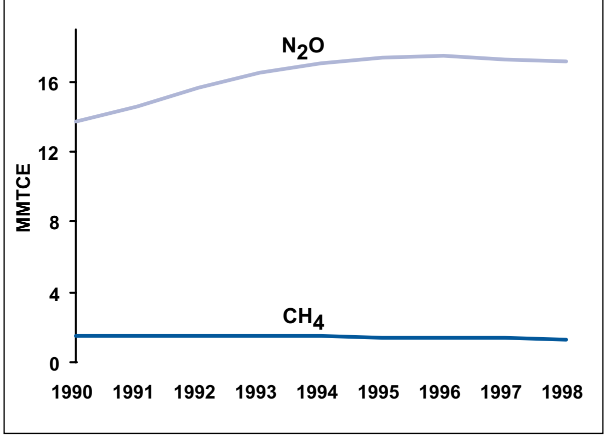
As with stationary combustion, N_2O and NO_x emissions are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, as well as usage of pollution control equipment. Nitrous oxide, in particular, can be formed by the catalytic processes used to control NO_x and CO emissions. Carbon monoxide emissions from mobile source combustion are significantly affected by combustion efficiency and presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. This occurs especially in idle, low speed and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions, such as catalytic converters.

Emissions from mobile combustion were estimated by transport mode (e.g., highway, air, rail, and water) and fuel type—motor gasoline, diesel fuel, jet fuel, aviation gas, natural gas, liquefied petroleum gas (LPG), and residual fuel oil—and vehicle type. Road transport accounted for the majority of mobile source fuel consumption, and hence, the majority of mobile combustion emissions. Table 2-17 through Table 2-20 provide CH_4 and N_2O emission estimates from mobile combustion by vehicle type, fuel type, and transport mode. Estimates of NO_x, CO, and NMVOC emissions in 1998 are given in Table 2-21.[17]

Mobile combustion was responsible for a small portion of national CH_4 emissions but were the second largest source of N_2O in the United States. From 1990 to 1998, CH_4 emissions declined by 10 percent, to 1.3 MMTCE (232 Gg). Nitrous oxide emissions, however, rose 25 percent to 17.2 MMTCE (203 Gg) (see Figure 2-13). The reason for this conflicting trend was that the control technologies employed on highway vehicles in the United States lowered CO, NO_x, NMVOC, and CH_4 emissions, but resulted in higher average N_2O emission rates. Fortunately, since 1994 improvements in the emission control technologies installed on new vehicles have reduced emission rates of both NO_x and N_2O per vehicle mile traveled. Overall, CH_4 and N_2O emissions were domi-

Figure 2-13

Mobile Combustion CH_4 and N_2O Emissions



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[17] See Annex C for a complete time series of criteria pollutant emission estimates for 1990 through 1998.

Table 2-17: CH_4 Emissions from Mobile Combustion (MMTCE)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Gasoline Highway	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.2**	**1.2**	**1.2**	**1.2**
Passenger Cars	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5
Light-Duty Trucks	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.5
Heavy-Duty Vehicles	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+	+	+	+
Diesel Highway	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Non-Highway	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Ships and Boats	+	+	+	+	+	+	+	+	+
Locomotives	+	+	+	+	+	+	+	+	+
Farm Equipment	+	+	+	+	+	+	+	+	+
Construction Equipment	+	+	+	+	+	+	+	+	+
Aircraft	+	+	+	+	+	+	+	+	+
Other*	+	+	+	+	+	+	+	+	+
Total	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.4**	**1.4**	**1.4**	**1.3**

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-18: N_2O Emissions from Mobile Combustion (MMTCE)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Gasoline Highway	**12.5**	**13.3**	**14.4**	**15.2**	**15.7**	**16.0**	**16.0**	**15.9**	**15.8**
Passenger Cars	8.0	8.0	8.3	8.6	8.8	8.9	8.9	8.7	8.6
Light-Duty Trucks	4.2	5.1	5.8	6.4	6.6	6.8	6.8	6.8	6.8
Heavy-Duty Vehicles	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4
Motorcycles	+	+	+	+	+	+	+	+	+
Diesel Highway	**0.5**	**0.5**	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	0.4	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6
Non-Highway	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**
Ships and Boats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Farm Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Construction Equipment	+	+	+	+	+	+	+	+	+
Aircraft	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Other*	+	+	+	+	+	+	+	+	+
Total	**13.8**	**14.6**	**15.7**	**16.5**	**17.1**	**17.4**	**17.5**	**17.3**	**17.2**

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-19: CH_4 Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Gasoline Highway	**226**	**224**	**225**	**223**	**221**	**218**	**213**	**207**	**201**
Passenger Cars	124	114	109	104	102	100	98	95	94
Light-Duty Trucks	82	91	96	99	98	97	94	92	88
Heavy-Duty Vehicles	16	15	15	16	17	17	16	16	16
Motorcycles	4	4	4	4	4	4	4	4	3
Diesel Highway	**10**	**10**	**10**	**11**	**11**	**12**	**12**	**12**	**12**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	10	10	10	10	11	11	11	12	12
Non-Highway	**21**	**21**	**21**	**21**	**21**	**22**	**22**	**20**	**19**
Ships and Boats	3	4	4	4	4	4	4	3	3
Locomotives	3	2	3	2	2	3	3	2	2
Farm Equipment	6	5	6	5	6	6	6	6	5
Construction Equipment	1	1	1	1	1	1	1	1	1
Aircraft	8	7	7	7	7	7	7	7	7
Other*	1	1	1	1	1	1	1	1	1
Total	**257**	**255**	**257**	**255**	**253**	**251**	**246**	**239**	**232**

+ Does not exceed 0.5 Gg

Note: Totals may not sum due to independent rounding.

* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-20: N_2O Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Gasoline Highway	**148**	**157**	**170**	**179**	**186**	**189**	**190**	**188**	**187**
Passenger Cars	95	95	99	101	104	106	105	103	102
Light-Duty Trucks	50	60	68	75	78	80	81	81	80
Heavy-Duty Vehicles	2	2	3	3	3	4	4	4	4
Motorcycles	+	+	+	+	+	+	+	+	+
Diesel Highway	**6**	**6**	**6**	**6**	**7**	**7**	**7**	**7**	**8**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	5	5	6	6	6	6	7	7	7
Non-Highway	**10**	**9**	**10**	**9**	**10**	**10**	**10**	**9**	**9**
Ships and Boats	1	1	1	1	1	2	1	1	1
Locomotives	1	1	1	1	1	1	1	1	1
Farm Equipment	1	1	1	1	1	1	1	1	1
Construction Equipment	+	+	+	+	+	+	+	+	1
Aircraft	6	6	5	5	6	6	6	6	6
Other*	+	+	+	+	+	+	+	+	+
Total	**163**	**172**	**185**	**195**	**202**	**206**	**207**	**205**	**203**

+ Does not exceed 0.5 Gg

Note: Totals may not sum due to independent rounding.

* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-21: NO_x, CO, and NMVOC Emissions from Mobile Combustion in 1998 (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,617**	**44,300**	**4,630**
Passenger Cars	2,574	24,357	2,534
Light-Duty Trucks	1,739	16,988	1,828
Heavy-Duty Vehicles	293	2,783	233
Motorcycles	11	173	35
Diesel Highway	**1,736**	**1,410**	**201**
Passenger Cars	31	27	11
Light-Duty Trucks	11	10	5
Heavy-Duty Vehicles	1,694	1,374	186
Non-Highway	**4,832**	**18,069**	**2,234**
Ships and Boats	971	2,085	742
Locomotives	903	110	47
Farm Equipment	913	573	120
Construction Equipment	1,120	1,166	208
Aircraft[a]	152	865	160
Other[b]	773	13,271	956
Total	**11,184**	**63,780**	**7,065**

[a] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.

[b] "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.

Note: Totals may not sum due to independent rounding. See Annex C for emissions in 1990 through 1998.

nated by gasoline-fueled passenger cars and light-duty gasoline trucks.

Emissions of criteria pollutants generally increased from 1990 through 1994, after which there were decreases of 3 (NO_x) to 14 (CO) percent by 1998. A drop in gasoline prices combined with a strengthening U.S. economy caused the initial increase. These factors pushed the vehicle miles traveled (VMT) by road sources up, resulting in increased fuel consumption and higher emissions. Some of this increased activity was later offset by an increasing portion of the U.S. vehicle fleet meeting established emissions standards.

Fossil-fueled motor vehicles comprise the single largest source of CO emissions in the United States and are a significant contributor to NO_x and NMVOC emissions. In 1998, CO emissions from mobile combustion contributed 74 percent of national CO emissions and 51 and 38 percent of NO_x and NMVOC emissions, respectively. Since 1990, emissions of CO and NMVOCs from mobile combustion decreased by 8 and 12 percent, respectively, while emissions of NO_x increased by 4 percent.

Methodology

Estimates for CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each category. Depending upon the category, activity data included such information as fuel consumption, fuel deliveries, and vehicle miles traveled (VMT). Emission estimates from highway vehicles were based on VMT and emission factors by vehicle type, fuel type, model year, and control technology. Fuel consumption data was employed as a measure of activity for non-highway vehicles and then fuel-specific emission factors were applied.[18] A complete discussion of the methodology used to estimate emissions from mobile combustion is provided in Annex C.

The EPA (1999) provided emissions estimates of NO_x, CO, and NMVOCs for eight categories of highway vehicles,[19] aircraft, and seven categories of off-highway vehicles.[20]

Data Sources

Emission factors used in the calculations of CH_4 and N_2O emissions are presented in Annex C. The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provided emission factors for CH_4, and were developed using MOBILE5a, a model used by the Envi-

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[18] The consumption of international bunker fuels is not included in these activity data, but are estimated separately under the International Bunker Fuels source category.

[19] These categories included: gasoline passenger cars, diesel passenger cars, light-duty gasoline trucks less than 6,000 pounds in weight, light-duty gasoline trucks between 6,000 and 8,500 pounds in weight, light-duty diesel trucks, heavy-duty gasoline trucks and buses, heavy-duty diesel trucks and buses, and motorcycles.

[20] These categories included: gasoline and diesel farm tractors, other gasoline and diesel farm machinery, gasoline and diesel construction equipment, snowmobiles, small gasoline utility engines, and heavy-duty gasoline and diesel general utility engines.

ronmental Protection Agency (EPA) to estimate exhaust and running loss emissions from highway vehicles. The MOBILE5a model uses information on ambient temperature, vehicle speeds, national vehicle registration distributions, gasoline volatility, and other variables in order to produce these factors (EPA 1997).

Emission factors for N_2O from gasoline highway vehicles came from EPA (1998). This report contains emission factors for older passenger cars—roughly pre-1992 in California and pre-1994 in the rest of the United States—from published references, and for newer cars from a recent testing program at EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL). These emission factors for gasoline highway vehicles are lower than the U.S. default values in the *Revised 1996 IPCC Guidelines,* but are higher than the European default values, both of which were published before the more recent tests and literature review conducted by the NVFEL. The U.S. default values in the *Revised 1996 IPCC Guidelines* were based on three studies that tested a total of five cars using European rather than U.S. test protocols. More details may be found in EPA (1998).

Emission factors for gasoline vehicles other than passenger cars were scaled from those for passenger cars with the same control technology, based on their relative fuel economy. This scaling was supported by limited data showing that light-duty trucks emit more N_2O than passenger cars with equivalent control technology. The use of fuel-consumption ratios to determine emission factors is considered a temporary measure only, to be replaced as additional testing data are available. For more details, see EPA (1998). Nitrous oxide emission factors for diesel highway vehicles were taken from the European default values found in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). There is little data addressing N_2O emissions from U.S. diesel-fueled vehicles, and in general, European countries have had more experience with diesel-fueled vehicles. U.S. default values in the *Revised 1996 IPCC Guidelines* were used for non-highway vehicles.

Activity data were gathered from several U.S. government sources including EIA (1999a), EIA (1999b), FHWA (1998), BEA (1999), DESC (1999), DOC (1999), FAA (1999), and DOT/BTS (1999). Control technology data for highway vehicles were obtained from the EPA's Office of Mobile Sources. Annual VMT data for 1990 through 1998 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database, as noted in EPA (1999).

Emissions estimates for NO_x, CO, NMVOCs were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900 - 1998* (EPA 1999).

Uncertainty

Mobile source emission estimates can vary significantly due to assumptions concerning fuel type and composition, technology type, average speeds, type of emission control equipment, equipment age, and operating and maintenance practices. Fortunately, detailed activity data for mobile combustion were available, including VMT by vehicle type for highway vehicles. The allocation of this VMT to individual model years was done using the profile of U.S. vehicle usage by vehicle age in 1990 as specified in MOBILE 5a. Data to develop a temporally variable profile of vehicle usage by model year instead of age was not available.

Average emission factors were developed based on numerous assumptions concerning the age and model of vehicle; percent driving in cold start, warm start, and cruise conditions; average driving speed; ambient temperature; and maintenance practices. The factors for regulated emissions from mobile combustion—CO, NO_x, and hydrocarbons—have been extensively researched, and thus involve lower uncertainty than emissions of unregulated gases. Although methane has not been singled out for regulation in the United States, overall hydrocarbon emissions from mobile combustion—a component of which is methane—are regulated.

Compared to methane, CO, NO_x, and NMVOCs, there is relatively little data available to estimate emission factors for nitrous oxide. Nitrous oxide is not a criteria pollutant, and measurements of it in automobile exhaust have not been routinely collected. Research data has shown that N_2O emissions from vehicles with catalytic converters are greater than those without emission controls, and that vehicles with aged catalysts emit more than new ones. The emission factors used were, therefore, derived from aged cars (EPA 1998b). The emission factors used for Tier 0 and older cars were based on tests of 28 vehicles; those for newer vehicles were based on tests of 22 vehicles. This sample is small considering that it is being used to characterize the entire U.S. fleet, and the associated uncertainty is therefore large. Currently, N_2O gasoline highway emission factors for vehicles other than passenger cars are scaled based on those for passenger cars and their relative fuel economy. Actual measurements should be substituted for this procedure when they become available. Further testing is needed to reduce the uncertainty in emission factors for all classes of vehicles, using realistic driving regimes, environmental conditions, and fuels.

Although aggregate jet fuel and aviation gasoline consumption data has been used to estimate emissions from aircraft, the recommended method for estimating emissions in the *Revised 1996 IPCC Guidelines* is to use data by specific aircraft type (IPCC/UNEP/OECD/IEA 1997). The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions. The EPA is attempting to develop revised estimates based on this more detailed activity data, and these estimates are to be presented in future inventories.

Overall, uncertainty for N_2O emissions estimates is considerably higher than for CH_4, CO, NO_x, or NMVOC; however, all these gases involve far more uncertainty than CO_2 emissions from fossil fuel combustion.

U.S. jet fuel and aviation gasoline consumption is currently all attributed to the transportation sector by EIA, and it is assumed here that it is all used to fuel aircraft. However it is likely that some fuel purchased by airlines is not necessarily be used in aircraft, but instead used to power auxiliary power units, in ground equipment, and to test engines. Some jet fuel may also be used for other purposes such as blending with diesel fuel or heating oil.

Lastly, in EPA (1999), U.S. aircraft emission estimates for CO, NOx, and NMVOCs are based upon landing and take-off (LTO) cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates presented here overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including LTO cycles by aircraft on international flights but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes.

Coal Mining

All underground and surface coal mining liberates (i.e., releases) methane as part of normal operations. The amount of methane liberated during mining is primarily dependent upon the amount of methane stored in the coal and the surrounding strata. This *in situ* methane content is a function of the quantity of methane generated during the coal formation process and its ability to migrate through the surrounding strata over time. The degree of coalification—defined by the rank or quality of the coal formed—determines the amount of methane generated; higher ranked coals generate more methane. The amount of methane remaining in the coal and surrounding strata depends upon geologic characteristics such as pressure within a coal seam. Deeper coal deposits tend to retain more of the methane generated during coalification. Accordingly, deep underground coal seams generally have higher methane contents than shallow coal seams or surface deposits.

Underground coal mines contribute the largest share of methane emissions. All underground coal mines employ ventilation systems to ensure that methane levels remain within safe concentrations. These systems can exhaust significant amounts of methane to the atmosphere in low concentrations. Additionally, over twenty gassy U.S. coal mines supplement ventilation systems with degasification systems. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large volumes of methane before, during or after mining. In 1998, 12 coal mines collected methane from degasification systems and sold this gas to a pipeline, thus reducing emissions to the atmosphere.

Table 2-22: CH_4 Emissions from Coal Mining (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Underground Mining	17.1	16.4	15.6	13.3	13.1	14.2	12.6	12.3	11.4
Liberated	18.8	18.1	17.8	16.0	16.3	17.7	16.5	16.8	16.1
Recovered & Used	(1.6)	(1.7)	(2.1)	(2.7)	(3.2)	(3.4)	(3.8)	(4.6)	(4.8)
Surface Mining	2.8	2.6	2.6	2.5	2.6	2.4	2.5	2.6	2.6
Post- Mining (Underground)	3.6	3.4	3.3	3.0	3.3	3.3	3.4	3.5	3.4
Post-Mining (Surface)	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	**24.0**	**22.8**	**22.0**	**19.2**	**19.4**	**20.3**	**18.9**	**18.8**	**17.8**

Note: Totals may not sum due to independent rounding.

Table 2-23: CH_4 Emissions from Coal Mining (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Underground Mining	2,991	2,863	2,731	2,328	2,289	2,487	2,204	2,141	1,983
Liberated	3,279	3,152	3,102	2,795	2,848	3,086	2,875	2,938	2,814
Recovered & Used	(288)	(289)	(372)	(468)	(559)	(599)	(671)	(797)	(831)
Surface Mining	488	450	449	434	455	425	436	451	450
Post- Mining (Underground)	626	589	582	523	572	567	590	609	598
Post-Mining (Surface)	79	73	73	71	74	69	71	73	73
Total	**4,184**	**3,975**	**3,835**	**3,356**	**3,390**	**3,550**	**3,301**	**3,274**	**3,104**

Note: Totals may not sum due to independent rounding.

Surface coal mines also release methane as the overburden is removed and the coal is exposed; however, the level of emissions is much lower than underground mines. Additionally, after coal has been mined, small amounts of methane retained in the coal are released during processing, storage, and transport.

Total methane emissions in 1998 were estimated to be 17.8 MMTCE (3,104.2 Gg), declining 26 percent since 1990 (see Table 2-22 and Table 2-23). Of this amount, underground mines accounted for 64 percent, surface mines accounted for 15 percent, and post-mining emissions accounted for 22 percent. With the exception of 1994 and 1995, total methane emissions declined in each successive year during this period. In 1993, methane generated from underground mining dropped to a low of 2,327.7 Gg, primarily due to labor strikes at many large underground mines. In 1995, there was an increase in methane emissions from underground mining due to particularly increased emissions at the highest-emitting coal mine in the country. The decline in methane emissions from underground mines is the result of the mining of less gassy coal, and an increase in gas recovery and use. Surface mine emissions and post-mining emissions remained relatively constant from 1990 to 1998.

In 1994, EPA's Coalbed Methane Outreach Program (CMOP) began working with the coal industry and other stakeholders to identify and remove obstacles to investments in coal mine methane recovery and use projects. Reductions attributed to CMOP were estimated to be 0.7, 0.8, 1.0, 1.3, and 1.7 MMTCE in 1994 through 1998, respectively, compared to business-as-usual emissions.

Methodology

The methodology for estimating methane emissions from coal mining consists of two steps. The first step involves estimating methane emissions from underground mines. Because of the availability of ventilation system measurements, underground mine emissions can be estimated on a mine-by-mine basis and then summed to determine total emissions. The second step involves estimating emissions from surface mines and post-mining activities by multiplying basin-specific coal production by basin-specific emissions factors.

Underground mines. Total methane emitted from underground mines is estimated to be the quantity of methane liberated from ventilation systems, plus methane liberated from degasification systems, minus methane recovered and used. The Mine Safety and Heath Administration (MSHA) samples methane emissions from ventilation systems for all mines with detectable[21] methane concentrations. These mine-by-mine measurements are used to estimate methane emissions from ventilation systems.

Some of the higher-emitting underground mines also use degasification systems (e.g., wells or boreholes) that remove methane before, during, or after mining. This methane can then be collected for use or vented to the atmosphere. Various approaches are employed to estimate the quantity of methane collected by each of the more than twenty mines using these systems, depending on available data. For example, some mines report to EPA the amounts of methane liberated from their degasification systems. For mines that sell recovered methane to a pipeline, pipeline sales data are used to estimate degasification emissions. Finally, for those mines for which no other data are available, default recovery efficiency values are developed, depending on the type of degasification system employed.

Finally, the amount of methane recovered by degasification systems and then used (i.e., not vented) is estimated. This calculation is complicated by the fact that methane is rarely recovered and used during the same year in which the particular coal seam is mined. In 1998, 12 active coal mines sold recovered methane to pipelines. Emissions avoided for these projects are estimated using gas sales data reported by various state agencies, and information supplied by coal mine operators regarding the number of years in advance of mining that gas recovery occurs. Additionally, some of the state agencies provide individual well production information, which is used to assign gas sales to a particular year.

Surface Mines and Post-Mining Emissions. Surface mining and post-mining methane emissions are estimated by multiplying basin-specific coal production by basin-specific emissions factors. For surface mining, emissions factors are developed by assuming that surface mines emit from one to three times as much methane as the average in situ methane content of the coal. This accounts for methane released from the strata surrounding the coal seam. For this analysis, it is assumed that twice the average in-situ methane content is emitted. For post-mining emissions, the emission factor is assumed to be from 25 to 40 percent of the average in situ methane content of coals mined in the basin. For this analysis, it is assumed that 32.5 percent of the average in-situ methane content is emitted.

Data Sources

The Mine Safety and Health Administration provides mine-specific information on methane liberated from ventilation systems at underground mines. EPA develops estimates of methane liberated from degasification systems at underground mines based on available data for each of the mines employing these systems. The primary sources of data for estimating emissions avoided at underground mines are gas sales data published by state petroleum and natural gas agencies, information supplied by mine operators regarding the number of years in advance of mining that gas recovery occurred, and reports of gas used on-site. Annual coal production data are taken from the Energy Information Agency's *Coal Industry Annual* (see Table 2-24) (EIA 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999). Data on in situ methane content and emissions factors are taken from EPA (1993).

Uncertainty

The emission estimates from underground ventilation systems are based upon actual measurement data for mines with detectable methane emissions. Accordingly, the uncertainty associated with these measurements is estimated to be low. Estimates of methane liberated from degasification systems are less certain because EPA assigns default recovery efficiencies for a subset of U.S. mines. Compared to underground mines,

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[21] MSHA records coal mine methane readings with concentrations of greater than 50 ppm (parts per million) methane. Readings below this threshold are considered non-detectable.

Table 2-24: Coal Production (Thousand Metric Tons)

Year	Underground	Surface	Total
1990	384,250	546,818	931,068
1991	368,635	532,656	901,291
1992	368,627	534,290	902,917
1993	318,478	539,214	857,692
1994	362,065	575,529	937,594
1995	359,477	577,638	937,115
1996	371,816	593,315	965,131
1997	381,620	607,163	988,783
1998*	377,397	636,972	1,014,369

*Total production for 1998 provided by EIA. Underground and surface proportions are estimated based on 1997 EIA data.

there is considerably more uncertainty associated with surface mining and post-mining emissions because of the difficulty in developing accurate emissions factors from field measurements. Because underground emissions comprise the majority of total coal mining emissions, the overall uncertainty is estimated to be only ±15 percent.[22] Currently, the estimate does not include emissions from abandoned coal mines because of limited data. The EPA is conducting research on the feasibility of including an estimate in future years.

Natural Gas Systems

Methane emissions from natural gas systems are generally process related, with normal operations, routine maintenance, and system upsets being the primary contributors. Emissions from normal operations include: natural gas combusting engine and turbine exhaust, bleed and discharge emissions from pneumatic devices, and fugitive emissions from system components. Routine maintenance emissions originate from pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions.

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, hundreds of thousands of miles of transmission pipeline, and over a million miles of distribution pipeline. The system, though, can be divided into four stages, each with different factors affecting methane emissions, as follows:

Field Production. In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, treatment facilities, gathering pipelines, and process units such as dehydrators and separators. Fugitive emissions and emissions from pneumatic devices account for the majority of emissions. Emissions from field production accounted for approximately 24 percent of methane emissions from natural gas systems between 1990 and 1998. Emissions rose between 1990 and 1996 due to an increased number of producing gas wells and related equipment, but returned to the 1990 level of 8.0 MMTCE in 1998 due to a decrease in domestic production and improvements in technology coupled with the normal replacement of older equipment.

Processing. In this stage, processing plants remove various constituents from the raw gas before it is injected into the transmission system. Fugitive emissions from compressors, including compressor seals, were the primary contributor from this stage. Processing plants accounted for about 12 percent of methane emissions from natural gas systems during the period of 1990 through 1998.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production areas to distribution centers or large volume customers. Throughout the transmission system, compressor stations pressurize the gas to move it through the pipeline. Fugitive emissions from compressor stations and metering and regulating stations accounted for the majority of the emissions from transmission. Pneumatic devices and engine exhaust were smaller sources of emissions from transmission facilities. A gradual increase in transmission pipeline mileage has increased methane emissions from natural gas transmission. Methane emissions from transmission and storage accounted for approximately 40 percent of the emissions from natural gas systems during the period of 1990 through 1998.

Natural gas is also injected and stored in under-

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[22] Preliminary estimate

Table 2-25: CH_4 Emissions from Natural Gas Systems (MMTCE)

Stage	1990	1991	1992	1993	1994	1995	1996	1997	1998
Field Production	8.0	8.2	8.5	8.7	8.3	8.4	8.5	8.2	8.0
Processing	4.0	4.0	4.0	4.0	4.1	4.1	4.1	4.1	4.0
Transmission and Storage	12.7	12.9	12.9	13.1	13.3	13.0	13.1	13.2	13.5
Distribution	8.3	8.4	8.6	8.8	8.6	8.5	8.9	8.6	8.1
Total	**33.0**	**33.4**	**33.9**	**34.6**	**34.3**	**34.0**	**34.6**	**34.1**	**33.6**

Note: Totals may not sum due to independent rounding.

Table 2-26: CH_4 Emissions from Natural Gas Systems (Gg)

Stage	1990	1991	1992	1993	1994	1995	1996	1997	1998
Field Production	1,404	1,427	1,478	1,513	1,450	1,469	1,489	1,435	1,388
Processing	702	693	698	704	724	712	708	710	698
Transmission and Storage	2,223	2,250	2,252	2,290	2,314	2,273	2,291	2,313	2,357
Distribution	1,441	1,470	1,496	1,535	1,499	1,477	1,553	1,504	1,416
Total	**5,770**	**5,840**	**5,923**	**6,042**	**5,987**	**5,931**	**6,041**	**5,961**	**5,860**

Note: Totals may not sum due to independent rounding.

ground formations during periods of low demand, and withdrawn, processed, and distributed during periods of high demand. Compressors and dehydrators were the primary contributors to emissions from these storage facilities. Less than one percent of total emissions from natural gas systems can be attributed to storage facilities.

Distribution. The distribution of natural gas requires the use of low-pressure pipelines to deliver gas to customers. There were 955,000 miles of distribution pipelines (i.e., main) in 1997 (the latest year for which distribution pipeline mileage data is available), increasing from a 1990 figure of just over 837,000 miles (AGA, 1998). Distribution system emissions, which account for approximately 24 percent of emissions from natural gas systems, resulted mainly from fugitive emissions from gate stations and non-plastic piping. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced the growth in emissions from this stage.

Overall, natural gas systems emitted 33.6 MMTCE (5,860 Gg) of methane in 1998, a slight increase over 1990 emissions of 33.0 MMTCE (5,770) in 1990 (see Table 2-25 and Table 2-26). Even though transmission and distribution pipeline mileage and natural gas production have increased from 1990 to 1998, emissions over that period have remained relatively constant. Improvements in management practices and technology, along with the normal replacement of older equipment, helped to stabilize emissions. In addition, EPA's Natural Gas STAR Program, initiated in 1993, is working with the gas industry to promote profitable practices that reduce methane emissions. The program is estimated to have reduced emissions by 0.7, 1.2, 1.3, 1.8 and 2.2 MMTCE in 1994 through 1998, respectively. In Table 2-25 and Table 2-26, Natural Gas STAR reductions are included in the emission estimates for each sector of the natural gas industry and are also reflected in the total emission estimate.

Methodology

The foundation for the estimate of methane emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute and EPA (GRI/EPA 1996). The GRI/EPA study developed over 100 detailed emission factors and activity levels through site visits to selected gas facilities, and arrived at a national point estimate for 1992. Since publication of this study, EPA conducted additional analysis to update the activity data for some of the components of the system, particularly field production equipment. Summing emissions across individual sources in the natural gas system provided a

1992 baseline emission estimate from which the emissions for the period 1990 through 1998 were derived.

Apart from the year 1992, detailed statistics on each of the over 100 activity levels were not available for the time series 1990 through 1998. To estimate these activity levels, aggregate annual statistics were obtained on select driving variables, including: number of producing wells, number of gas plants, miles of transmission pipeline, miles of distribution pipeline, and miles of distribution services. By assuming that the relationships among these variables remained constant (e.g., the number of heaters per well remained the same), the statistics on these variables formed the basis for estimating other activity levels.

For the period 1990 through 1995, the emission factors were held constant. A gradual improvement in technology and practices is expected to reduce the emission factors slightly over time. To reflect this trend, the emission factors were reduced by about 0.2 percent per year starting with 1996, a rate that, if continued, would lower the emission factors by 5 percent in 2020. See Annex E for more detailed information on the methodology and data used to calculate methane emissions from natural gas systems.

Data Sources

Activity data were taken from the American Gas Association (AGA 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999), *Natural Gas Annual* (EIA 1998), and *Natural Gas Monthly* (EIA 1998), Independent Petroleum Association of America (IPAA 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998), and the Department of Transportation's Office of Pipeline Safety (OPS 2000). The U.S. Department of Interior (DOI 1997, 1998, 1999) supplied offshore platform data. All emission factors were taken from GRI/EPA (1996).

Uncertainty

The heterogeneous nature of the natural gas industry makes it difficult to sample facilities that are completely representative of the entire industry. Because of this, scaling up from model facilities introduces a degree of uncertainty. Additionally, highly variable emission rates were measured among many system components, making the calculated average emission rates uncertain. Despite the difficulties associated with estimating emissions from this source, the uncertainty in the total estimated emissions are believed to be on the order of ±40 percent.

Petroleum Systems

Methane emissions from petroleum systems are primarily associated with crude oil production, transportation, and refining operations. During each of these activities, methane is released to the atmosphere as fugitive emissions, vented emissions, operational upset emissions, and emissions from the combustion of fuels. These activities and associated methane emissions are detailed below.

Production Field Operations. Production field operations account for approximately 97 percent of total methane emissions from petroleum systems. The major sources of methane from production operations are venting from storage tanks and pneumatic devices, wellhead fugitives, combustion products, and process upsets. Vented methane from oil wells, storage tanks, and related production field processing equipment was the primary contributor to emissions from the oil industry, accounting for, on average, 89 percent. Field storage tanks and natural-gas-powered pneumatic devices used to operate valves and small pumps were the dominant contributors to venting emissions. Oil wells and offshore platforms accounted for most of the remaining venting emissions.

Fugitive and combustion emissions from production field operations accounted for three percent and two percent, respectively, of total methane emissions from the oil industry. Most fugitive methane emissions in the field were from oil wellheads and the equipment used to separate natural gas and water from the crude oil. Nearly all of the combustion emissions in the field were from engine exhaust. The EPA expects future emissions from production fields to decline as the number of oil wells declines and crude production slows.

Crude Oil Transportation. Crude transportation activities accounted for less than one half percent of total methane emissions from the oil industry. Venting

Table 2-27: CH_4 Emissions from Petroleum Systems (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Production Field Operations	**7.2**	**7.3**	**7.1**	**6.7**	**6.6**	**6.5**	**6.4**	**6.4**	**6.2**
Tank venting	3.2	3.3	3.1	3.0	2.9	2.8	2.8	2.8	2.7
Pneumatic device venting	3.2	3.2	3.1	3.0	2.9	2.9	2.8	2.8	2.7
Wellhead fugitives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Combustion & process upsets	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Misc. venting & fugitives	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Crude Oil Transportation	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Refining	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.2**	**0.2**
Total	**7.4**	**7.5**	**7.2**	**6.9**	**6.7**	**6.7**	**6.5**	**6.5**	**6.3**

\+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding.

Table 2-28: CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Production Field Operations	**1,263**	**1,276**	**1,232**	**1,175**	**1,144**	**1,136**	**1,111**	**1,109**	**1,075**
Tank venting	564	570	548	519	502	493	485	484	466
Pneumatic device venting	559	564	545	521	506	507	491	490	475
Wellhead fugitives	24	26	25	24	25	25	25	24	24
Combustion & process upsets	46	46	45	45	45	45	45	46	45
Misc. venting & fugitives	70	70	69	67	66	66	65	65	64
Crude Oil Transportation	**7**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**
Refining	**25**	**24**	**24**	**25**	**25**	**25**	**26**	**27**	**27**
Total	**1,294**	**1,307**	**1,262**	**1,206**	**1,175**	**1,168**	**1,143**	**1,142**	**1,108**

Note: Totals may not sum due to independent rounding.

from tanks and marine vessel loading operations accounted for the majority of methane emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, accounted for the remainder.

Crude Oil Refining. Crude oil refining processes and systems accounted for only two percent of total methane emissions from the oil industry because most of the methane in crude oil is removed or escapes before the crude oil is delivered to the refineries. Within refineries, vented emissions accounted for 86 percent, while fugitive and combustion emissions were seven percent each. Refinery system blowdowns for maintenance and the process of asphalt blowing—with air to harden it—were the primary venting contributors. Most of the fugitive emissions from refineries were from leaks in the fuel gas system. Refinery combustion emissions accumulate from small amounts of unburned methane in process heater stack emissions and from unburned methane in engine exhausts and flares.

The EPA estimates total methane emissions from petroleum systems in 1998 were 6.3 MMTCE (1,108 Gg). Since 1990, emissions declined gradually primarily due to a decline in domestic oil production. Emission estimates are provided below in Table 2-27 and Table 2-28.

Methodology

The EPA's methodology for estimating methane emissions from petroleum systems is based on a comprehensive study of methane emissions from U.S. petroleum systems, *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report) (EPA 1999).* The study estimated emissions from 70 activities occurring in petroleum systems from the oil wellhead through crude oil refining, including 39 activities for crude oil production field operations, 11 for crude oil transportation activities, and 20 for refining operations. Annex F explains the emission estimates for these 70 activities in greater detail. The estimate of methane emissions from petroleum systems does not include emissions downstream from oil refineries because these emissions are very small compared to methane emissions upstream from oil refineries.

The methodology for estimating methane emissions from the 70 oil industry activities employs emission factors and activity factors initially developed in EPA (1999). The EPA estimates emissions for each activity by multiplying emission factors (e.g., emission rate per equipment item or per activity) by their corresponding activity factor (e.g., equipment count or frequency of activity). The report (EPA 1999) provides emission factors and activity factors for all activities except those related to offshore oil production. For offshore oil production, the EPA calculated an emission factor by dividing an emission estimate from the Minerals Management Service (MMS) by the number of platforms (the activity factor).

The EPA collected activity factors for 1990 through 1998 from a wide variety of historical resources. For 1995, data on activity factors were available; however, some activity factor data are not reported for other years. When activity factor data were not available, the EPA employed one of three options. Where appropriate, the activity factor was assumed to be directly proportional to annual oil production. (Proportionality constants were calculated by dividing the activity factor for 1995 by the annual oil production for 1995. The resulting proportionality constants were then multiplied by the annual oil production in years for which activity factors must be estimated.) In other cases, the activity factor was kept constant between 1990 and 1998. Lastly, 1997 data was used when 1998 data were not yet available.

Emission factors were held constant for the period 1990 through 1998, with the exception of engine emissions. Over time, more efficient engines are used to drive pumps, compressors, and generators. The emission factor for these engines was adjusted accordingly.

Data Sources

Nearly all emission factors were taken from earlier work performed by Radian International LLC (Radian 1996e). Other emission factors were taken from API publication 4638 (API 1996), EPA default values, MMS reports (MMS 1995 and 1999), the Exploration and Production (E&P) Tank model (API and GRI), reports by the Canadian Association of Petroleum Producers (CAPP 1992 and 1993), and consensus of industry peer review panels.

The EPA uses many references to obtain activity factors. Among the more important references are Energy Information Administration annual and monthly reports (EIA 1995, 1996, 1997, 1998), the *API Basic Petroleum Data Book* (API 1997 and 1999), the GRI/EPA report (Radian 1996a-d), *Methane Emissions from the Natural Gas Industry*, consensus of industry peer review panels, MMS reports (MMS 1995 and 1999), and the *Oil & Gas Journal* (OGJ 1990-1998a,b). Appendix F

Table 2-29: Uncertainty in CH_4 Emissions from Production Field Operations (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Tank venting (point estimate)	**564**	**570**	**548**	**519**	**502**	**493**	**485**	**484**	**466**
Low	423	427	411	389	377	370	364	363	349
High	705	712	685	649	628	617	606	605	582
Pneumatic devices (point estimate)	**559**	**564**	**545**	**521**	**506**	**507**	**491**	**490**	**475**
Low	372	376	363	347	338	338	328	327	317
High	698	705	681	651	633	634	614	613	594

provides a complete list of references.

Uncertainty

The detailed, bottom-up analysis used to evaluate U.S. petroleum systems for the current Inventory reduces the uncertainty related to the methane emission estimates compared to previous estimates. However, a number of uncertainties remain. Because published activity factors are not available every year for all 70 activities analyzed for petroleum systems, the EPA must estimate some of them. For example, there is uncertainty associated with the estimate of annual venting emissions in production field operations because a recent census of tanks and other tank battery equipment, such as separators and pneumatic devices, is not available. These uncertainties are important because the production sector accounted for 97 percent of total 1998 methane emissions from petroleum systems. Uncertainties are also associated with emission factors because highly variable emission rates are summarized in one emission factor. The majority of methane emissions occur during production field operations, where methane can first escape crude oil, so a better understanding of tank battery equipment and tanks would reduce the uncertainty associated with the estimate of methane emissions from petroleum systems. Table 2-29 provides emission estimate ranges given the uncertainty in the estimates of vented emissions from producing field tanks and pneumatic devices.

Natural Gas Flaring and Criteria Pollutant Emissions from Oil and Gas Activities

The flaring of natural gas from oil wells is a small source of carbon dioxide (CO_2). In addition, oil and gas activities also release small amounts of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs). This source accounts for only a small proportion of overall emissions of each of these gases. Emissions of CO_2, NO_x, and CO from petroleum and natural gas production activities were all less than 1 percent of national totals, while NMVOC emissions were roughly 2 percent of national totals.

Carbon dioxide emissions from petroleum production result from natural gas that is flared (i.e., combusted) at the production site. Barns and Edmonds (1990) noted that of total reported U.S. venting and flaring, approximately 20 percent may be vented, with the remaining 80 percent flared; however, it is now believed that flaring accounts for an even greater proportion, although some venting still occurs. Methane emissions from venting are accounted for under Petroleum Systems. For 1998, the CO_2 emissions from the flaring were estimated to be approximately 3.4 MMTCE (12,296 Gg), an increase of 148 percent since 1990 (see Table 2-30).

Criteria pollutant emissions from oil and gas production, transportation, and storage, constituted a relatively small and stable portion of the total emissions of these gases from the 1990 to 1998 (see Table 2-31).

Methodology

The estimates for CO_2 emissions were prepared using an emission factor of 14.92 MMTCE/QBtu of flared gas, and an assumed flaring efficiency of 100 percent. The quantity of flared gas was estimated as the total reported vented and flared gas minus a constant 12,031 million cubic feet, which was assumed to be vented.[23]

Criteria pollutant emission estimates for NO_x, CO, and NMVOCs were determined using industry-published production data and applying average emission factors.

Data Sources

Activity data in terms of total natural gas vented and flared for estimating CO_2 emissions from natural gas flaring were taken from *EIA's Natural Gas Annual* (EIA 1998). The emission and thermal conversion factors were also provided by EIA (see Table 2-32).

EPA (1999) provided emission estimates for NO_x, CO, and NMVOCs from petroleum refining, petroleum product storage and transfer, and petroleum marketing operations. Included are gasoline, crude oil and distillate fuel oil storage and transfer operations, gasoline bulk terminal and bulk plants operations, and retail gaso-

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[23] See the methodological discussion under Petroleum Systems for the basis of the portion of natural gas assumed vented.

Table 2-30: CO_2 Emissions from Natural Gas Flaring

Year	MMTCE	Gg
1990	2.5	9,097
1991	2.8	10,295
1992	2.8	10,169
1993	3.7	13,716
1994	3.8	13,800
1995	4.7	17,164
1996	4.5	16,506
1997	4.2	15,521
1998	3.9	14,214

Table 2-31: NO_x, NMVOCs, and CO Emissions from Oil and Gas Activities (Gg)

Year	NO_x	CO	NMVOCs
1990	139	302	555
1991	110	313	581
1992	134	337	574
1993	111	337	588
1994	106	307	587
1995	100	316	582
1996	121	287	459
1997	121	292	461
1998	122	296	464

Table 2-32: Total Natural Gas Reported Vented and Flared (Million Ft^3) and Thermal Conversion Factor (Btu/Ft^3)

Year	Vented and Flared	Thermal Conversion Factor
1990	150,415	1,106
1991	169,909	1,108
1992	167,519	1,110
1993	226,743	1,106
1994	228,336	1,105
1995	283,739	1,106
1996	272,117	1,109
1997	263,819	1,107
1998	261,000	1,107

line service stations operations.

Uncertainty

Uncertainties in CO_2 emission estimates primarily arise from assumptions concerning what proportion of natural gas is flared and the flaring efficiency. The portion assumed vented as methane in the methodology for Petroleum Systems is currently held constant over the period 1990 through 1998 due to the uncertainties involved in the estimate. Uncertainties in criteria pollutant emission estimates are partly due to the accuracy of the emission factors used and projections of growth.

International Bunker Fuels

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the United Nations Framework Convention on Climate Change (UNFCCC), are currently not included in national emission totals, but are reported separately based upon location of fuel sales. The decision to report emissions from international bunker fuels separately, instead of allocating them to a particular country, was made by the Intergovernmental Negotiating Committee in establishing the Framework Convention on Climate Change.[24] These decisions are reflected in the *Revised 1996 IPCC Guidelines*, in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC/UNEP/OECD/IEA 1997). The Parties to the UNFCCC have yet to decide on a methodology for allocating these emissions.[25]

Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), oxides of nitrogen (NO_x), nonmethane volatile organic compounds (NMVOCs), particulate matter, and sulfur dioxide (SO_2).[26] Two transport modes are addressed under the IPCC definition of

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[24] See report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the work of its ninth session, held at Geneva from 7 to 18 February 1994 (A/AC.237/55, annex I, para. 1c) (contact secretariat@unfccc.de).

[25] See FCCC/SBSTA/1996/9/Add.1 and Add.2 for a discussions of allocation options for international bunker fuels (see http://www.unfccc.de/fccc/docs/1996/sbsta/09a01.pdf and /09a02.pdf).

international bunker fuels: aviation and marine. Emissions from ground transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

The IPCC Guidelines distinguish between different modes of air traffic. Civil aviation comprises aircraft used for the commercial transport of passengers and freight, military aviation comprises aircraft under the control of national armed forces, and general aviation applies to recreational and small corporate aircraft. The IPCC Guidelines further define international bunker fuel use from civil aviation as the fuel combusted for civil (e.g., commercial) aviation purposes by aircraft arriving or departing on international flight segments. However, as mentioned above, and in keeping with the IPCC Guidelines, only the fuel purchased in the United States and used by aircraft taking-off (i.e., departing) from the United States are reported here. The standard fuel used for civil aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[27]

Emissions of CO_2 from aircraft are a function of fuel use, whereas emissions per flight or ton-mile in the case of cargo, are a function of flight path, fuel efficiency of the aircraft and its engines, occupancy, and load factor. Methane, N_2O, CO, NO_x, and NMVOC emissions depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Methane, CO, and NMVOCs are the product of incomplete combustion and occur mainly during the landing and take-off phases. In jet engines, N_2O and NO_x are primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase. The impact of NO_x on atmospheric chemistry depends on the altitude of the actual emission. The cruising altitude of supersonic aircraft, near or in the ozone layer, is higher than that of subsonic aircraft. At this higher altitude, NO_x emissions contribute to ozone depletion.[28] At the cruising altitudes of subsonic aircraft, however, NO_x emissions contribute to the formation of ozone. At these lower altitudes, the positive radiative forcing effect of ozone is most potent.[29] The vast majority of aircraft NO_x emissions occur at these lower cruising altitudes of commercial subsonic aircraft (NASA 1996).[30]

International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger carrying, military (i.e., navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going vessels: distillate diesel fuel and residual fuel oil. Carbon dioxide is the primary greenhouse gas emitted from marine shipping. In comparison to aviation, the atmospheric impacts of NO_x from shipping are relatively minor, as the emissions occur at ground level.

Overall, aggregate greenhouse gas emissions in 1998 from the combustion of international bunker fuels from both aviation and marine activities decreased by 3 percent since 1990, to 31.6 MMTCE (see Table 2-33). Although emissions from international flights departing from the United States have increased significantly (22 percent), emissions from international shipping voyages departing the United States appear to have decreased by 19 percent since 1990. Increased military activity during the Persian Gulf War resulted in an increased level of military marine emissions in 1990 and 1991; civilian marine emissions during this period exhibited a similar trend.[31] Since 1994, marine emissions have steadily in-

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[26] Sulfur dioxide emissions from jet aircraft and marine vessels, although not estimated here, are mainly determined by the sulfur content of the fuel. In the U.S., jet fuel, distillate diesel fuel, and residual fuel oil average sulfur contents of 0.05, 0.3, and 2.3 percent, respectively. These percentages are generally lower than global averages.

[27] Naphtha-type jet fuel is used primarily by the military in turbojet and turboprop aircraft engines.

[28] In 1996, there were only around a dozen civilian supersonic aircraft in service around the world which flew at these altitudes, however.

[29] However, at this lower altitude, ozone does little to shield the earth from ultraviolet radiation.

[30] Cruise altitudes for civilian subsonic aircraft generally range from 8.2 to 12.5 km (27,000 to 41,000 feet).

creased. The majority of these emissions were in the form of carbon dioxide; however, small amounts of CH_4 and N_2O were also emitted. Of the criteria pollutants, emissions of NO_x by aircraft at cruising altitudes are of primary concern because of their effects on ozone formation (see Table 2-34).

Emissions from both aviation and marine international transport activities are expected to grow in the future as both air traffic and trade increase, although emission rates should decrease over time due to technological changes.[32]

Methodology

Emissions of CO_2 were estimated through the application of carbon content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under CO_2 from Fossil Fuel Combustion. A complete description of the methodology and a listing of the various factors employed can be found in Annex A. See Annex G for a specific discus-

Table 2-33: Emissions from International Bunker Fuels (MMTCE)

Gas/Mode	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**32.2**	**32.7**	**30.0**	**27.2**	**26.7**	**27.5**	**27.9**	**29.9**	**31.3**
Aviation	12.7	12.7	12.9	13.0	13.2	13.9	14.2	15.2	15.5
Marine	19.4	20.0	17.1	14.3	13.6	13.6	13.7	14.7	15.8
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Aviation	+	+	+	+	+	+	+	+	+
Marine	+	+	+	+	+	+	+	+	+
N_2O	**0.3**	**0.3**	**0.3**	**0.2**	**0.2**	**0.2**	**0.2**	**0.3**	**0.3**
Aviation	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Marine	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**32.5**	**33.0**	**30.3**	**27.5**	**27.0**	**27.8**	**28.1**	**30.2**	**31.6**

\+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 2-34: Emissions from International Bunker Fuels (Gg)

Gas/Mode	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**117,965**	**120,019**	**109,965**	**99,886**	**98,017**	**101,014**	**102,197**	**109,788**	**114,700**
Aviation	46,728	46,682	47,143	47,615	48,327	51,093	52,135	55,899	56,917
Marine	71,237	73,337	62,822	52,270	49,690	49,921	50,062	53,889	57,783
CH_4	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Aviation	1	1	1	1	1	1	1	2	2
Marine	1	1	1	0	0	0	0	0	1
N_2O	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Aviation	1	1	1	2	2	2	2	2	2
Marine	2	2	2	1	1	1	1	1	1
CO	**118**	**120**	**114**	**109**	**109**	**113**	**115**	**124**	**128**
Aviation	77	77	77	78	80	84	86	92	94
Marine	42	43	37	31	29	29	29	32	34
NO_x	**2,093**	**2,148**	**1,870**	**1,591**	**1,523**	**1,541**	**1,548**	**1,665**	**1,776**
Aviation	184	184	186	188	191	202	207	221	225
Marine	1,908	1,964	1,683	1,403	1,332	1,339	1,341	1,444	1,550
NMVOC	**62**	**64**	**56**	**49**	**47**	**48**	**49**	**52**	**55**
Aviation	12	11	12	12	12	13	13	14	14
Marine	51	52	45	37	35	36	36	38	41

Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

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[31] See Uncertainty section for a discussion of data quality issues.

[32] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

sion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4, N_2O, CO, NO_x, and NMVOCs were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Data Sources

Carbon content and fraction oxidized factors for kerosene-type and naptha-type jet fuel, distillate fuel oil, and residual fuel oil were taken directly from the Energy Information Administration (EIA) of the U.S. Department of Energy and are presented in Annex A. Heat content and density conversions were taken from EIA (1998) and USAF (1998). Emission factors used in the calculations of CH_4, N_2O, CO, NO_x, and NMVOC emissions were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). For aircraft emissions, the following values, in units of grams of pollutant per kilogram of fuel consumed (g/kg), were employed: 0.09 for CH_4, 0.1 for N_2O, 5.2 for CO, 12.5 for NO_x, and 0.78 for NMVOCs. For marine vessels consuming either distillate diesel or residual fuel oil the following values, in the same units, except where noted, were employed: 0.03 for CH_4, 0.08 for N_2O, 1.9 for CO, 87 for NO_x, and 0.052 g/MJ for NMVOCs.

Activity data on aircraft fuel consumption were collected from three government agencies. Jet fuel consumed by U.S. flag air carriers for international flight segments was supplied by the Bureau of Transportation Statistics (DOT/BTS 1999). It was assumed that 50 percent of the fuel used by U.S. flagged carriers for international flights—both departing and arriving in the United States—was purchased domestically for flights departing from the United States. In other words, only one-half of the total annual fuel consumption estimate was used in the calculations. Data on jet fuel expenditures by foreign flagged carriers departing U.S. airports was taken from unpublished data collected by the Bureau of Economic Analysis (BEA) under the U.S. Department of Commerce (BEA 1999). Approximate average fuel prices paid by air carriers for aircraft on international flights was taken from DOT/BTS (1999) and used to convert the BEA expenditure data to gallons of fuel consumed. Data on jet fuel expenditures by the U.S. military was supplied by the Office of the Under Secretary of Defense (Environmental Security), U.S. Department of Defense (DoD). Estimates of the percentage of each services' total operations that were international operations were developed by DoD. Military aviation bunkers included international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Data on fuel delivered to the military within the United States was provided from unpublished data by the Defense Energy Support Center, under DoD's Defense Logistics Agency (DESC 1999). Together, the data allow the quantity of fuel used in military international operations to be estimated. Jet fuel densities for each fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 2-35. See Annex G for additional discussion of military data.

Activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were taken from unpublished data collected by the Foreign Trade Division

Table 2-35: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990	1991	1992	1993	1994	1995	1996	1997	1998
U.S. Carriers	1,982	1,970	2,069	2,078	2,155	2,256	2,329	2,482	2,363
Foreign Carriers	2,062	2,075	2,185	2,252	2,326	2,549	2,629	2,918	3,138
U.S. Military	862	855	700	677	608	581	540	496	502
Total	**4,905**	**4,900**	**4,954**	**5,007**	**5,090**	**5,385**	**5,497**	**5,895**	**6,003**

Note: Totals may not sum due to independent rounding.

of the U.S. Department of Commerce's Bureau of the Census (DOC 1998). Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by the Defense Energy Support Center (DESC). The total amount of fuel provided to naval vessels was reduced by 13 percent to account for fuel used while the vessels were not-underway (i.e., in port). Data on the percentage of steaming hours underway versus not-underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 2-36.

Uncertainty

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[33] For example, smaller aircraft on shorter routes often carry sufficient fuel to complete several flight segments without refueling in order to minimize time spent at the airport gate or take advantage of lower fuel prices at particular airports. This practice, called tankering, when done on international flights, complicates the use of fuel sales data for estimating bunker fuel emissions. Tankering is less common with the type of large, long-range aircraft that make many international flights from the United States, however. Similar practices occur in the marine shipping industry where fuel costs represent a significant portion of overall operating costs and fuel prices vary from port to port, leading to some tankering from ports with low fuel costs.

Particularly for aviation, the DOT/BTS (1998) international flight segment fuel data used for U.S. flagged carriers does not include smaller air carriers and unfortunately defines flights departing to Canada and some flights to Mexico as domestic instead of international. As for the BEA (1998) data on foreign flagged carriers, there is some uncertainty as to the average fuel price, and to the completeness of the data. It was also not possible to determine what portion of fuel purchased by foreign carriers at U.S. airports was actually used on domestic flight segments; this error, however, is believed to be small.[34]

Although aggregate fuel consumption data has been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO_2 in the *Revised 1996 IPCC Guidelines* is to use data by specific aircraft type (IPCC/UNEP/OECD/IEA 1997). The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[35] The EPA is developing revised

Table 2-36: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Residual Fuel Oil	5,137	5,354	4,475	3,567	3,504	3,495	3,583	3,843	3,974
Distillate Diesel Fuel & Other	598	595	561	609	510	573	456	421	627
U.S. Military Naval Fuels	522	481	491	448	364	334	362	477	506
Total	**6,257**	**6,431**	**5,527**	**4,624**	**4,378**	**4,402**	**4,402**	**4,740**	**5,107**

Note: Totals may not sum due to independent rounding.

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[33] See uncertainty discussions under CO_2 from Fossil Fuel Combustion and Mobile Combustion.

[34] Although foreign flagged air carriers are prevented from providing domestic flight services in the United States, passengers may be collected from multiple airports before an aircraft actually departs on its international flight segment. Emissions from these earlier domestic flight segments should be classified as domestic, not international, according to the IPCC.

estimates based on this more detailed activity data, and these estimates are to be presented in future inventories.

There is also concern as to the reliability of the existing DOC (1998) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation. Of note is that fuel consumption data were not available for the year 1990; therefore, an average of 1989 and 1991 data was employed.

Wood Biomass and Ethanol Consumption

The combustion of biomass fuels—such as wood, charcoal, and wood waste—and biomass-based fuels—such as ethanol from corn and woody crops—generates carbon dioxide (CO_2). However, in the long run the carbon dioxide emitted from biomass consumption does not increase atmospheric carbon dioxide concentrations, assuming the biogenic carbon emitted is offset by the uptake of CO_2 resulting from the growth of new biomass. As a result, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel-based emissions and are not included in the U.S. totals. Net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands are accounted for in the Land-Use Change and Forestry chapter.

In 1998, CO_2 emissions due to burning of woody biomass within the industrial and residential/commercial sectors and by electric utilities were about 64.2 MMTCE (235,554 Gg) (see Table 2-37 and Table 2-38). As the largest consumer of woody biomass, the industrial sector in 1998 was responsible for 83 percent of the CO_2 emissions from this source. The combined residential/commercial[36] sector was the second largest emitter, making up 16 percent of total emissions from woody biomass. The commercial end-use sector and electric utilities accounted for the remainder.

Biomass-derived fuel consumption in the United States consisted mainly of ethanol use in the transportation sector. Ethanol is primarily produced from corn

Table 2-37: CO_2 Emissions from Wood Consumption by End-Use Sector (MMTCE)

End-Use Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Electric Utility	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Industrial	42.4	42.3	44.5	45.4	48.3	49.8	51.6	52.1	53.6
Residential/Commercial	12.7	13.4	14.1	12.9	12.7	14.0	14.0	10.4	10.2
Total	**55.6**	**56.2**	**59.0**	**58.8**	**61.4**	**64.2**	**66.1**	**62.9**	**64.2**

Note: Totals may not sum due to independent rounding.

Table 2-38: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998
Electric Utility	1,715	1,698	1,725	1,636	1,635	1,356	1,580	1,542	1,598
Industrial	155,614	155,232	163,195	166,480	177,145	182,658	189,370	190,968	196,561
Residential/Commercial	46,424	48,981	51,537	47,303	46,504	51,218	51,440	37,959	37,395
Total	**203,753**	**205,910**	**216,457**	**215,419**	**225,284**	**235,232**	**242,390**	**230,470**	**235,554**

Note: Totals may not sum due to independent rounding.

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[35] It should be noted that in the EPA's *National Air Pollutant Emissions Trends, 1900 - 1998* (EPA 1999), U.S. aviation emission estimates for CO, NOx, and NMVOCs are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates given under Mobile Source Fossil Fuel Combustion overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes. EPA (1998) is also likely to include emissions from ocean-going vessels departing from U.S. ports on international voyages.

[36] For this emissions source, data are not disaggregated into residential and commercial sectors.

Table 2-39: CO_2 Emissions from Ethanol Consumption

Year	MMTCE	Gg
1990	1.6	5,701
1991	1.2	4,519
1992	1.5	5,492
1993	1.7	6,129
1994	1.8	6,744
1995	2.0	7,230
1996	1.4	5,145
1997	1.8	6,744
1998	2.0	7,300

grown in the Midwest, and was used mostly in the Midwest and South. Pure ethanol can be combusted, or it can be mixed with gasoline as a supplement or octane-enhancing agent. The most common mixture is a 90 percent gasoline, 10 percent ethanol blend known as gasohol. Ethanol and ethanol blends are often used to fuel public transport vehicles such as buses, or centrally fueled fleet vehicles. Ethanol and ethanol blends are believed to burn "cleaner" than gasoline (i.e., lower in NO_x and hydrocarbon emissions), and have been employed in urban areas with poor air quality. However, because ethanol is a hydrocarbon fuel, its combustion emits CO_2.

In 1998, the United States consumed an estimated 105 trillion Btus of ethanol. Emissions of CO_2 in 1998 due to ethanol fuel burning were estimated to be approximately 2.0 MMTCE (6,744 Gg) (see Table 2-39).

Ethanol production dropped sharply in the middle of 1996 because of short corn supplies and high prices. Plant output began to increase toward the end of the growing season, reaching close to normal levels at the end of the year. However, total 1996 ethanol production fell far short of the 1995 level (EIA 1997). Production in 1998 returned to normal historic levels.

Methodology

Woody biomass emissions were estimated by converting U.S. consumption data in energy units (17.2 million Btu per short ton) to megagrams (Mg) of dry matter using EIA assumptions. Once consumption data for each sector were converted to megagrams of dry matter, the carbon content of the dry fuel was estimated based on default values of 45 to 50 percent carbon in dry biomass. The amount of carbon released from combustion was estimated using 87 percent for the fraction oxidized (i.e., combustion efficiency). Ethanol consumption data in energy units were also multiplied by a carbon coefficient (18.96 mg C/Btu) to produce carbon emission estimates.

Data Sources

Woody biomass consumption data were provided

Table 2-40: Woody Biomass Consumption by Sector (Trillion Btu)

Year	Industrial	Residential/ Commercial	Electric Utility
1990	1,948	581	21
1991	1,943	613	21
1992	2,042	645	22
1993	2,084	592	20
1994	2,217	582	20
1995	2,286	641	17
1996	2,370	644	20
1997	2,390	475	19
1998	2,460	468	20

Table 2-41: Ethanol Consumption

Year	Trillion Btu
1990	82
1991	65
1992	79
1993	88
1994	97
1995	104
1996	74
1997	97
1998	105

by EIA (1999) (see Table 2-40). The factor for converting energy units to mass was supplied by EIA (1994). Carbon content and combustion efficiency values were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Emissions from ethanol were estimated using consumption data from EIA (1999) (see Table 2-41). The carbon coefficient used was provided by OTA (1991).

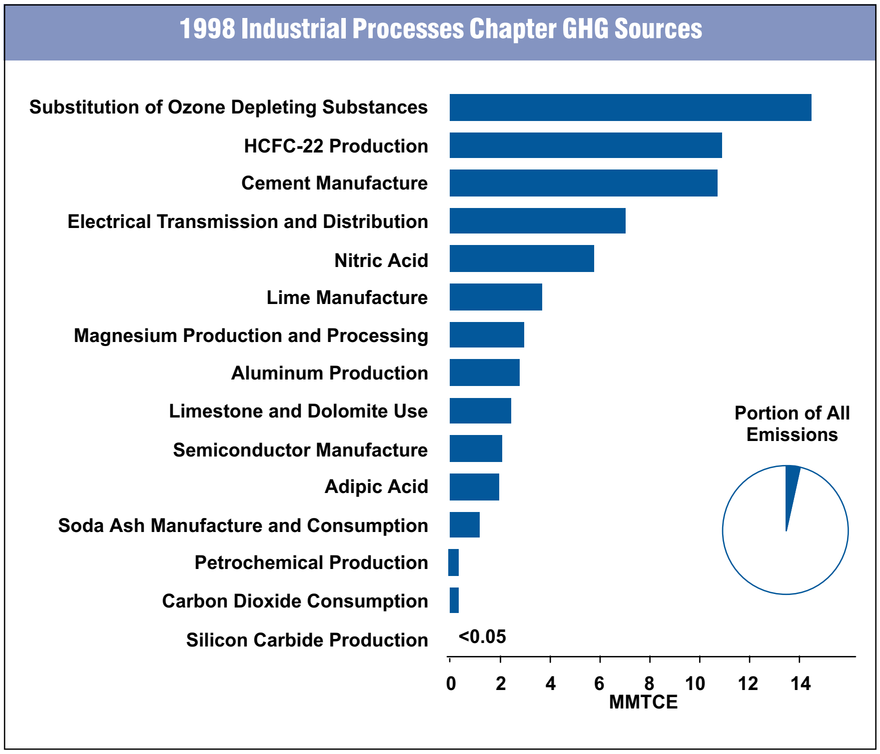
Uncertainty

The combustion efficiency factor used is believed to under estimate the efficiency of wood combustion processes in the United States. The IPCC emission factor has been used because better data are not yet available. Increasing the combustion efficiency would increase emission estimates. In addition, according to EIA (1994) commercial wood energy use is typically not reported because there are no accurate data sources to provide reliable estimates. Emission estimates from ethanol production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

3. Industrial Processes

Greenhouse gas emissions are produced as a by-product of various non-energy-related industrial activities. That is, these emissions are produced from an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), or nitrous oxide (N_2O). The processes addressed in this chapter include cement production, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and use, CO_2 consumption, iron and steel production, ammonia manufacture, ferroalloy production, aluminum production, petrochemical production, silicon carbide production, adipic acid production, and nitric acid production (see Figure 3-1).[1]

Figure 3-1



1998 Industrial Processes Chapter GHG Sources

In addition to the three greenhouse gases listed above, there are also industrial sources of several classes of man-made fluorinated compounds called hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The present contribution of these gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, they will continue to accumulate in the atmosphere as long as emissions continue. Sulfur hexafluoride, itself, is the most potent greenhouse gas the IPCC has ever evaluated. Usage of these gases, especially HFCs,

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[1] Carbon dioxide emissions from iron and steel production, ammonia manufacture, ferroalloy production, and aluminum production are accounted for in the Energy chapter under Fossil Fuel Combustion of industrial coking coal, natural gas, and petroleum coke.

Table 3-1: Emissions from Industrial Processes (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**14.8**	**14.5**	**14.6**	**15.0**	**16.0**	**16.8**	**17.2**	**18.0**	**18.4**
Cement Manufacture	9.1	8.9	8.9	9.4	9.8	10.0	10.1	10.5	10.7
Lime Manufacture	3.0	3.0	3.1	3.1	3.2	3.4	3.6	3.7	3.7
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.9	2.0	2.3	2.4
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2
Carbon Dioxide Consumption	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4
Iron and Steel Production*	23.9	19.2	20.7	21.0	21.6	22.2	21.6	21.6	21.9
Ammonia Manufacture*	6.3	6.4	6.7	6.4	6.6	6.5	6.7	6.6	7.3
Ferroalloy Production*	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5
Aluminum Production*	1.6	1.7	1.6	1.5	1.3	1.4	1.4	1.4	1.5
CH_4	**0.3**	**0.3**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Petrochemical Production	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Silicon Carbide Production	+	+	+	+	+	+	+	+	+
N_2O	**9.9**	**10.1**	**9.8**	**10.2**	**10.9**	**11.0**	**11.3**	**10.5**	**7.7**
Adipic Acid Production	5.0	5.2	4.8	5.2	5.5	5.5	5.7	4.7	2.0
Nitric Acid Production	4.9	4.9	5.0	5.1	5.3	5.4	5.6	5.8	5.8
HFCs, PFCs, and SF_6	**23.3**	**22.0**	**23.5**	**23.8**	**25.1**	**29.0**	**33.5**	**35.3**	**40.3**
Substitution of Ozone Depleting Substances	0.3	0.2	0.4	1.4	2.7	7.0	9.9	12.3	14.5
Aluminum Production	5.4	4.7	4.4	3.8	3.2	3.1	3.2	3.0	2.8
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2	10.9
Semiconductor Manufacture	0.8	0.8	0.8	1.0	1.1	1.5	1.9	1.9	2.1
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	3.0	3.0	3.0
Total	**48.3**	**46.9**	**48.3**	**49.5**	**52.3**	**57.2**	**62.5**	**64.2**	**66.9**

+ Does not exceed 0.05 MMTCE

* Emissions from these sources are accounted for in the Energy chapter and are not included in the Industrial Processes totals.

Note: Totals may not sum due to independent rounding.

is growing rapidly as they are the primary substitutes for ozone depleting substances (ODSs), which are being phased-out under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. In addition to ODS substitutes, HFCs, PFCs, and other fluorinated compounds are employed and emitted by a number of other industrial sources in the United States. These industries include aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing.

In 1998, industrial processes generated emissions of 67.0 MMTCE, or 3.7 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 18.4 MMTCE (67,447 Gg) in the same year. This amount accounted for only 1 percent of national CO_2 emissions. Methane emissions from petrochemical and silicon carbide production resulted in emissions of approximately 0.4 MMTCE (78 Gg) in 1998, which was less than 1 percent of U.S. CH_4 emissions. Nitrous oxide emissions from adipic acid and nitric acid production were 7.7 MMTCE (91 Gg) in 1998, or 6 percent of total U.S. N_2O emissions. In the same year, combined emissions of HFCs, PFCs and SF_6 totaled 40.5 MMTCE. Overall, emissions from industrial processes increased by 39 percent from 1990 to 1998, due mainly to growth in the use of HFCs.

Emission estimates are presented in this chapter for several industrial processes that are actually ac-

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[2] See Annex P for a discussion of emission sources excluded.

Table 3-2: Emissions from Industrial Processes (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**54,427**	**53,197**	**53,512**	**55,137**	**58,432**	**61,735**	**63,170**	**66,021**	**67,447**
Cement Manufacture	33,278	32,535	32,792	34,624	36,087	36,847	37,079	38,323	39,227
Lime Manufacture	11,092	10,891	11,245	11,496	11,895	12,624	13,179	13,434	13,627
Limestone and Dolomite Use	5,113	4,896	4,502	4,058	5,541	6,987	7,499	8,537	8,854
Soda Ash Manufacture and Consumption	4,144	4,035	4,091	4,048	4,012	4,309	4,273	4,434	4,325
Carbon Dioxide Consumption	800	840	882	912	898	968	1,140	1,294	1,413
Iron and Steel Production[a]	87,600	70,560	75,840	77,120	79,040	81,440	79,040	79,360	80,160
Ammonia Manufacture[a]	23,138	23,364	24,391	23,399	24,316	23,682	24,390	24,346	26,880
Ferroalloy Production[a]	1,809	1,580	1,579	1,516	1,607	1,625	1,695	1,789	1,790
Aluminum Production[a]	5,951	6,058	5,942	5,432	4,850	4,961	5,258	5,296	5,458
CH_4	**57**	**58**	**61**	**67**	**71**	**72**	**76**	**77**	**78**
Petrochemical Production	56	57	60	66	70	72	75	77	77
Silicon Carbide Production	1	1	1	1	1	1	1	1	1
N_2O	**117**	**119**	**116**	**121**	**129**	**130**	**134**	**124**	**91**
Adipic Acid Production	59	62	57	61	65	66	67	55	23
Nitric Acid Production	58	58	59	60	63	64	67	68	68
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M	M
HCFC-22 Production[b]	3	3	3	3	3	2	3	3	3
Semiconductor Manufacture	M	M	M	M	M	M	M	M	M
Electrical Transmission and Distribution[c]	1	1	1	1	1	1	1	1	1
Magnesium Production and Processing[c]	+	+	+	+	+	+	+	+	+

\+ Does not exceed 50 Gg
M (Mixture of gases)
[a] Emissions from these sources are accounted for in the Energy chapter and are not included in the Industrial Processes totals.
[b] HFC-23 emitted
[c] SF_6 emitted
Note: Totals may not sum due to independent rounding.

counted for within the Energy chapter. Although CO_2 emissions from iron and steel production, ammonia manufacture, ferroalloy production, and aluminum production are not the result of the combustion of fossil fuels for energy, their associated emissions are captured in the fuel data for industrial coking coal, natural gas, industrial coking coal, and petroleum coke, respectively. Consequently, if all emissions were attributed to their appropriate chapter, then emissions from energy would decrease by roughly 31 MMTCE in 1998, and industrial process emissions would increase by the same amount.

Greenhouse gases are also emitted from a number of industrial processes not addressed in this chapter. For example, caprolactam—a chemical feedstock for the manufacture of nylon 6,6—and urea production are believed to be industrial sources of N_2O emissions. However, emissions for these and other sources have not been estimated at this time due to a lack of information on the emission processes, manufacturing data, or both. As more information becomes available, emission estimates for these processes will be calculated and included in future greenhouse gas emission inventories, although their contribution is expected to be small.[2]

The general method employed to estimate emissions for industrial processes, as recommended by the Intergovernmental Panel on Climate Change (IPCC), generally involved multiplying production data for each process by an emission factor per unit of production. The emission factors used were either derived using calculations that assume precise and efficient chemical reactions or were based upon empirical data in published references. As a result, uncertainties in the emission coefficients can be attributed to, among other things, inefficiencies in the chemical reactions associated with each production process or to the use of empirically derived emission factors that are biased and, therefore, may not represent U.S. national averages. Additional sources of uncertainty specific to an individual source category are discussed in each section.

Table 3-1 summarizes emissions for the Industrial Processes chapter in units of million metric tons of carbon equivalents (MMTCE), while unweighted gas emissions in Gigagrams (Gg) are provided in Table 3-2.

Cement Manufacture

Cement manufacture is an energy and raw material intensive process resulting in the generation of carbon dioxide (CO_2) from both the energy consumed in making the cement and the chemical process itself.[3] Cement production accounts for about 2.4 percent of total global industrial and energy-related CO_2 emissions (IPCC 1996), and the United States is the world's third largest cement producer. Cement is manufactured in almost every state and is used in all of them. Carbon dioxide, emitted from the chemical process of cement production, represents one of the largest sources of industrial CO_2 emissions in the United States.

During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature of about 1,300°C (2,400°F) to form lime (i.e., calcium oxide or CaO) and CO_2. This process is known as calcination or calcining. Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the earlier by-product CO_2 being released to the atmosphere. The clinker is then allowed to cool, mixed with a small amount of gypsum, and used to make Portland cement. The production of masonry cement from Portland cement requires additional lime and, thus, results in additional CO_2 emissions. However, this additional lime is already accounted for in the Lime Manufacture source category in this chapter; therefore, the additional emissions from making masonry cement from clinker are not counted in this source's total. They are presented here for informational purposes only.

In 1998, U.S. clinker production—including Puerto Rico—totaled 75,859 thousand metric tons, and U.S. masonry cement production reached 3,910 thousand metric tons (USGS 1999). The resulting emissions of CO_2 from clinker production were estimated to be 10.7 MMTCE (39,227 Gg) (see Table 3-3). Emissions from masonry production from clinker raw material were estimated to be 0.02 MMTCE (88 Gg) in 1998, but again are accounted for under Lime Manufacture.

After falling in 1991 by 2 percent from 1990 levels, cement production emissions have grown every year since. Overall, from 1990 to 1998, emissions increased by 18 percent. In 1998, output by cement plants increased 2 percent over 1997, to 75,859 thousand metric tons. Cement is a critical component of the construction industry; therefore, the availability of public construction funding, as well as overall economic growth, will have considerable influence on cement production in the future. In the near term, a strong domestic economy is a key factor in maintaining high demand for construction materials and, hence, growth in the cement industry and associated CO_2 emissions.

Table 3-3: CO_2 Emissions from Cement Production*

Year	MMTCE	Gg
1990	9.1	33,278
1991	8.9	32,535
1992	8.9	32,792
1993	9.4	34,624
1994	9.8	36,087
1995	10.0	36,847
1996	10.1	37,079
1997	10.5	38,323
1998	10.7	39,227

* Totals exclude CO_2 emissions from making masonry cement from clinker, which are accounted for under Lime Manufacture.

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[3] The CO_2 emissions related to the consumption of energy for cement manufacture are accounted for under CO_2 from Fossil Fuel Combustion in the Energy chapter.

Methodology

Carbon dioxide emissions from cement manufacture are created by the chemical reaction of carbon-containing minerals (i.e., calcining limestone). While in the kiln, limestone is broken down into CO_2 and lime with the CO_2 released to the atmosphere. The quantity of the CO_2 emitted during cement production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ (i.e., limestone) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

Carbon dioxide emissions were estimated by applying an emission factor, in tons of CO_2 released per ton of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis is the product of the average lime fraction for clinker of 64.6 percent (IPCC/UNEP/OECD/IEA 1997) and a constant reflecting the mass of CO_2 released per unit of lime. This yields an emission factor of 0.507 tons of CO_2 per ton of clinker produced. The emission factor was calculated as follows:

$$EF_{\text{Clinker}} = 0.646\ \text{CaO} \times \left[\frac{44.01\ \text{g/mole}\ CO_2}{56.08\ \text{g/mole CaO}}\right] = 0.507\ \text{tons}\ CO_2/\text{ton clinker}$$

During clinker production, some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker emission factor. The IPCC recommends that these additional CKD CO_2 emissions should be estimated as 2 percent of the CO_2 emissions calculated from clinker production. Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC/OECD/IEA 1999).

Masonry cement requires additional lime over and above the lime used in clinker production. In particular, non-plasticizer additives such as lime, slag, and shale are added to the cement, increasing its weight by approximately 5 percent. Lime accounts for approximately 60 percent of this added weight. Thus, the additional lime is equivalent to roughly 2.86 percent of the starting amount of the product, since:

$$0.6 \times 0.05/(1 + 0.05) = 2.86\%$$

An emission factor for this added lime can then be calculated by multiplying this percentage (2.86 percent) by the molecular weight ratio of CO_2 to CaO (0.785) to yield 0.0224 metric tons of additional CO_2 emitted for every metric ton of masonry cement produced.

As previously mentioned, the CO_2 emissions from the additional lime added during masonry cement production are accounted for in the section on CO_2 emissions from Lime Manufacture. Thus, these emissions were estimated in this chapter for informational purposes only, and are not included in the cement emission totals.

Data Sources

The activity data for clinker and masonry cement production (see Table 3-4) were obtained from U.S. Geological Survey (USGS 1992, 1995, 1996, 1997, 1998, 1999). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants. The 1998 value for masonry cement production was furnished by Hendrick van Oss, USGS.

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker, in the amount of lime added to masonry cement, and in the percentage of CKD recycled inside the clinker kiln. The lime content of clinker varies from 64 to 66 percent. CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some

Table 3-4: Cement Production (Thousand Metric Tons)

Year	Clinker	Masonry
1990	64,355	3,209
1991	62,918	2,856
1992	63,415	3,093
1993	66,957	2,975
1994	69,786	3,283
1995	71,257	3,603
1996	71,706	3,469
1997	74,112	3,634
1998	75,859	3,910

amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated.

Lime Manufacture

Lime, or calcium oxide (CaO),[4] is an important manufactured product with many industrial, chemical, and environmental applications. Its major uses are in steel making, flue gas desulfurization (FGD) at coal-fired electric power plants, construction, pulp and paper manufacturing, and water purification. Lime has historically ranked fifth in total production of all chemicals in the United States.

Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce CaO and CO_2. The CO_2 is driven off as a gas and is normally emitted to the atmosphere. Some of the CO_2 generated during the production process, however, is recovered at some facilities for use in sugar refining and precipitated calcium carbonate (PCC)[5] production. It is also important to note that for certain applications, lime reabsorbs CO_2 during use (see Uncertainty, below).

Lime production in the United States—including Puerto Rico—was reported to be 20,100 thousand metric tons in 1998 (USGS 1999). This resulted in CO_2 emissions of 3.7 MMTCE (13,627 Gg) (see Table 3-5 and Table 3-6).

At the turn of the century, over 80 percent of lime consumed in the United States went for construction uses. However, the contemporary lime market is distributed across its four end-use categories as follows: metallurgical uses, 39 percent; environmental uses, 26 percent; chemical and industrial uses, 24 percent, and construction uses, 9 percent. Domestic lime manufacture has increased every year since 1991, when it declined by 1 percent from 1990 levels. Production in 1998 increased 2 percent over the previous year to about 20,100 thousand metric tons. Overall, from 1990 to 1998, lime production, and hence process CO_2 emissions, increased by 23 percent. The increase in production is attributed in part to growth in demand for environmental applications, especially flue gas desulfurization technologies. In 1993, the U.S. Environmental Protection Agency (EPA) completed regulations under the Clean Air Act capping sul-

Table 3-5: Net CO_2 Emissions from Lime Manufacture

Year	MMTCE
1990	3.0
1991	3.0
1992	3.1
1993	3.1
1994	3.2
1995	3.4
1996	3.6
1997	3.7
1998	3.7

Table 3-6: CO_2 Emissions from Lime Manufacture (Gg)

Year	Potential	Recovered*	Net Emissions
1990	11,574	(483)	11,092
1991	11,454	(563)	10,891
1992	11,843	(598)	11,245
1993	12,261	(765)	11,496
1994	12,699	(804)	11,895
1995	13,502	(878)	12,624
1996	14,013	(834)	13,179
1997	14,378	(944)	13,434
1998	14,670	(1,043)	13,627

* For sugar refining and precipitated calcium carbonate production
Note: Totals may not sum due to independent rounding.

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[4] Lime also exists in a dolomitic form (CaO·MgO).

[5] Precipitated calcium carbonate is a specialty filler used in premium-quality coated and uncoated papers.

fur dioxide (SO_2) emissions from electric utilities. Lime scrubbers' high efficiencies and increasing affordability have allowed the FGD end-use to expand from 12 percent of total lime consumption in 1994 to 15 percent in 1998 (USGS 1999).

Methodology

During the calcination stage of lime manufacture, CO_2 is driven off as a gas and normally exits the system with the stack gas. Carbon dioxide emissions were estimated by applying a CO_2 emission factor to the total amount of lime produced. The emission factor used in this analysis is the product of a constant reflecting the mass of CO_2 released per unit of lime and the average calcium plus magnesium oxide (CaO + MgO) content for lime. This yields an emission factor of 0.73 tons of CO_2 per ton of lime produced. The emission factor was calculated as follows:

$$[(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole CaO})] \times (0.93 \text{ CaO/lime}) = 0.73 \text{ g } CO_2\text{/g lime}$$

Lime production in the United States was 20,100 thousand metric tons in 1998 (USGS 1999), resulting in potential CO_2 emissions of 14,670 Gg. Some of the CO_2 generated during the production process, however, was recovered for use in sugar refining and precipitated calcium carbonate (PCC) production. Combined lime manufacture by these producers was 1,785 thousand metric tons in 1998, generating 1.0 Gg of CO_2. It was assumed that approximately 80 percent of the CO_2 involved in sugar refining and PCC was recovered.

Table 3-7: Lime Production and Lime Use for Sugar Refining and PCC (Thousand Metric Tons)

Year	Production	Use
1990	15,859	826
1991	15,694	964
1992	16,227	1,023
1993	16,800	1,310
1994	17,400	1,377
1995	18,500	1,504
1996	19,200	1,428
1997	19,700	1,616
1998	20,100	1,785

Data Sources

The activity data for lime manufacture and lime consumption by sugar refining and precipitated calcium carbonate (PCC) for 1990 through 1992 (see Table 3-7) were obtained from USGS (1991, 1992); for 1993 through 1994 from Michael Miller (1995); for 1995 through 1998 from USGS (1997, 1998, 1999). The CaO purity of lime was obtained from ASTM (1996) and Schwarzkopf (1995).

Uncertainty

The term "lime" is actually a general term that includes various chemical and physical forms of this commodity. Uncertainties in the emission estimate can be attributed to slight differences in the chemical composition of these products. For example, although much care is taken to avoid contamination during the production process, lime typically contains trace amounts of impurities such as iron oxide, alumina and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants manufacture lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime manufacture will actually be reabsorbed when the lime is consumed. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate (PCC) reacts with CO_2; whereas most of the lime used in steelmaking reacts with impurities such as silica, sulfur, and aluminum compounds. A detailed accounting of lime use in the United States and further research into the associated processes are required to quantify the amount of CO_2 that is reabsorbed.[6] As more information becomes available, this emission estimate will be adjusted accordingly.

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[6] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime offsets as much as a third of the CO_2 emissions from calcination.

In some cases, lime is generated from calcium carbonate by-products at paper mills and water treatment plants.[7] The lime generated by these processes is not included in the USGS data for commercial lime consumption. In the paper industry, mills that employ the sulfate process (i.e., Kraft) consume lime in order to causticize a waste sodium carbonate solution (i.e., black liquor). Most sulfate mills recover the waste calcium carbonate after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. However, some of these mills capture the CO_2 released in this process to be used as precipitated calcium carbonate (PCC). Further research is necessary to determine to what extent CO_2 is released to the atmosphere through generation of lime by paper mills.

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Limestone and Dolomite Use

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[8] are basic raw materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass manufacture, and environmental pollution control. Limestone is widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. For some of these applications, limestone is sufficiently

Table 3-8: CO_2 Emissions from Limestone & Dolomite Use (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Flux Stone	0.8	0.7	0.6	0.5	0.8	1.1	1.2	1.4	1.5
Glass Making	+	+	0.1	0.1	0.1	0.1	0.2	0.2	0.2
FGD	0.5	0.6	0.5	0.5	0.6	0.7	0.7	0.8	0.8
Total	**1.4**	**1.3**	**1.2**	**1.1**	**1.5**	**1.9**	**2.0**	**2.3**	**2.4**

+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding.

Table 3-9: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Flux Stone	**3,002**	**2,699**	**2,314**	**1,903**	**2,950**	**3,903**	**4,249**	**5,042**	**5,327**
Limestone	2,550	2,294	1,957	1,597	2,108	2,523	3,330	3,970	4,194
Dolomite	451	406	357	306	842	1,380	919	1,072	1,132
Glass Making	**189**	**170**	**218**	**274**	**356**	**526**	**555**	**593**	**626**
Limestone	189	170	218	274	356	421	445	475	502
Dolomite	NA	NA	NA	NA	NA	105	110	118	124
FGD	**1,922**	**2,027**	**1,971**	**1,880**	**2,235**	**2,558**	**2,695**	**2,902**	**2,902**
Total	**5,113**	**4,896**	**4,502**	**4,058**	**5,541**	**6,987**	**7,499**	**8,537**	**8,854**

NA (Not Available)
Note: Totals may not sum due to independent rounding.

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[7] Some carbide producers may also regenerate lime from their calcium hydroxide by-products, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2$ + heat $\rightarrow CaO + H_2O$] and no CO_2 is released to the atmosphere.

[8] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

heated during the process to generate CO_2 as a by-product. Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, or as a raw material in glass manufacturing.

In 1998, approximately 17,268 thousand metric tons of limestone and 2,597 thousand metric tons of dolomite were used for these applications. Overall, both limestone and dolomite usage resulted in aggregate CO_2 emissions of 2.4 MMTCE (8,854 Gg) (see Table 3-8 and Table 3-9).

Emissions in 1998 increased 4 percent from the previous year. Although they decreased slightly in 1991, 1992, and 1993, CO_2 emissions from this source have since increased 73 percent from the 1990 baseline. In the future, increases in demand for crushed stone are anticipated. Demand for crushed stone from the transportation sector continues to drive growth in limestone and dolomite use. The Transportation Equity Act for the 21st Century, which commits over $200 billion dollars to highway work through 2003, promises to maintain the upward trend in consumption.

Methodology

Carbon dioxide emissions were calculated by multiplying the amount of limestone consumed by an average carbon content for limestone, approximately 12.0 percent for limestone and 13.2 percent for dolomite (based on stoichiometry). Assuming that all of the carbon was released into the atmosphere, the appropriate emission factor was multiplied by the annual level of consumption for flux stone, glass manufacturing, and FGD systems to determine emissions.

Data Sources

Consumption data for 1990 through 1998 of limestone and dolomite used as flux stone and in glass manufacturing (see Table 3-10) were obtained from the USGS (1991, 1993, 1996, 1997, 1998, 1999). Consumption data for limestone used in FGD were taken from unpublished survey data in the Energy Information Administration's Form EIA-767, "Steam Electric Plant Operation and Design Report," (EIA 1997, 1998). For 1990 and 1994, the USGS did not provide a breakdown of limestone and dolomite production by end-use and for 1998 the end-use breakdowns had not yet been finalized at the time of publication. Consumption figures for these years were estimated by assuming that limestone and dolomite accounted for the same percentage of total crushed stone consumption for a given year as the average of the percentages for the years before and after (exception: 1990 and 1998 consumption were estimated using the percentages for only 1991 and 1997, respectively). Furthermore, starting in 1996, USGS discontinued reporting glass manufacture separately. From 1996 onward, limestone used in glass manufacture is estimated based on its percent of total crushed stone for 1995.

Table 3-10: Limestone & Dolomite Consumption (Thousand Metric Tons)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Flux Stone									
Limestone	5,797	5,213	4,447	3,631	4,792	5,734	7,569	9,024	9,533
Dolomite	932	838	738	632	1,739	2,852	1,899	2,215	2,340
Glass Making									
Limestone	430	386	495	622	809	958	1,011	1,079	1,140
Dolomite	NA	NA	NA	NA	NA	216	228	243	257
FGD	4,369	4,606	4,479	4,274	5,080	5,815	6,125	6,595	6,595

NA (Not Available)

It should be noted that there is a large quantity of crushed stone reported to the USGS under the category "unspecified uses". A portion of this consumption is believed to be limestone or dolomite used as flux stone and for glass manufacture. The quantity listed for "unspecified uses" was, therefore, allocated to each reported end-use according to each end-uses fraction of total consumption in that year.[9]

Uncertainty

Uncertainties in this estimate are due in part, to variations in the chemical composition of limestone. In addition to calcite, limestone may contain smaller amounts of magnesia, silica, and sulfur. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process, the kind of ore processed, and the final use of the slag. Similarly, the quality of the limestone used for glass manufacturing will depend on the type of glass being manufactured. Uncertainties also exist in the activity data. Much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. Furthermore, some of the limestone reported as "limestone" is believed to actually be dolomite, which has a higher carbon content than limestone.

Soda Ash Manufacture and Consumption

Table 3-11: CO_2 Emissions from Soda Ash Manufacture and Consumption

Year	MMTCE
1990	1.1
1991	1.1
1992	1.1
1993	1.1
1994	1.1
1995	1.2
1996	1.2
1997	1.2
1998	1.2

Table 3-12: CO_2 Emissions from Soda Ash Manufacture and Consumption (Gg)

Year	Manufacture	Consumption	Total
1990	1,435	2,709	4,144
1991	1,429	2,605	4,035
1992	1,451	2,639	4,091
1993	1,412	2,635	4,048
1994	1,422	2,590	4,012
1995	1,607	2,702	4,309
1996	1,587	2,685	4,273
1997	1,666	2,768	4,434
1998	1,607	2,718	4,325

Note: Totals may not sum due to independent rounding.

Soda ash (sodium carbonate, Na_2CO_3) is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. It is used primarily as an alkali, either in glass manufacturing or simply as a material that reacts with and neutralizes acids or acidic substances. Internationally, two types of soda ash are produced—natural and synthetic. The United States produces only natural soda ash and is the largest soda ash-producing country in the world. Trona is the principal ore from which natural soda ash is made.

Only two states produce natural soda ash: Wyoming and California. Of these two states, only Wyoming has net emissions of CO_2. This difference is a result of the production processes employed in each state.[10] During the production process used in Wyoming, natural sources of sodium carbonate are heated and transformed into a crude soda ash that requires further refining. Carbon dioxide (CO_2) is generated as a by-product of this

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[9] This approach was recommended by USGS.

[10] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a by-product, the CO_2 is recovered and recycled for use in the carbonation stage and is never actually released.

reaction, and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed.

In 1998, CO_2 emissions from the manufacture of soda ash from trona were approximately 0.4 MMTCE (1,600 Gg). Soda ash consumption in the United States also generated 0.7 MMTCE (2,700 Gg) of CO_2 in 1998. Total emissions from this source in 1998 were then 1.2 MMTCE (4,325 Gg) (see Table 3-11 and Table 3-12). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 1998 decreased by 2 percent from the previous year, but have increased 4 percent since 1990.

The United States has the world's largest deposits of trona and represents about one-third of total world soda ash output. The distribution of soda ash by end-use in 1998 was glass making, 49 percent; chemical production, 27 percent; soap and detergent manufacturing, 11 percent; distributors, 5 percent; flue gas desulfurization, 3 percent; pulp and paper production, 2 percent; and water treatment and miscellaneous combined for the remaining 3 percent (USGS 1999).

Soda ash production and consumption decreased by 3.5 and 1.8 percent from 1997 values, respectively. Exports are a driving force behind U.S. soda ash production and the Asian economic crisis beginning in late 1997 has been cited as a major cause for the drop in world soda ash demand. Moderate growth (between 1.5 and 2 percent) is expected for 1999 as the Asian economy recovers and as demand in South America continues to grow (USGS 1999).

Construction is currently underway on a major soda ash plant that will use a new feedstock—nahcolite, a natural sodium bicarbonate found in deposits in Colorado's Piceance Creek Basin. By 2001, the plant is expected to be mining more than 1.4 million tons of nahcolite per year and converting it into 1 million tons of soda ash (C&EN, 1999). Part of this process involves the stripping of CO_2. At this point, it is unknown whether any CO_2 will be released to the atmosphere or captured and used for conversion back to sodium bicarbonate.

Methodology

During the production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as by-products of the calcination process. Carbon dioxide emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$\underset{\text{[trona]}}{2(Na_3H(CO_3)_2 \times 2H_2O)} \rightarrow \underset{\text{[soda ash]}}{3Na_2CO_3} + 5H_2O + CO_2$$

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2. Thus, the 16.5 million metric tons of trona mined in 1998 for soda ash production (USGS 1999) resulted in CO_2 emissions of approximately 0.4 MMTCE (1,600 Gg).

Once manufactured, most soda ash is consumed in glass and chemical production, with minor amounts in soap and detergents, pulp and paper, flue gas desulfurization and water treatment. As soda ash is consumed for these purposes, additional CO_2 is usually emitted. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed.

Data Sources

The activity data for trona production and soda ash consumption (see Table 3-13) were taken from USGS

Table 3-13: Soda Ash Manufacture and Consumption (Thousand Metric Tons)

Year	Manufacture*	Consumption
1990	14,734	6,527
1991	14,674	6,278
1992	14,900	6,360
1993	14,500	6,350
1994	14,600	6,240
1995	16,500	6,510
1996	16,300	6,470
1997	17,100	6,670
1998	16,500	6,550

* Soda ash manufactured from trona ore only.

(1993, 1994, 1995, 1998, and 1999). Soda ash manufacture and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. All six of the soda ash manufacturing operations in the United States completed surveys to provide data to the USGS.

Uncertainty

Emissions from soda ash manufacture are considered to be relatively certain. Both the emissions factor and activity data are reliable. However, emissions from soda ash consumption are dependent upon the type of processing employed by each end-use. Specific information characterizing the emissions from each end-use is limited. Therefore, uncertainty exists as to the accuracy of the emission factors.

Carbon Dioxide Consumption

Carbon dioxide (CO_2) is used for a variety of applications, including food processing, chemical production, carbonated beverages, and enhanced oil recovery (EOR). Carbon dioxide used for EOR is injected into the ground to increase reservoir pressure, and is therefore considered sequestered.[11] For the most part, however, CO_2 used in non-EOR applications will eventually enter the atmosphere.

Carbon dioxide is produced from a small number of natural wells, as a by-product from the production of chemicals (e.g., ammonia), or separated from crude oil and natural gas. Depending on the raw materials that are used, the by-product CO_2 generated during these production processes may already be accounted for in the CO_2 emission estimates from fossil fuel consumption (either during combustion or from non-fuel uses). For example, ammonia is primarily manufactured using natural gas as a feedstock. Carbon dioxide emissions from this process are accounted for in the Energy chapter under Fossil Fuel Combustion and, therefore, are not included here.

In 1998, CO_2 emissions from this source not accounted for elsewhere were 0.4 MMTCE (1,413 Gg) (see Table 3-14). This amount represents an increase of 9 percent from the previous year and is 77 percent higher than emissions in 1990.

Table 3-14: CO_2 Emissions from Carbon Dioxide Consumption

Year	MMTCE	Gg
1990	0.2	800
1991	0.2	840
1992	0.2	882
1993	0.2	912
1994	0.2	898
1995	0.3	968
1996	0.3	1,140
1997	0.4	1,294
1998	0.4	1,413

Methodology

Carbon dioxide emission estimates were based on CO_2 consumption with the assumption that the end-use applications, except enhanced oil recovery, eventually release 100 percent of the CO_2 into the atmosphere. Carbon dioxide consumption for uses other than enhanced oil recovery was about 7,067 thousand metric tons in 1998. The Freedonia Group estimates that, in the United States, there is an 80 to 20 percent split between CO_2 produced as a by-product and CO_2 produced from natural wells. Thus, emissions are equal to 20 percent of CO_2 consumption. The remaining 80 percent was assumed to

Table 3-15: Carbon Dioxide Consumption

Year	Thousand Metric Tons
1990	4,000
1991	4,200
1992	4,410
1993	4,559
1994	4,488
1995	4,842
1996	5,702
1997	6,468
1998	7,067

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[11] It is unclear to what extent the CO_2 used for EOR will be re-released. For example, the CO_2 used for EOR may show up at the wellhead after a few years of injection (Hangebrauk et al. 1992). This CO_2, however, is typically recovered and re-injected into the well. More research is required to determine the amount of CO_2 that in fact escapes from EOR operations. For the purposes of this analysis, it is assumed that all of the CO_2 remains sequestered.

already be accounted for in the CO_2 emission estimates from other categories (the most important being Fossil Fuel Combustion).

Data Sources

Carbon dioxide consumption data (see Table 3-15) were obtained from *Industrial Gases to 2003,* published by the Freedonia Group Inc. (1994, 1996, 1999). The 1999 report contains actual data for 1998 only. Data for 1996 were obtained by personal communication with Paul Ita of the Freedonia Group Inc. (1997). Data for 1997 production was calculated from annualized growth rates for 1994 through 1996 while the 1997 value for enhanced oil recovery was set equal to the 1998 value. The percent of carbon dioxide produced from natural wells was obtained from Freedonia Group Inc. (1991).

Uncertainty

Uncertainty exists in the assumed allocation of carbon dioxide produced from fossil fuel by-products (80 percent) and carbon dioxide produced from wells (20 percent). In addition, it is possible that CO_2 recovery exists in particular end-use sectors. Contact with several organizations did not provide any information regarding recovery. More research is required to determine the quantity, if any, that may be recovered.

Iron and Steel Production

In addition to being an energy intensive process, the production of iron and steel also generates process-related emissions of CO_2. Iron is produced by first reducing iron oxide (ore) with metallurgical coke in a blast furnace to produce pig iron (impure iron of about 4 to 4.5 percent carbon by weight). Carbon dioxide is produced as the coke used in this process is oxidized. Steel (less than 2 percent carbon by weight) is produced from pig iron in a variety of specialized steel furnaces. The majority of CO_2 emissions come from the production of iron, with smaller amounts evolving from the removal of carbon from pig iron to produce steel.

Emissions of CO_2 from iron and steel production in 1998 were 21.9 MMTCE (80,200 Gg). Emissions fluctuated significantly from 1990 to 1998 due to changes in domestic economic conditions and changes in imports and exports. Forecasts for iron and steel production remain mixed. Despite a 5 percent increase in capital expenditures during 1998, plant capacity utilization sank below 80 percent and steel imports continued to climb.

CO_2 emissions from iron and steel production are not included in totals for the Industrial Processes chapter because they are accounted for with Fossil Fuel Combustion emissions from industrial coking coal in the Energy chapter.[12] Emissions estimates are presented here for informational purposes only (see Table 3-16). Additional CO_2 emissions also occur from the use of limestone or dolomite flux during production; however, these emissions are accounted for under Limestone and Dolomite Use.

Methodology

Carbon dioxide emissions were calculated by multiplying annual estimates of pig iron production by the ratio of CO_2 emitted per unit of iron produced (1.6 metric ton CO_2/metric ton iron). The emission factor employed was applied to both pig iron production and integrated pig iron plus steel production; therefore, emissions were estimated using total U.S. pig iron production for all uses including making steel.

Table 3-16: CO_2 Emissions from Iron and Steel Production

Year	MMTCE	Gg
1990	23.9	87,600
1991	19.2	70,560
1992	20.7	75,840
1993	21.0	77,120
1994	21.6	79,040
1995	22.2	81,440
1996	21.6	79,040
1997	21.6	79,360
1998	21.9	80,160

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[12] Although the CO_2 emissions from the use of industrial coking coal as a reducing agent should be included in the Industrial Processes chapter, information to distinguish individual non-energy uses of fossil fuels is unfortunately not available in DOE/EIA fuel statistics.

Table 3-17: Pig Iron Production

Year	Thousand Metric Tons
1990	54,750
1991	44,100
1992	47,400
1993	48,200
1994	49,400
1995	50,900
1996	49,400
1997	49,600
1998	50,100

Data Sources

The emission factor was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Production data for 1990 through 1997 (see Table 3-17) were obtained from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Volume I-Metals and Minerals* (USGS 1996, 1997, 1998); data for 1998 were obtained from USGS's *Mineral Commodity Summaries* (1999).

Uncertainty

The emission factor employed was assumed to be applicable to both pig iron production and integrated pig iron plus steel production. This assumption was made because the uncertainty in the factor is greater than the additional emissions generated when steel is produced from pig iron. Using plant-specific emission factors could yield a more accurate estimate, but these factors were not available. The most accurate alternative would be to calculate emissions based on the amount of reducing agent used, rather than on the amount of iron or steel produced; however, these data were also not available.

Ammonia Manufacture

Emissions of CO_2 occur during the production of ammonia. In the United States, roughly 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas, and the remainder is produced using naphtha (a petroleum fraction) or the electrolysis of brine at chlorine plants (EPA 1997). The former two fossil fuel-based reactions produce carbon monoxide and hydrogen gas; however, the latter reaction does not lead to CO_2 emissions. Carbon monoxide (CO) in the first two processes is transformed into CO_2 in the presence of a catalyst (usually a metallic oxide). The hydrogen gas is diverted and combined with nitrogen gas to produce ammonia. The CO_2, included in a gas stream with other process impurities, is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released.

$$\overset{\text{(catalyst)}}{CH_4 + H_2O \rightarrow 4H_2 + CO_2}$$
$$3H_2 + N_2 \rightarrow 2NH_3$$

Emissions of CO_2 from ammonia production in 1998 were 7.3 MMTCE (26,900 Gg). Carbon dioxide emissions from this source are not included in totals for the Industrial Processes chapter because these emissions are accounted for with non-energy use of natural gas under Fossil Fuel Combustion in the Energy chapter.[13] Emissions estimates are presented here for informational purposes only (see Table 3-18).

Table 3-18: CO_2 Emissions from Ammonia Manufacture

Year	MMTCE	Gg
1990	6.3	23,138
1991	6.4	23,364
1992	6.7	24,391
1993	6.4	23,399
1994	6.6	24,316
1995	6.5	23,682
1996	6.7	24,390
1997	6.6	24,346
1998	7.3	26,880

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[13] Although the CO_2 emissions from the use of natural gas as a feedstock should be included in the Industrial Processes chapter, information to distinguish individual non-energy uses of fossil fuels is unfortunately not available in DOE/EIA fuel statistics.

Methodology

Emissions of CO_2 were calculated by multiplying annual estimates of ammonia production by an emission factor (1.5 ton CO_2/ton ammonia). It was assumed that all ammonia was produced using catalytic steam reformation, although small amounts may have been produced using chlorine brines. The actual amount produced using this latter method is not known, but assumed to be small.

Data Sources

The emission factor was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Ammonia production data (see Table 3-19) were obtained from the Census Bureau of the U.S. Department of Commerce (Census Bureau 1998, 1999) as reported in *Chemical and Engineering News*, "Facts & Figures for the Chemical Industry."

Uncertainty

It is uncertain how accurately the emission factor used represents an average across all ammonia plants. By using natural gas consumption data for each ammonia plant, more accurate estimates could be calculated. However, these consumption data are often considered confidential and are difficult to acquire. All ammonia production in this analysis was assumed to be from the same process; however, actual emissions could differ because processes other than catalytic steam reformation may have been used.

Table 3-19: Ammonia Manufacture

Year	Thousand Metric Tons
1990	15,425
1991	15,576
1992	16,261
1993	15,599
1994	16,211
1995	15,788
1996	16,260
1997	16,231
1998	17,920

Ferroalloy Production

Carbon dioxide is emitted from the production of several ferroalloys. Ferroalloys are composites of iron and other elements often including silicon, manganese, and chromium. When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel. Estimates from two types of ferrosilicon (50 and 75 percent silicon) and silicon metal (about 98 percent silicon) have been calculated. Emissions from the production of ferrochromium and ferromanganese are not included here because of the small number of manufacturers of these materials. As a result, government information disclosure rules prevent the publication of production data for them. Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing environment, CO is initially produced. The CO is eventually oxidized, becoming CO_2. A representative reaction equation for the production of 50 percent ferrosilicon is given below:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

Emissions of CO_2 from ferroalloy production in 1998 were 0.5 MMTCE (1,800 Gg). Carbon dioxide emissions from this source are not included in the totals for the Industrial Processes chapter because these emissions are accounted for in the calculations for industrial coking coal under Fossil Fuel Combustion in the Energy chapter.[14] Emission estimates are presented here for informational purposes only (see Table 3-20).

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[14] Although the CO_2 emissions from the use of industrial coking coal as a reducing agent should be included in the Industrial Processes chapter, information to distinguish individual non-energy uses of fossil fuels is unfortunately not available in DOE/EIA fuel statistics.

Table 3-20: CO_2 Emissions from Ferroalloy Production

Year	MMTCE	Gg
1990	0.5	1,809
1991	0.4	1,580
1992	0.4	1,579
1993	0.4	1,516
1994	0.4	1,607
1995	0.4	1,625
1996	0.5	1,695
1997	0.5	1,789
1998	0.5	1,790

Methodology

Emissions of CO_2 were calculated by multiplying annual estimates of ferroalloy production by material-specific emission factors. Emission factors were applied to production data for ferrosilicon 50 and 75 percent (2.35 and 3.9 metric ton CO_2/metric ton, respectively) and silicon metal (4.3 metric ton CO_2/metric ton). It was assumed that all ferroalloy production was produced using coking coal, although some ferroalloys may have been produced with wood, other biomass, or graphite carbon inputs.

Data Sources

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Ferroalloy production data for 1990 through 1997 (see Table 3-21) were obtained from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Volume I—Metals and Minerals* (USGS, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998); data for 1998 were obtained from USGS (1999) *Mineral Industry Surveys: Silicon in December 1998.*

Uncertainty

Although some ferroalloys may be produced using wood or other biomass as a carbon source, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood would not be counted under this source because wood-based carbon is of biogenic origin.[15] Emissions from ferroalloys produced with graphite inputs would be counted in national totals, but may generate differing amounts of CO_2 per unit of ferroalloy produced compared to the use of coking coal. As with emissions from iron and steel production, the most accurate method for these estimates would be basing calculations on the amount of reducing agent used in the process, rather than on the amount of ferroalloys produced. These data were not available, however.

Petrochemical Production

Small amounts of methane (CH_4) are released during the production of some petrochemicals. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. Emissions are presented here from the production of five chemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol.

Carbon black is an intensely black powder made by the incomplete combustion of an aromatic petroleum feedstock. Almost all output is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. Ethylene is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE), polyvinyl chloride (PVC), ethylene dichloride, ethylene oxide, and ethylbenzene. Ethylene dichloride is one of the first

Table 3-21: Production of Ferroalloys (Metric Tons)

Year	Ferrosilicon 50%	Ferrosilicon 75%	Silicon Metal
1990	321,385	109,566	145,744
1991	230,019	101,549	149,570
1992	238,562	79,976	164,326
1993	199,275	94,437	158,000
1994	198,000	112,000	164,000
1995	181,000	128,000	163,000
1996	182,000	132,000	175,000
1997	175,000	147,000	187,000
1998	166,000	144,000	195,000

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[15] Emissions and sinks of biogenic carbon are accounted for in the Land-Use Change and Forestry chapter.

manufactured chlorinated hydrocarbons with reported production as early as 1795. In addition to being an important intermediate in the synthesis of chlorinated hydrocarbons, ethylene dichloride is used as an industrial solvent and as a fuel additive. Styrene is a common precursor for many plastics, rubber, and resins. It can be found in many construction products, such as foam insulation, vinyl flooring, and epoxy adhesives. Methanol is an alternative transportation fuel as well as a principle ingredient in windshield wiper fluid, paints, solvents, refrigerants, and disinfectants. In addition, methanol-based acetic acid is used in making PET plastics and polyester fibers. The United States produces close to one quarter of the world's supply of methanol.

Aggregate emissions of CH_4 from petrochemical production in 1998 were 0.4 MMTCE (77 Gg) (see Table 3-22). Production levels of all five chemicals increased from 1990 to 1998. Petrochemicals are currently in oversupply and production for 1999 and 2000 is expected to decrease.

Table 3-22: CH_4 Emissions from Petrochemical Production

Year	MMTCE	Gg
1990	0.3	56
1991	0.3	57
1992	0.3	60
1993	0.4	66
1994	0.4	70
1995	0.4	72
1996	0.4	75
1997	0.4	77
1998	0.4	77

Methodology

Emissions of CH_4 were calculated by multiplying annual estimates of chemical production by an emission factor. The following factors were used: 11 kg CH_4/metric ton carbon black, 1 kg CH_4/metric ton ethylene, 0.4 kg CH_4/metric ton ethylene dichloride,[16] 4 kg CH_4/metric ton styrene, and 2 kg CH_4/metric ton methanol. These emission factors were based upon measured material balances. Although the production of other chemicals may also result in methane emissions, there were not sufficient data to estimate their emissions.

Data Sources

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Annual production data (see Table 3-23) were obtained from the Chemical Manufacturers Association *Statistical Handbook* (CMA 1999).

Uncertainty

The emission factors used here were based on a limited number of studies. Using plant-specific factors instead of average factors could increase the accuracy of the emissions estimates, however, such data were not available. There may also be other significant sources of methane arising from petrochemical production activities that have not been included in these estimates.

Silicon Carbide Production

Methane is emitted from the production of silicon carbide, a material used as an industrial abrasive. To make silicon carbide (SiC), quartz (SiO_2) is reacted with car-

Table 3-23: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	1990	1991	1992	1993	1994	1995	1996	1997	1998
Carbon Black	1,306	1,225	1,365	1,452	1,492	1,524	1,560	1,588	1,610
Ethylene	16,542	18,124	18,563	18,709	20,201	21,199	22,197	23,088	23,474
Ethylene Dichloride	6,282	6,221	6,872	8,141	8,482	7,829	8,596	9,152	8,868
Styrene	3,637	3,681	4,082	4,565	5,112	5,167	5,387	5,171	5,183
Methanol	3,785	3,948	3,666	4,782	4,904	4,888	5,330	5,806	5,693

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[16] The emission factor obtained from IPCC/UNEP/OECD/IEA (1997), page 2.23 is assumed to have a misprint; the chemical identified should be dichloroethylene ($C_2H_2Cl_2$) instead of ethylene dichloride ($C_2H_4Cl_2$).

bon in the form of petroleum coke. Methane is produced during this reaction from volatile compounds in the petroleum coke. Although CO_2 is also emitted from this production process, the requisite data were unavailable for these calculations. Regardless, they are already accounted for under CO_2 from Fossil Fuel Combustion in the Energy chapter. Emissions of CH_4 from silicon carbide production in 1998 (see Table 3-24) were 1 Gg (less than 0.05 MMTCE).

Methodology

Emissions of CH_4 were calculated by multiplying annual estimates of silicon carbide production by an emission factor (11.6 kg CH_4/metric ton silicon carbide). This emission factor was derived empirically from measurements taken at Norwegian silicon carbide plants (IPCC/UNEP/OECD/IEA 1997).

Data Sources

The emission factor was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Production data for 1990 through 1998 (see Table 3-25) were obtained from the *Minerals Yearbook: Volume I-Metals and Minerals, Manufactured Abrasives* (USGS, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999).

Uncertainty

The emission factor used here was based on one study of Norwegian plants. The applicability of this factor to average U.S. practices at silicon carbide plants is uncertain. A better alternative would be to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced. These data were not available, however.

Table 3-25: Production of Silicon Carbide

Year	Metric Tons
1990	105,000
1991	78,900
1992	84,300
1993	74,900
1994	84,700
1995	75,400
1996	73,600
1997	68,200
1998	69,800

Table 3-24: CH_4 Emissions from Silicon Carbide Production

Year	MMTCE	Gg
1990	+	1
1991	+	1
1992	+	1
1993	+	1
1994	+	1
1995	+	1
1996	+	1
1997	+	1
1998	+	1

+ Does not exceed 0.05 MMTCE

Adipic Acid Production

Adipic acid production has been identified as an anthropogenic source of nitrous oxide (N_2O) emissions. Worldwide, there are few adipic acid plants. The United States is the major producer with three companies in four locations accounting for approximately one-half of world production. Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Ninety percent of all adipic acid produced in the United States is used in the production of nylon 6,6. It is also used to provide some foods with a "tangy" flavor.

Adipic acid is produced through a two-stage process during which N_2O is generated in the second stage. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone / cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce adipic acid. Nitrous oxide is generated as a by-product of the nitric acid oxidation stage and is emitted in the waste gas stream. Process emissions from the production of adipic acid will vary with the types of technologies and level of emissions controls employed by a facility. In 1990, two of the three major adipic acid producing plants implemented N_2O abatement technologies and as of 1998, all of the major adipic acid production facilities had control systems in place.[17] Only one small plant does not control for N_2O, representing approximately 3 percent of production.

Adipic acid production for 1998 was 866 thousand metric tons. Nitrous oxide emissions from this source were estimated to be 2.0 MMTCE (23 Gg) in 1998 (see Table 3-26).

In 1998, adipic acid production reached its highest level in fourteen years. This increase is chiefly due to rising demand for engineering plastics. Though production continues to increase, emissions have been significantly reduced due to the widespread installation of pollution control measures. By 1998, all of the three major producing plants had voluntarily implemented N_2O abatement technology, which resulted in an overall reduction of emissions by approximately 60 percent.

Methodology

Nitrous oxide emissions were calculated by multiplying adipic acid production by the ratio of N_2O emitted per unit of adipic acid produced and adjusting for the actual percentage of N_2O released as a result of plant-specific emission controls. Because emissions of N_2O in the United States are not regulated, emissions have not been well characterized. However, on the basis of experiments (Thiemens and Trogler 1991), the overall reaction stoichiometry for N_2O production in the preparation of adipic acid was estimated at approximately 0.3 kg of N_2O per kilogram of product. Emissions are determined using the following equation:

$$\begin{gathered}N_2O \text{ emissions} = [\text{production of adipic acid}] \\ \times [0.3 \text{ kg } N_2O / \text{kg adipic acid}] \\ \times\ [1 - (N_2O \text{ destruction factor} \\ \times \text{ abatement system utility factor})\ ]\end{gathered}$$

The "N_2O destruction factor" represents the amount of N_2O expressed as a percentage of N_2O emissions that are destroyed by the currently installed abatement technology. The "abatement system utility factor" represents the percent of time that the abatement equipment operates. Overall in the U.S., 63 percent of production employs catalytic destruction, 34 percent uses thermal destruction, and 3 percent of production has no N_2O abatement measures. The N_2O abatement system destruction factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer 1999a, 1999b). The abatement system utility factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer 1999a, 1999b).

Data Sources

Adipic acid production data for 1990 through 1995 (see Table 3-27) were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992, 1993, 1994, 1995, 1996). For 1996 and 1997 data were projected from the

Table 3-26: N_2O Emissions from Adipic Acid Production

Year	MMTCE	Gg
1990	5.0	59
1991	5.2	62
1992	4.8	57
1993	5.2	61
1994	5.5	65
1995	5.5	66
1996	5.7	67
1997	4.7	55
1998	2.0	23

Table 3-27: Adipic Acid Production

Year	Thousand Metric Tons
1990	735
1991	771
1992	708
1993	765
1994	815
1995	816
1996	835
1997	860
1998	866

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[17] During 1997, the N_2O emission controls installed by the third plant operated for approximately a quarter of the year.

1995 manufactured total based upon suggestions from industry contacts. For 1998, production data were obtained from *Chemical Week*, Product focus: adipic acid/ adiponitrile (CW 1999). The emission factor was taken from Thiemens, M.H. and W.C. Trogler (1991). Adipic acid plant capacities for 1998 were updated using *Chemical Week*, Product focus: adipic acid/adiponitrile (CW 1999). Plant capacities for previous years were obtained from *Chemical Market Reporter* (1998).

Uncertainty

Because N_2O emissions are controlled in some adipic acid production facilities, the amount of N_2O that is actually released will depend on the level of controls in place at a specific production plant. Thus, in order to calculate accurate emission estimates, it is necessary to have production data on a plant-specific basis. In most cases, however, these data are confidential. As a result, plant-specific production figures were estimated by allocating total adipic acid production using existing plant capacities. This creates a degree of uncertainty in the adipic acid production data used to derive the emission estimates as it is necessary to assume that all plants operate at equivalent utilization levels.

The emission factor was based on experiments (Thiemens and Trogler 1991) that attempt to replicate the industrial process and, thereby, measure the reaction stoichiometry for N_2O production in the preparation of adipic acid. However, the extent to which the lab results are representative of actual industrial emission rates is not known.

Nitric Acid Production

Nitric acid (HNO_3) is an inorganic compound used primarily to make synthetic commercial fertilizers. It is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. Virtually all of the nitric acid produced in the United States is manufactured by the catalytic oxidation of ammonia (EPA 1997). During this reaction, N_2O is formed as a by-product and is released from reactor vents into the atmosphere.

Table 3-28: N_2O Emissions from Nitric Acid Production

Year	MMTCE	Gg
1990	4.9	58
1991	4.9	58
1992	5.0	59
1993	5.1	60
1994	5.3	63
1995	5.4	64
1996	5.6	67
1997	5.8	68
1998	5.8	68

Currently, the nitric acid industry controls for NO and NO_2, i.e., NO_x. As such the industry uses a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NOx, NSCR systems are also very affective at destroying N_2O. However, NSCR units are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. NSCRs were widely installed in nitric plants built between 1971 and 1977. Currently, it is estimated that approximately 20 percent of nitric acid plants use NSCR (Choe, et al. 1993). The remaining 80 percent use SCR or extended absorption, neither of which is known to reduce N_2O.

Nitric acid production was 8,504 thousand metric tons in 1998 (C&EN 1999). Nitrous oxide emissions from this source were estimated at 5.8 MMTCE (68 Gg) (see Table 3-28). Nitric acid production for 1998 decreased 1 percent from the previous year, but has increased 18 percent since 1990.

Methodology

Nitrous oxide emissions were calculated by multiplying nitric acid production by the amount of N_2O emitted per unit of nitric acid produced. An emissions factor of 8 kg N_2O / tonne HNO_3 was used and represents a combined factor comprising of 2 kg for plants using non-selective catalytic reduction (NSCR) systems and 9.5 kg for plants not equipped with NSCR (Reimer & Slaten 1992). An estimated 20 percent of HNO_3 plants in the

U.S. were equipped with NSCR (Choe, et al. 1993). In the process of destroying NO_x, NSCR systems also destroy 80 to 90 percent of the N_2O. Hence, the emission factor is equal to $(9.5 \times 0.80) + (2 \times 0.20) = 8$ kg N_2O / mt HNO_3.

Data Sources

Nitric acid production data for 1990 through 1998 (see Table 3-29) were obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 1999). The emission factor range was taken from Reimer, R.A., Parrett, R.A., and Slaten, C.S. (1992).

Uncertainty

In general, the nitric acid industry is not well categorized. A significant degree of uncertainty exists in nitric acid production figures because nitric acid plants are often part of larger production facilities, such as fertilizer or explosive manufacturing. As a result, only a small volume of nitric acid is sold on the market making production figures difficult to track. Emission factors are also difficult to determine because of the large number of plants using many different technologies. Based on expert judgment, it is estimated that the N_2O destruction factor for NSCR nitric acid facilities is associated with an uncertainty of approximately ± 10 percent.

Table 3-29: Nitric Acid Production

Year	Thousand Metric Tons
1990	7,196
1991	7,191
1992	7,381
1993	7,488
1994	7,905
1995	8,020
1996	8,351
1997	8,557
1998	8,504

Substitution of Ozone Depleting Substances

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used primarily as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[18] Ozone depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs, unlike ODSs, are not harmful

Table 3-30: Emissions of HFCs and PFCs from ODS Substitution (MMTCE)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998
HFC-23	+	+	+	+	+	+	+	+	+
HFC-125	+	+	0.2	0.4	0.2	0.4	0.5	0.6	0.8
HFC-134a	0.2	0.2	0.2	1.0	2.3	5.2	6.9	8.5	9.8
HFC-143a	+	+	+	+	0.1	0.1	0.2	0.4	0.5
HFC-236fa	+	+	+	+	+	+	+	+	0.3
C_4F_{10}	+	+	+	+	+	+	+	+	+
C_6F_{14}	+	+	+	+	+	+	+	+	+
Others*	0.1	+	+	+	0.2	1.3	2.3	2.7	3.1
Total	**0.3**	**0.2**	**0.4**	**1.4**	**2.7**	**7.0**	**9.9**	**12.3**	**14.5**

+ Does not exceed 0.05 MMTCE

* Others include HFC-152a, HFC-227ea, HFC-4310mee and PFC/PFPEs, which are a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C_6F_{14}.

Note: Totals may not sum due to independent rounding.

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[18] [42 U.S.C § 7671, CAA § 601]

Table 3-31: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998
HFC-23	+	+	+	+	+	2	5	9	15
HFC-125	+	+	236	481	295	459	637	828	1,027
HFC-134a	564	564	626	2,885	6,408	14,596	19,350	24,065	27,693
HFC-143a	+	+	+	12	63	132	234	358	506
HFC-236fa	+	+	+	+	+	+	+	18	148
C_4F_{10}	+	+	+	+	+	+	+	+	+
C_6F_{14}	+	+	+	+	+	+	+	+	+
Others*	M	M	M	M	M	M	M	M	M

M (Mixture of Gases)
+ Does not exceed 0.5 Mg
* Others include HFC-152a, HFC-227ea, HFC-4310mee and PFC/PFPEs, which are a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

to the stratospheric ozone layer, they are powerful greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 3-30 and Table 3-31.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—a component of the refrigerant blend R-500 used in chillers—and HFC-134a in refrigeration end-uses. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air conditioners and in refrigerant blends such as R-404.[19] In 1993, use of HFCs in foams and aerosols began, and in 1994 these compounds also found applications as solvents and sterilants. In 1995, ODS substitutes for halons entered widespread use in the United States as halon production was phased-out.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes increased dramatically, from small amounts in 1990, to 14.5 MMTCE in 1998. This increase was the result of efforts to phase-out CFCs and other ODSs in the United States. This trend is expected to continue for many years, and will accelerate in the early part of the next century as HCFCs, which are interim substitutes in many applications, are themselves phased out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*.

Methodology and Data Sources

The EPA used a detailed vintaging model of ODS-containing equipment and products to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs and PFCs. The name of the model refers to the fact that the model tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. This vintaging model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for more than 40 different end-uses, the model produces estimates of annual use and emissions of each compound.

The major end-use categories defined in the vintaging model to characterize ODS use in the United States were: refrigeration and air conditioning, aerosols, solvent cleaning, fire extinguishing equipment, sterilization, and foams.

The vintaging model estimates HFC and PFC use

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[19] R-404 contains HFC-125, HFC-143a, and HFC-134a.

and emissions resulting from their use as replacements for ODSs by undertaking the following steps:

Step 1: Estimate ODS Use in the United States Prior to Phase-out Regulations

The model begins by estimating CFC, halon, methyl chloroform, and carbon tetrachloride use prior to the restrictions on the production of these compounds in the United States. For modeling purposes, total ODS use was divided into more than 40 separate end-uses. The methodology used to estimate baseline ODS use varied depending on the end-use under consideration. The next section describes the methodology used for estimating baseline ODS use in the refrigeration, air conditioning, and fire extinguishing (halon) end-uses. The subsequent section details the methodology used for all other end-uses.

Step 1.1: Estimate Baseline ODS Use for Refrigeration, Air Conditioning, and Fire Extinguishing

For each equipment type, the model estimates the total stock of ODS-containing equipment during the period 1985 to 1997. The key data required to develop stock estimates for each end-use were as follows:

- Total stock of ODS-containing equipment in use in the United States in 1985
- The annual rate of growth in equipment consumption in each end-use
- The retirement function for equipment in each end-use

Historical production and consumption data were collected for each equipment type to develop estimates of total equipment stock in 1985. For some end-uses, the only data available were estimates of ODS usage. In these cases, the total 1985 stock was estimated by dividing total ODS use by the average charge of ODS in a typical piece of equipment.

Stocks of ODS-containing equipment change over time. In the vintaging model, the growth in equipment stocks in each end-use was simulated after 1985 using growth rates that define the total number of pieces of new equipment added to the stock each year. The model also uses a retirement function to calculate the length of time each piece of equipment is expected to remain in service. These retirement functions are a critical part of the vintaging model because they determine the speed at which the stock of equipment turns over and is replaced by new equipment. In this analysis, point estimates of the average lifetime of equipment in each end-use were used to develop retirement functions. These retirement functions assume 100 percent survival of equipment up to this average age and zero percent survival thereafter.

Given these data, the total equipment stock in service in a given year *t* was estimated as the equipment stock in the year (*t*-1), plus new equipment added to the stock in year *t*, minus retirements in year *t*.

Annual ODS use was then estimated for each equipment type during the period 1985 through 1998. Because control technologies can reduce particular kinds of ODS use, use estimates were broken down by type of use (e.g., use in new equipment at manufacture and use required to maintain existing equipment). Baseline estimates of ODS use were based on the following data collected for each equipment type:

ODS charge size (the number of kilograms of ODS installed in new equipment during manufacture)

ODS required to maintain existing equipment (In many end-uses, chemical must be regularly added to equipment to replace chemical emitted from the equipment. Such emissions result from normal leakage and from loss during servicing of the equipment.)

With these data, ODS usage for each refrigeration, air conditioning, and fire extinguishing end-use was calculated using the following equation:

(Total stock of existing equipment in use) × (ODS required to maintain each unit of existing equipment) + (New equipment additions) × (ODS charge size)

Step 1.2: Estimate Baseline ODS Use in Foams, Solvents, Sterilization, and Aerosol End-Uses

For end-uses other than refrigeration, air conditioning, and fire extinguishing, a simpler approach was used because these end-uses do not require partial refilling of existing equipment each year. Instead, such equipment either does not require any ODS after initial production (e.g., foams and aerosols), or requires complete re-filling or re-manufacturing of the equipment each year (e.g., solvents and sterilants). ODS use does not need to be differentiated between new and existing equipment for these end-uses. Thus, it is not necessary to track the stocks of new and existing equipment separately over time.

The approach used for these end-uses was to estimate total ODS use in 1985 based on available industry data. Future ODS use was estimated using growth rates that predict ODS consumption growth in these end-uses over time, based upon input from industry.

Step 2: Specification and Implementation of Control Technologies

Having established a baseline for ODS equipment in 1985, the vintaging model next defines controls that may be undertaken for purposes of reducing ODS use and emissions within each end-use. The following controls were implemented in the model:

- Replacement of ODS used in the manufacturing of new equipment or in the operation of existing equipment (i.e., retrofits) with alternative chemicals, such as HFCs and PFCs
- Replacement of ODS-based processes or products with alternative processes or products (e.g., the use of aqueous cleaning to replace solvent cleaning with CFC-113)
- Modification of the operation and servicing of equipment to reduce use and emission rates through the application of engineering and recycling controls

Assumptions addressing these types of controls in each end-use were used to develop “substitution scenarios” that simulate the phase-out of ODSs in the United States by end-use. These scenarios represent the EPA’s best estimates of the use of control technologies towards the phase-out ODS in the United States, and are periodically reviewed by industry experts.

In addition to the chemical substitution scenarios, the model also assumes that a portion of ODS substitutes are recycled during servicing and retirement of the equipment. Recycling is assumed to occur in the refrigeration and air conditioning and fire extinguishing end-uses.

The substitution scenarios defined for each equipment type were applied to the relevant equipment stocks. The equipment life-cycle was then simulated after the imposition of controls. Substitute chemical use and emissions—including HFCs and PFCs—were calculated for each scenario using the methods described below.

Step 3: Estimate ODS Substitute Use and Emissions (HFCs and PFCs)

ODS substitute use (i.e., HFC and PFC use) was calculated using the same routine described above for refrigeration, air conditioning, and fire extinguishing equipment. In terms of chemical usage, a key question was whether implementation of a given ODS substitute in an end-use changed the quantity of chemical required to manufacture new equipment or service existing equipment. In this analysis, it was assumed that the use of ODS alternatives in new equipment—including HFCs and PFCs—did not change the total charge of initial chemical used in the equipment in each end-use. For certain refrigeration and air conditioning end-uses, however, it was assumed that new equipment manufactured with HFCs and PFCs would have lower leak rates than older equipment. Existing ODS-containing equipment that was retrofitted with HFCs or PFCs was assumed to have a higher leak rate than new HFC/PFC equipment.

The use of HFCs and PFCs in all other end-uses was calculated by simply replacing ODS use with the chemical alternatives defined in the substitution scenarios. The use of HFCs and PFCs was not assumed to change the quantity of chemical used in new or existing equipment for these end-uses.

The vintaging model estimates HFC and PFC emissions over the lifetime of equipment in each end-use. Emissions may occur at the following points in the lifetime of the equipment:

- Emissions upon manufacture of equipment
- Annual emissions from equipment (due to normal leakage, and if applicable, servicing of equipment)
- Emissions upon retirement of equipment

The emissions that occur upon manufacture of refrigeration and air conditioning equipment were assumed to be less than 0.1 percent. Annual emissions of HFCs and PFCs from equipment—due to normal leakage and servicing—were assumed to be constant each year over the life of the equipment. The quantity of emissions at disposal is a function of the prevalence of recycling at disposal.

Emissions for open cell foam were assumed to be 100 percent in the year of manufacture. Closed cell foams were assumed to emit a portion of total HFC/PFC use upon manufacture, a portion at a constant rate over the lifetime of the foam, and the rest at disposal. There were no foam recycling technologies in use in the United States; therefore, HFCs and PFCs remaining in closed cell foam were assumed to be emitted by the end of the product lifetime.

Emissions were assumed to occur at manufacture, during normal operation, and upon retirement of fire extinguishing systems. Emissions at manufacture were assumed to be negligible and emissions upon disposal were assumed to be minimal because of the use of recovery technologies.

For solvent applications, 15 percent of the chemical used in equipment was assumed to be emitted in that year. The remainder of the used solvent was assumed to be reused or disposed without being released to the atmosphere.

For sterilization applications, all chemicals that were used in the equipment were assumed to be emitted in that year.

All HFCs and PFCs used in aerosols were assumed to be emitted in the same year. No technologies were known to exist that recycle or recover aerosols.

Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the EPA vintaging model or the methods outlined in IPCC/UNEP/OECD/IEA (1997). Though the EPA's model is more comprehensive than the IPCC methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

Aluminum Production

Aluminum is a light-weight, malleable, and corrosion resistant metal that is used in many manufactured products including aircraft, automobiles, bicycles, and kitchen utensils. The United States was the largest producer of primary aluminum, with 17 percent of the world total in 1998 (USGS 1999). The United States was also a major importer of primary aluminum. The production of primary aluminum—in addition to consuming large quantities of electricity—results in emissions of several greenhouse gases including carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Occasionally, sulfur hexafluoride (SF_6) is also used by the aluminum industry as a fluxing and degassing agent in experimental and specialized casting operations. In these cases it is normally mixed with argon, nitrogen, and/or chlorine and blown through molten aluminum; however, this practice is not used by primary aluminum production firms in the United States and is not believed to be extensively used by secondary casting firms. Where it does occur, the concentration of SF_6 in the mixture is small and a portion of the SF_6 is decomposed in the process (Waite and Bernard 1990, Corns 1990). It has been estimated that 230 Mg of SF_6 were used by the

Table 3-32: CO_2 Emissions from Aluminum Production

Year	MMTCE	Gg
1990	1.6	5,951
1991	1.7	6,058
1992	1.6	5,942
1993	1.5	5,432
1994	1.3	4,850
1995	1.4	4,961
1996	1.4	5,258
1997	1.4	5,296
1998	1.5	5,458

Table 3-33: PFC Emissions from Aluminum Production (MMTCE)

Year	CF_4	C_2F_6	Total
1990	4.7	0.7	5.4
1991	4.1	0.6	4.7
1992	3.9	0.6	4.4
1993	3.3	0.4	3.8
1994	2.8	0.4	3.2
1995	2.8	0.4	3.1
1996	2.8	0.4	3.2
1997	2.6	0.3	3.0
1998	2.5	0.3	2.8

Note: Totals may not sum due to independent rounding.

aluminum industry in the United States and Canada (Maiss and Brenninkmeijer 1998); however, this estimate is highly uncertain. Emissions of SF_6 have not been estimated for this source.

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Heroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, some of this carbon is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated at 1.5 MMTCE (5,500 Gg) in 1998 (see Table 3-32). The CO_2 emissions from this source, however, are accounted for under the non-energy use portion of CO_2 from Fossil Fuel Combustion of petroleum coke and tar pitch in the Energy chapter. Thus, to avoid double counting, CO_2 emissions from aluminum production are not included in totals for the Industrial Processes chapter. They are provided here for informational purposes only.

In addition to CO_2 emissions, the aluminum production industry was also the largest source of PFC emissions in the United States. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, termed "anode effects." These anode effects cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given level of production depends on the frequency and duration of these anode effects. The more frequent and long-lasting the anode effects, the greater the emissions.

Primary aluminum production-related emissions of PFCs are estimated to have declined 48 percent since 1990 to 2.5 MMTCE of CF_4 (1.42 Gg) and 0.3 MMTCE of C_2F_6 (0.12 Gg) in 1998, as shown in Table 3-33 and Table 3-34. This decline was both due to reductions in domestic aluminum production and actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. The EPA supports aluminum smelters with these efforts through the Voluntary Aluminum Industrial Partnership (VAIP).

Table 3-34: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.67	0.28
1991	2.32	0.24
1992	2.18	0.23
1993	1.88	0.18
1994	1.57	0.15
1995	1.57	0.14
1996	1.60	0.14
1997	1.49	0.13
1998	1.42	0.12

U.S. primary aluminum production for 1998—totaling 3,713 thousand metric tons—increased slightly from 1997. This increase can be attributed to the reintroduction of previously idled production capacity (USGS 1999). In general, U.S. primary aluminum production is very responsive to imports, mainly from Russia and other republics of the Former Soviet Union. For example, in 1994 these countries exported 60 percent more ingots (metal cast for easy transformation) to the United States than in 1993, leading to a significant decline in domestic production. However, 1998 imports from Russia were 10 percent below their peak level in 1994 (USGS 1999).

The transportation industry remained the largest domestic consumer of aluminum, accounting for about 29 percent (USGS 1998). Leading automakers have announced new automotive designs that will expand the use of aluminum materials in the near future. The U.S. Geological Survey believes that demand for and production of aluminum will continue to increase.

Methodology

Carbon dioxide is generated during alumina reduction to aluminum metal following the reaction below:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

The CO_2 emission factor employed was estimated from the production of primary aluminum metal and the carbon consumed by the process. During alumina reduction, approximately 1.5 to 2.2 metric tons of CO_2 are emitted for each metric ton of aluminum produced (Abrahamson 1992). Based upon the mass balance for a "typical" aluminum smelter (Drexel University Project Team 1996), the emission factor was set at 1.5 metric tons CO_2 per metric ton of aluminum smelted. This value is at the low end of the Abrahamson (1992) range.

The CO_2 emissions from this source are already accounted for under CO_2 Emissions from Fossil Fuel Combustion in the Energy chapter.[20] Thus, to avoid double counting, CO_2 emissions from aluminum production are not included in totals for the Industrial Processes chapter.

PFC emissions from aluminum production were estimated using a per unit production emission factor that is expressed as a function of operating parameters (anode effect frequency and duration), as follows:

PFC (CF_4 or C_2F_6) kg/ton Al = S × Anode Effect Minutes/Cell-Day

where:

S = Slope coefficient

Anode Effect Minutes/Cell-Day = Anode Effect Frequency × Anode Effect Duration

The slope coefficient was established for each smelter based on actual field measurements, where available, or default coefficients by technology-type based on field measurements. Once established, the slope coefficient was used along with smelter anode effect data, collected by aluminum companies and reported to the VAIP, to estimate emissions factors over time. Emissions factors were multiplied by annual production to estimate annual emissions at the smelter level. Emissions were then aggregated across smelters to estimate national emissions. The methodology used to estimate emissions is consistent with the methodologies recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

Data Sources

Table 3-35: Production of Primary Aluminum

Year	Thousand Metric Tons
1990	4,048
1991	4,121
1992	4,042
1993	3,695
1994	3,299
1995	3,375
1996	3,577
1997	3,603
1998	3,713

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[20] Although the carbon contained in the anode is considered a non-energy use of petroleum coke or tar pitch and the CO_2 emissions it generates should be included in the Industrial Processes chapter, information to distinguish individual non-energy uses of fossil fuels is unfortunately not available in DOE/EIA fuel statistics.

Primary aluminum production data for 1990 through 1997 (see Table 3-35) were obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998). The data for 1998 were taken from *Mineral Industry Surveys: Aluminum in January 1999* (USGS 1999). The USGS requested data from the 13 domestic producers, all of whom responded. The CO_2 emission factor range was taken from Abrahamson (1992). The mass balance for a "typical" aluminum smelter was taken from Drexel University Project Team (1996).

PFC emission estimates were provided by the EPA's Climate Protection Division in cooperation with participants in the Voluntary Aluminum Industrial Partnership (VAIP) program.

Uncertainty

Uncertainty exists as to the most accurate CO_2 emission factor for aluminum production. Emissions vary depending on the specific technology used by each plant. However, evidence suggests that there is little variation in CO_2 emissions from plants utilizing similar technologies (IPCC/UNEP/OECD/IEA 1997). A less uncertain method would be to calculate emissions based upon the amount of carbon—in the form of petroleum coke or tar pitch—consumed by the process; however, this type of information was not available.

For PFC emission estimates, the uncertainty in the aluminum production data is relatively low (± 1 to 2 percent) compared to the uncertainty in the emissions factors (± 10 to 50 percent). Uncertainty in the emissions factors arises from the lack of comprehensive data for both the slope coefficients and anode effect data. Currently, insufficient measurement data exist to quantify a relationship between PFC emissions and anode effect minutes for all smelters. Future inventories will incorporate additional data reported by aluminum companies and ongoing research into PFC emissions from aluminum production.

Emissions of SF_6 from aluminum fluxing and degassing have not been estimated. Uncertainties exist as to the quantity of SF_6 used by the aluminum industry and its rate of destruction as it is blown through molten aluminum.

HCFC-22 Production

Trifluoromethane (HFC-23 or CHF_3) is generated as a by-product during the manufacture of chlorodifluoromethane (HCFC-22), which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Since 1990, production and use of HCFC-22 has increased significantly as it has replaced chlorofluorocarbons (CFCs) in many applications. Because HCFC-22 depletes stratospheric ozone, HCFC-22 production for non-feedstock uses is scheduled to be phased out by 2020 under the U.S. Clean Air Act.[21] Feedstock production, in contrast, is permitted to continue indefinitely.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where $x + y = 5$), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. HCl is recovered as a useful byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 is generally vented to the atmosphere as an unwanted byproduct, or may be captured for use in a limited number of applications.

Emissions of HFC-23 in 1998 were estimated to be 10.9 MMTCE (3.4 Gg), which represents a 15 percent

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[21] As construed, interpreted, and applied in the terms and conditions of the *Montreal Protocol on Substances that Deplete the Ozone Layer*. [42 U.S.C. §7671m(b), CAA §614]

Table 3-36: HFC-23 Emissions from HCFC-22 Production

Year	MMTCE	Gg
1990	9.5	3.0
1991	8.4	2.6
1992	9.5	3.0
1993	8.7	2.7
1994	8.6	2.7
1995	7.4	2.3
1996	8.5	2.7
1997	8.2	2.6
1998	10.9	3.4

increase in emissions since 1990 (see Table 3-36). This increase is attributable to the 30 percent increase in HCFC-22 production that occurred since 1990; one third of this increase occurred between 1997 and 1998. Separately, the intensity of HFC-23 emissions (the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined significantly since 1990.

In the future, production of HCFC-22 in the United States is expected to decline as non-feedstock HCFCs production is phased-out. In contrast, feedstock production is anticipated to continue growing steadily, mainly for manufacturing Teflon® and other chemical products. All U.S. producers of HCFC-22 are participating in a voluntary program with the EPA to reduce HFC-23 emissions.

Methodology

The EPA studied the conditions of HFC-23 generation, methods for measuring emissions, and technologies for emissions control. This effort was undertaken in cooperation with the manufacturers of HCFC-22.

The methodology employed for estimating emissions was based upon measurements of critical feed components at individual HCFC-22 production plants. Individual producers also measured HFC-23 concentrations in their output stream by gas chromatography. Using measurements of feed components and HFC-23 concentrations in output streams, the amount of HFC-23 generated was estimated. HFC-23 concentrations were determined at the point the gas leaves the chemical reactor; therefore, estimates also include fugitive emissions.

Data Sources

Emission estimates were provided by the EPA's Climate Protection Division in cooperation with the U.S. manufacturers of HCFC-22.

Uncertainty

A high level of confidence has been attributed to the HFC-23 concentration data employed because measurements were conducted frequently and accounted for day-to-day and process variability. It is estimated that the emissions reported are within 20 percent of the true value. This methodology accounted for the declining intensity of HFC-23 emissions over time. The use of a constant emission factor would not have allowed for such accounting. Earlier emission estimates assumed that HFC-23 emissions were between 2 and 4 percent of HCFC-22 production on a mass ratio basis. By 1996, the rate of HFC-23 generated as a percent of HCFC-22 produced dropped, on average, below 2 percent in the United States.

Semiconductor Manufacture

The semiconductor industry uses multiple long-lived fluorinated gases in plasma etching and chemical vapor deposition (CVD) processes. The gases most commonly employed are trifluoromethane (HFC-23), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

Plasma etching is performed to provide pathways for the electrical conducting material to connect individual circuit components in the silicon, using HFCs, PFCs, SF_6 and other gases in plasma. The etching process creates fluorine atoms that react at the semiconductor surface according to prescribed patterns to selectively remove substrate material. A single semiconductor wafer may require as many as 100 distinct process steps that utilize these gases. Chemical vapor deposition chambers, used for depositing materials that will act as insulators and wires, are cleaned periodically using PFCs and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. However, due to the low destruction efficiency (high dissociation energy) of PFCs, a portion of the gas flowing into the chamber flows unreacted through the chamber and, unless emission abatement technologies are used, this portion is emitted into the atmosphere.

In addition to being directly used in the manufacturing processes, these gases can also be transformed during the process into a different HFC or PFC compound, which is then exhausted into the atmosphere. For example, when either CHF_3 or C_2F_6 is used in cleaning or etching, CF_4 is often generated and emitted as a process by-product.

For 1998, it was estimated that total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were 2.1 MMTCE. Combined emissions of all fluorinated greenhouse gases are presented in Table 3-37 below. The rapid growth of this industry and the increasing complexity of semiconductor products could increase emissions in the future.

Methodology

Emissions were estimated using two sets of data. For 1990 through 1994, emissions were estimated based on the historical consumption of silicon (square centimeters), the estimated average number of interconnecting layers in the chips produced, and an estimated per-layer emission factor. (The number of layers per chip, and hence the PFC emissions per square centimeter of silicon, increases as the line-width of the chip decreases.) The average number of layers per chip was based on industry estimates of silicon consumption by line-width and of the number of layers per line-width. The per-layer emission factor was based on the total annual emissions reported by the participants in the EPA's PFC Emission Reduction Partnership for the Semiconductor Industry. For the three years for which gas sales data are available (1992 through 1994), the estimates derived using historical silicon consumption are within 10 percent of the estimates derived using gas sales data and average values for emission factors and GWPs.

For 1995 through 1998, emissions were estimated based on total annual emissions reported by participants in the EPA's PFC Emission Reduction Partnership for the Semiconductor Industry. As part of the program, partners estimated their emissions using a range of methods; the partners with relatively high emissions typically multiplied estimates of their PFC consumption by process-specific emission factors that they have either measured or obtained from suppliers of PFC-based manufacturing equipment. To estimate total U.S. emissions from semiconductor manufacturing based on reported partner emissions, a per-plant emissions factor was estimated for the partners. This per-plant emission factor was then applied to PFC-using plants operated by semiconductor manufacturers who were not partners, considering the varying characteristics of the plants operated by partners and non-partners (e.g., typical plant size and type of device produced). The resulting estimate of non-partner emissions was added to the emissions reported by the partners to obtain total U.S. emissions.

Table 3-37: Emissions of Fluorinated Greenhouse Gases from Semiconductor Manufacture

Year	MMTCE*
1990	0.8
1991	0.8
1992	0.8
1993	1.0
1994	1.1
1995	1.5
1996	1.9
1997	1.9
1998	2.1

* Combined radiative forcing effect of all gases.

Data Sources

Aggregate emissions estimates for the semiconductor manufacturers participating in the PFC Emission Reduction Partnership were provided by manufacturers (partners). Estimates of the numbers of plants operated by partners and non-partners, and information on the characteristics of those plants, were derived from the International Fabs on Disk database. Estimates of silicon consumed by line-width from 1990 through 1994 were derived from information from VLSI Research, and the number of layers per line-width was obtained from the Semiconductor Industry Association's 1997 National Technology Roadmap.

Uncertainty

Emission estimates for this source are improving, but are still relatively uncertain. Emissions vary depending upon the total amount of gas used and the tool and process in which the gas is used, but not all semiconductor manufacturers track this information. In addition, the relationship between the emissions from semiconductor manufacturers participating in the PFC Emission Reduction Partnership and total U.S. emissions from semiconductor manufacturing is uncertain.

Electrical Transmission and Distribution

The largest use for sulfur hexafluoride (SF_6), both domestically and internationally, is as an electrical insulator in equipment that transmits and distributes electricity. It has been estimated that 30 percent of the worldwide use of SF_6 is leaked from electrical transmission and distribution equipment (Maiss and Brenninkmeijer 1998). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. Sulfur hexafluoride has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas.

Table 3-38: SF_6 Emissions from Electrical Transmission and Distribution

Year	MMTCE	Gg
1990	5.6	0.86
1991	5.9	0.90
1992	6.2	0.95
1993	6.4	0.99
1994	6.7	1.03
1995	7.0	1.07
1996	7.0	1.07
1997	7.0	1.07
1998	7.0	1.07

Fugitive emissions of SF_6 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. It can also be released during equipment installation and when equipment is opened for servicing, which typically occurs every few years. In the past, some utilities vented SF_6 to the atmosphere during servicing; however, it is believed that increased awareness and the relatively high cost of the gas have reduced this practice.

Emissions of SF_6 from electrical transmission and distribution systems were estimated to be 7.0 MMTCE (1.07 Gg) in 1998. This quantity amounts to a 25 percent increase over the estimate for 1990 (see Table 3-38).

Methodology

The EPA developed its methodology for estimating SF_6 emissions from electrical transmission and distribution systems in 1994. The method estimates actual emissions of SF_6 using a top-down, or production-based approach. Specifically, emissions were calculated based upon the following factors: 1) the estimated U.S. production capacity for SF_6, 2) the estimated use of this production capacity, 3) the fraction of U.S. SF_6 production estimated to be sold annually to fill or refill electrical equipment, and 4) the fraction of these sales estimated to replace emitted gas.

Based on information gathered from chemical manufacturers, it was estimated that in 1994 U.S. production capacity for SF_6 was approximately 3,000 metric tons. It was assumed that plants were operating at 90 percent capacity, which was consistent with industry averages and implied that 2,700 metric tons of SF_6 were produced in 1994. It was further assumed that 75 percent of U.S. SF_6 sales were made to electric utilities and electrical transmission and distribution equipment manufacturers. This assumption is consistent with the estimate given in Ko, et al. (1993) that worldwide, 80 percent of SF_6 sales is for electrical transmission and distribution systems. Seventy-five percent of annual U.S. production in 1994 was 2,000 metric tons.

Finally, it was assumed that approximately 50 percent of this production, or 1.0 thousand metric tons, replaced gas emitted into the atmosphere in 1994. This amount is equivalent to 6.7 MMTCE (when rounding is performed at the end of the calculation). EPA's estimate was based on information that emissions rates from this equipment were significant and atmospheric measurements that indicated that most of the SF_6 produced internationally since the 1950s had been released. Emissions from electrical equipment were known to occur from the service and disposal of the equipment and leaks during operation. Leaks from older equipment were reported to release up to 50 percent of the equipment's charge per year, although leaks from newer equipment were reported to release considerably less (e.g., less than 1 percent of the charge per year).

It was assumed that emissions have remained constant at 7 MMTCE since 1995.

Data Sources

Emission estimates were provided by EPA's Climate Protection Division in cooperation with U.S. electric utilities and chemical producers.

Uncertainty

There is currently little verifiable data for estimating SF_6 emissions from electrical transmission and distribution systems. Neither U.S. gas consumption nor emission monitoring data were available when these estimates were developed. The EPA has recently launched a voluntary program with electrical power systems to reduce emissions of SF_6 from equipment used to transmit and distribute electricity such as high voltage circuit breakers, substations, transformers, and transmission lines. The EPA anticipates that better information on SF_6 emissions from electrical equipment will be provided through its voluntary agreements with electrical utilities that use SF_6 in equipment.

Magnesium Production and Processing

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a covergas to prevent the violent oxidation of molten magnesium in the presence of air. Small concentrations of SF_6 in combination with carbon dioxide and/or air are blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A minute portion of the SF_6 applied reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and some magnesium fluoride. Little conversion or destruction of SF_6 occurs in the magnesium production or casting processes, and it is currently assumed that all SF_6 is emitted to the atmosphere. SF_6 has been used in this application around the world for the last twenty years. It has largely replaced salt fluxes, sulfur dioxide (SO_2), and boron trifluoride (BF_3), which are toxic and more corrosive at higher concentrations.

For 1998, a total of 3.0 MMTCE (0.5 Gg) of SF_6 was estimated to have been emitted by the magnesium industry, 76 percent more than was estimated for 1990 (see Table 3-39). There are no significant plans for expansion of primary magnesium production in the United States, but demand for magnesium metal for die casting is growing as auto manufacturers design more magne-

Table 3-39: SF_6 Emissions from Magnesium Production and Processing

Year	MMTCE	Gg
1990	1.7	0.3
1991	2.0	0.3
1992	2.2	0.3
1993	2.5	0.4
1994	2.7	0.4
1995	3.0	0.5
1996	3.0	0.5
1997	3.0	0.5
1998	3.0	0.5

Box 3-1: Potential Emission Estimates of HFCs, PFCs, and SF_6

Emissions of HFCs, PFCs and SF_6 from industrial processes can be estimated in two ways, either as potential emissions or as actual emissions. Emission estimates in this chapter are “actual emissions,” which are defined by the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 1997) as estimates that take into account the time lag between consumption and emissions. In contrast, “potential emissions” are defined to be equal to the amount of a chemical consumed in a country, minus the amount of a chemical recovered for destruction or export in the year of consideration. Potential emissions will generally be greater for a given year than actual emissions, since some amount of chemical consumed will be stored in products or equipment and will not be emitted to the atmosphere until a later date, if ever. Because all chemicals consumed will eventually be emitted into the atmosphere, in the long term the cumulative emission estimates using the two approaches should be equivalent unless the chemical is captured and destroyed. Although actual emissions are considered to be the more accurate estimation approach for a single year, estimates of potential emissions are provided for informational purposes.

Separate estimates of potential emissions were not made for industrial processes that fall into the following categories:

€ *By-product emissions*. Some emissions do not result from the consumption or use of a chemical, but are the unintended by-products of another process. For such emissions, which include emissions of CF_4 and C_2F_6 from aluminum production and of HFC-23 from HCFC-22 production, the distinction between potential and actual emissions is not relevant.

- *Potential emissions that equal actual emissions*. For some sources, such as magnesium production and processing, it is assumed that there is no delay between consumption and emission and that no destruction of the chemical takes place. It this case, actual emissions equal potential emissions.
- *Emissions that are not easily defined*. In some processes, such as semiconductor manufacture, the gases used in the process may be destroyed or transformed into other compounds, which may also be greenhouse gases. It is therefore not logical to estimate potential emissions based on consumption of the original chemical.

Table 3-40 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances and SF_6 emissions from electrical transmission and distribution and other miscellaneous sources such as tennis shoes and sound insulating windows.[22] Potential emissions associated with the substitution for ozone depleting substances were calculated through a combination of the EPA’s Vintaging Model and information provided by U.S. chemical manufacturers. For other SF_6 sources, estimates were based on an assumed U.S. SF_6 production capacity and plant utilization to estimate total sales. The portion of this amount used for magnesium processing and assumed to be used for semiconductor manufacture were subtracted.

Table 3-40: 1998 Potential and Actual Emissions of HFCs, PFCs, and SF_6 from Selected Sources (MMTCE)

Source	Potential	Actual
Substitution of Ozone Depleting Substances	45.7	40.3
Aluminum Production	-	2.8
HCFC-22 Production	-	10.9
Semiconductor Manufacture	-	2.1
Magnesium Production and Processing	3.0	3.0
Other SF_6 Sources*	15.0	7.0

- Not applicable.

*Includes Electrical Transmission and Distribution and, in the case of potential emissions, other miscellaneous sources.

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[22] See Annex P for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

sium parts into vehicle models. The increased demand for primary magnesium is expected to be met by magnesium producers located outside the United States

Methodology

Emissions were estimated from gas usage information supplied to the EPA by primary magnesium producers. Consumption was assumed to equal emissions in the same year. Although not directly employed, the Norwegian Institute for Air Research (NIAR 1993) has reported a range of emission factors for primary magnesium production as being from 1 to 5 kg of SF_6 per metric ton of magnesium. A survey of magnesium die casters has also reported an average emission factor of 4.1 kg of SF_6 per metric ton of magnesium parts die cast (Gjestland and Magers 1996).

Data Sources

Emission estimates were provided by the EPA's Climate Protection Division in cooperation with the U.S. primary magnesium metal producers and casting firms.

Uncertainty

There are a number of uncertainties in these estimates, including the assumption that SF_6 does not react nor decompose during use. It is possible that the melt surface reactions and high temperatures associated with molten magnesium would cause some gas degradation. As is the case for other sources of SF_6 emissions, verifiable SF_6 consumption data for magnesium production and processing in United States were not available. The EPA has recently launched a voluntary partnership with magnesium producers and casters to reduce emissions of SF_6 from magnesium production and processing. The EPA anticipates that data provided by magnesium firms will improve future SF_6 emission estimates.

Sulfur hexafluoride may also be used as a covergas for the casting of molten aluminum with a high magnesium content; however, it is uncertain to what extent this practice actually occurs.

Industrial Sources of Criteria Pollutants

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of criteria air pollutants. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from non-energy industrial processes from 1990 to 1998 are reported in Table 3-41.

Methodology and Data Sources

The emission estimates for this source were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1998* (EPA 1999). Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and accurate estimates of activity data.

Table 3-41: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
NO_x	**921**	**802**	**785**	**774**	**939**	**842**	**979**	**890**	**915**
Chemical & Allied Product Manufacturing	152	149	148	141	145	144	130	131	133
Metals Processing	88	69	74	75	82	89	69	70	72
Storage and Transport	3	5	4	4	5	5	5	5	5
Other Industrial Processes	343	319	328	336	353	362	343	348	354
Miscellaneous*	335	259	231	219	354	242	433	334	351
CO	**9,502**	**7,088**	**5,401**	**5,421**	**7,708**	**5,291**	**7,899**	**7,432**	**7,669**
Chemical & Allied Product Manufacturing	1,074	1,022	1,009	992	1,063	1,109	668	676	684
Metals Processing	2,395	2,333	2,264	2,301	2,245	2,159	1,383	1,416	1,449
Storage and Transport	69	25	15	46	22	22	72	73	74
Other Industrial Processes	487	497	494	538	544	566	533	546	559
Miscellaneous*	5,479	3,210	1,619	1,544	3,833	1,435	5,242	4,721	4,903
NMVOCs	**3,179**	**2,983**	**2,811**	**2,893**	**3,043**	**2,859**	**2,859**	**3,002**	**3,066**
Chemical & Allied Product Manufacturing	575	644	649	636	627	599	332	332	336
Metals Processing	111	112	113	112	114	113	409	422	435
Storage and Transport	1,356	1,390	1,436	1,451	1,478	1,499	1,193	1,211	1,225
Other Industrial Processes	364	355	376	401	397	409	398	400	409
Miscellaneous*	774	482	238	292	428	240	525	637	662

* Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, TSDFs (Transport, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act), cooling towers, and fugitive dust. It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Agricultural Residue Burning source.

Note: Totals may not sum due to independent rounding.

4. Solvent Use

The use of solvents and other chemical products can result in emissions of various ozone precursors (i.e., criteria pollutants).[1] Nonmethane volatile organic compounds (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum based solvents, along with small amounts of carbon monoxide (CO) and oxides of nitrogen (NO_x) whose emissions are associated with control devices used to reduce NMVOC emissions. Surface coatings accounted for just under a majority of NMVOC emissions from solvent use—44 percent in 1998—while "non-industrial"[2] uses accounted for about 37 percent and degreasing applications for 8 percent. Overall, solvent use accounted for approximately 30 percent of total U.S. emissions of NMVOCs in 1998, and increased less than 1 percent since 1990.

Although NMVOCs are not considered direct greenhouse gases, their role as precursors to the formation of ozone—which is a greenhouse gas—results in their inclusion in a greenhouse gas inventory. Emissions from solvent use have been reported separately by the United States to be consistent with the inventory reporting guidelines recommended by the IPCC. These guidelines identify solvent use as one of the major source categories for which countries should report emissions. In the United States, emissions from solvents are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The evaporation process varies depending on different solvent uses and solvent types. The major categories of solvents uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (i.e., electronics, etc.), dry cleaning, and non-industrial uses (i.e., uses of paint thinner, etc.). Because many of these industrial applications also employ thermal incineration as a control technology, CO and NO_x combustion by-products are also reported with this source category.

Total emissions of nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), and carbon monoxide (CO) from 1990 to 1998 are reported in Table 4-1.

Methodology

Emissions were calculated by aggregating solvent use data based on information relating to solvent uses from different applications such as degreasing, graphic arts, etc. Emission factors for each consumption category were then applied to the data to estimate emissions. For example, emissions from surface coatings were mostly due to solvent evaporation as the coatings solidify. By applying the appropriate solvent emission factors to the type of solvents used for surface coatings, an estimate of emissions was obtained. Emissions of CO and NO_x result primarily from thermal and catalytic incineration of sol-

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[1] Solvent usage in the United States also results in the emission of small amounts of hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances in the Industrial Processes chapter.

[2] "Non-industrial" uses include cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Table 4-1: Emissions of NO_x, CO, and NMVOC from Solvent Use (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
NO_x	**1**	**2**	**2**	**2**	**2**	**3**	**3**	**3**	**2**
Degreasing	+	+	+	+	+	+	+	+	+
Graphic Arts	+	+	1	1	1	1	1	1	+
Dry Cleaning	+	+	+	+	+	+	+	+	+
Surface Coating	1	1	2	2	2	2	2	2	1
Other Industrial Processes[a]	+	+	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+	+
CO	**4**	**4**	**5**	**4**	**5**	**5**	**5**	**5**	**5**
Degreasing	+	+	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+	+	+
Dry Cleaning	+	+	+	+	1	1	1	1	1
Surface Coating	+	1	1	1	1	1	1	1	1
Other Industrial Processes[a]	4	3	3	3	3	3	3	3	3
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+	+
NMVOCs	**5,217**	**5,245**	**5,353**	**5,458**	**5,590**	**5,609**	**5,569**	**5,672**	**5,239**
Degreasing	675	651	669	683	703	716	604	623	429
Graphic Arts	249	273	280	292	302	307	300	302	304
Dry Cleaning	195	198	203	204	207	209	171	173	175
Surface Coating	2,289	2,287	2,338	2,388	2,464	2,432	2,501	2,558	2,291
Other Industrial Processes[a]	85	89	93	93	90	87	87	88	90
Non-Industrial Processes[b]	1,724	1,746	1,771	1,798	1,825	1,858	1,906	1,928	1,950

[a] Includes rubber and plastics manufacturing, and other miscellaneous applications.

[b] Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Note: Totals may not sum due to independent rounding.

\+ Does not exceed 0.5 Gg

vent laden gas streams from painting booths, printing operations, and oven exhaust.

Data Sources

The emission estimates for this source were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1998* (EPA 1999). Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of solvent purchased) as an indicator of emissions. National activity data were collected for individual applications from various agencies.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA data bases.

Uncertainty

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and the reliability of correlations between activity data and actual emissions.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter includes the following sources: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and agricultural residue burning (see Figure 5-1). Agriculture-related land-use activities, such as conversion of grassland to cultivated land, are discussed in the Land-Use Change and Forestry chapter.

In 1998, agricultural activities were responsible for emissions of 148.4 MMTCE, or 8 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent about 19 and 13 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of methane. Rice cultivation and agricultural crop residue burning were minor sources of methane. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 71 percent. Manure management and agricultural residue burning were also smaller sources of N_2O emissions.

Figure 5-1

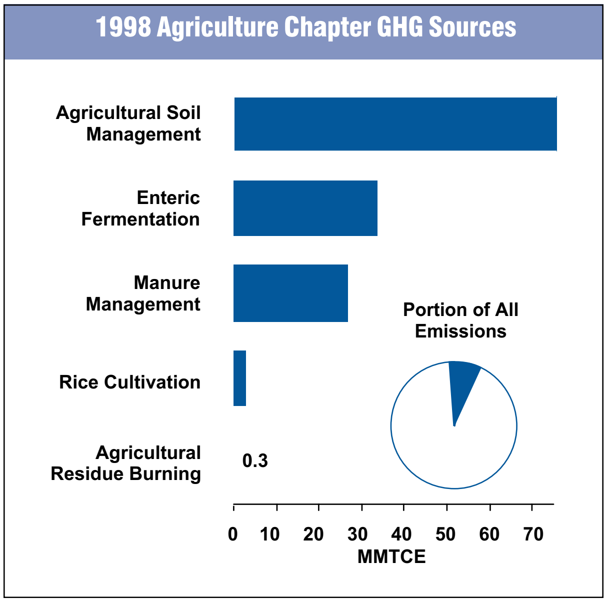

Table 5-1 and Table 5-2 present emission estimates for the Agriculture chapter. Between 1990 and 1998, CH_4 emissions from agricultural activities increased by 19 percent while N_2O emissions increased by 12 percent. In addition to CH_4 and N_2O, agricultural residue burning was also a minor source of the criteria pollutants carbon monoxide (CO) and nitrogen oxides (NO_x).

Table 5-1: Emissions from Agriculture (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**50.2**	**50.8**	**52.1**	**53.3**	**56.2**	**57.4**	**57.6**	**59.1**	**59.5**
Enteric Fermentation	32.7	32.8	33.2	33.7	34.5	34.9	34.5	34.2	33.7
Manure Management	15.0	15.5	16.0	17.1	18.8	19.7	20.4	22.1	22.9
Rice Cultivation	2.4	2.3	2.6	2.4	2.7	2.6	2.4	2.6	2.7
Agricultural Residue Burning	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2
N_2O	**78.8**	**80.0**	**81.8**	**81.0**	**87.4**	**84.3**	**86.4**	**88.3**	**88.0**
Agricultural Soil Management	75.3	76.3	78.2	77.3	83.5	80.4	82.4	84.2	83.9
Manure Management	3.4	3.6	3.5	3.7	3.8	3.7	3.8	3.9	4.0
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**129.9**	**131.6**	**134.7**	**135.1**	**144.4**	**142.5**	**144.8**	**148.2**	**148.4**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**8,769**	**8,872**	**9,091**	**9,306**	**9,809**	**10,015**	**10,051**	**10,320**	**10,386**
Enteric Fermentation	5,712	5,732	5,804	5,876	6,016	6,094	6,032	5,973	5,885
Manure Management	2,613	2,708	2,801	2,990	3,283	3,447	3,567	3,861	3,990
Rice Cultivation	414	404	453	414	476	445	420	453	476
Agricultural Residue Burning	30	28	33	26	34	28	32	34	35
N_2O	**932**	**946**	**968**	**958**	**1,033**	**997**	**1,021**	**1,044**	**1,041**
Agricultural Soil Management	891	903	925	914	988	951	975	996	992
Manure Management	40	42	42	43	44	44	45	46	47
Agricultural Residue Burning	1	1	1	1	1	1	1	1	1

+ Does not exceed .5 Gg
Note: Totals may not sum due to independent rounding.

Enteric Fermentation

Methane (CH_4) is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces methane as a by-product, which can be exhaled or eructated by the animal. The amount of methane produced and excreted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Among domestic animal types, ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of anthropogenic methane because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into soluble products that can be utilized by the animal. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest methane emissions among all animal types.

Non-ruminant domestic animals (e.g., pigs, horses, mules, rabbits, and guinea pigs) also produce anthropogenic methane emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants have significantly lower methane emissions than ruminants because the capacity of the large intestine to produce methane is lower.

In addition to the type of digestive system, an animal's feed intake also affects methane excretion. In general, a higher feed intake leads to higher methane emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types.

Methane emission estimates from enteric fermentation are shown in Table 5-3 and Table 5-4. Total livestock emissions in 1998 were 33.7 MMTCE (5,885 Gg). Emissions from dairy cattle remained relatively constant from 1990 to 1998 despite a steady increase in milk production. During this time, emissions per cow increased due to a rise in milk production per dairy cow (see Table 5-5); however, this trend was offset by a decline in the dairy cow population. Beef cattle emissions continued to decline, caused by the second consecutive year of declining cattle populations. Methane emissions from other animals have remained relatively constant.

Methodology

Livestock emission estimates fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of methane emissions from livestock in the United States and are handled separately. Also, cattle production systems in the United States are well characterized in comparison with other livestock management systems. Overall, emissions estimates were derived using emission factors, which were multiplied by animal population data.

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that describes the quantity of methane produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of feeding practices and production characteristics was used to estimate emissions from cattle populations.

To derive emission factors for the various types of cattle found in the United States, a mechanistic model of rumen digestion and animal production was applied to data on thirty-two different diets and nine different cattle types (Baldwin et al. 1987a and b).[1] The cattle types were defined to represent the different sizes, ages, feeding systems, and management systems that are typically found in the United States. Representative diets were

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMTCE)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Dairy Cattle	8.4	8.4	8.4	8.4	8.4	8.4	8.3	8.3	8.3
Beef Cattle	22.6	22.8	23.1	23.6	24.4	24.9	24.7	24.3	23.9
Other	1.6	1.7	1.7	1.6	1.7	1.6	1.6	1.6	1.6
Sheep	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4
Goats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Hogs	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Total	**32.7**	**32.8**	**33.2**	**33.7**	**34.5**	**34.9**	**34.5**	**34.2**	**33.7**

Table 5-4: CH_4 Emissions from Enteric Fermentation (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Dairy Cattle	1,474	1,465	1,473	1,468	1,471	1,473	1,454	1,453	1,443
Beef Cattle	3,951	3,979	4,039	4,120	4,256	4,340	4,305	4,246	4,165
Other	286	288	293	288	290	281	274	274	277
Sheep	91	89	86	82	79	72	68	64	63
Goats	13	12	13	13	13	12	13	11	10
Horses	102	102	105	106	108	108	109	111	111
Hogs	81	85	88	87	90	88	84	88	93
Total	**5,712**	**5,732**	**5,804**	**5,876**	**6,016**	**6,094**	**6,032**	**5,973**	**5,885**

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[1] The basic model of Baldwin et al. (1987a and b) was revised somewhat to allow for evaluations of a greater range of animal types and diets. See EPA (1993).

defined for each category of animal, reflecting the feeds and forages consumed by cattle type and region. Using this model, emission factors were derived for each combination of animal type and representative diet. Based upon the level of use of each diet in the five regions, average regional emission factors for each of the nine cattle types were derived.[2] These emission factors were then multiplied by the applicable animal populations from each region.

For dairy and beef cows and replacements, emission estimates were developed using regional emission factors. Dairy cow emission factors were modified to reflect changing—primarily increasing—milk production per cow over time in each region. All other emission factors were held constant over time. Emissions from other cattle types were estimated using national average emission factors.

Emissions estimates for other animal types were based upon average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total methane emissions from livestock in the United States. Also, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle.

See Annex H for more detailed information on the methodology and data used to calculate methane emissions from enteric fermentation.

Data Sources

The emission estimates for all domestic livestock were determined using a mechanistic model of rumen digestion and emission factors developed in EPA (1993). For dairy and beef cows and replacements, regional emission factors were used from EPA (1993). Emissions from other cattle types were estimated using national average emission factors from EPA (1993). Methane emissions from sheep, goats, pigs, and horses were estimated by using emission factors utilized in Crutzen et al. (1986) and annual population data from U.S. Department of Agriculture statistical reports (USDA 1994a-b, 1995a-d, 1996, 1997, 1998a-c, 1999a-i). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology employed in EPA (1993) is the same as those recommended in IPCC (1997). All livestock population data were taken from USDA statistical reports. See the following section on manure management for a complete listing of reports cited. Table 5-5 provides a summary of cattle population and milk production data.

Uncertainty

The diets analyzed using the rumen digestion model include broad representations of the types of feed consumed within each region. Therefore, the full diversity of feeding strategies employed in the United States is not represented and the emission factors used may be biased. The rumen digestion model, however, has been validated by experimental data. Animal population and production statistics, particularly for beef cows and other grazing cattle, are also uncertain. Overall, the uncertainty in the emission estimate is estimated to be roughly “20 percent (EPA 1993).

Manure Management

The management of livestock manure can produce anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide is produced as part of the nitrogen cycle through the nitrification and

Table 5-5: Cow Populations (Thousands) and Milk Production (Million Kilograms)

Year	Dairy Cow Population	Beef Cow Population	Milk Production
1990	10,007	32,677	67,006
1991	9,883	32,960	66,995
1992	9,714	33,453	68,441
1993	9,679	34,132	68,328
1994	9,504	35,101	69,673
1995	9,491	35,645	70,440
1996	9,410	35,509	69,857
1997	9,309	34,629	70,802
1998	9,200	34,143	71,415

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[2] Feed intake of bulls does not vary significantly by region, so only a national emission factor was derived for this cattle type.

denitrification of the organic nitrogen in livestock manure and urine.

When livestock and poultry manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid in lagoons, ponds, tanks, or pits), the decomposition of materials in manure tends to produce methane. When manure is handled as a solid (e.g., in stacks or pits) or deposited on pastures and range lands, it tends to decompose aerobically and produce little or no methane. A number of other factors related to how the manure is handled also affect the amount of methane produced: 1) air temperature and moisture affect the amount of methane produced because they influence the growth of the bacteria responsible for methane formation; 2) methane production generally increases with rising temperature and residency time; and 3) for non-liquid based manure systems, moist conditions (which are a function of rainfall and humidity) favor methane production. Although the majority of manure is handled as a solid, producing little methane, the general trend in manure management, particularly for dairy and swine producers, is one of increasing usage of liquid systems.

The composition of the manure also affects the amount of methane produced. Manure composition varies by animal type and diet. The greater the energy content and digestibility of the feed, the greater the potential for methane emissions. For example, feedlot cattle fed a high energy grain diet generate manure with a high methane-producing capacity. Range cattle feeding on a low energy diet of forage material produce manure with roughly half the methane-producing potential of feedlot cattle manure.

The amount of N_2O produced depends on the manure and urine composition, the type of bacteria involved in the process and the amount of oxygen and liquid in the manure system. Nitrous oxide emissions result from livestock manure and urine that is managed using liquid and slurry systems, as well as manure and urine that is collected and stored as a solid. Nitrous oxide emissions from unmanaged livestock manure and urine on pastures, ranges, and paddocks, as well as from manure and urine that is spread onto fields either directly as “daily spread,” or after it is removed from manure management systems (e.g., lagoon, pit, etc.) is accounted for and discussed under Agricultural Soil Management.

Table 5-6, Table 5-7, and Table 5-8 provide estimates of methane and N_2O emissions from manure management by animal category. Estimates for methane emissions in 1998 were 22.9 MMTCE (3,990 Gg), 53 percent higher than in 1990. The majority of the increase in methane emissions was from swine and dairy cow manure and are attributed to shifts by the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use flush or scrape liquid systems. Thus the shift towards larger facilities is translated into an increasing use of liquid systems. This shift was accounted for by incorporating weighted methane conversion factor (MCF) values calculated from the 1997 farm-size distribution reported in the *1997 Census of Agriculture* (USDA 1999m). An increase in feed consumption by dairy cows to maximize milk production is also accounted for in the estimates. A detailed description of the methodology is provided in Annex I.

Total N_2O emissions from managed manure systems in 1998 were estimated to be 4.0 MMTCE (47 Gg). The 19 percent increase in N_2O emissions from 1990 to 1998 can be partially attributed to an increase in the population of poultry and swine. The population of beef cattle in feedlots, which tend to use managed manure systems, also increased. As stated previously, N_2O emissions from unmanaged livestock manure is accounted for under Agricultural Soil Management. Methane emissions were mostly unaffected by this increase in the beef cattle population because feedlot cattle use solid storage systems, which produce little methane.

Methodology

The methodologies presented in EPA (1993) form the basis of the methane emissions estimates for each animal type. The calculation of emissions requires the following information:

- Amount of manure produced (amount per head times number of head)
- Portion of the manure that is volatile solids (by animal type)
- Methane producing potential of the volatile solids (by animal type)

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMTCE)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**15.0**	**15.5**	**16.0**	**17.1**	**18.8**	**19.7**	**20.4**	**22.1**	**22.9**
Dairy Cattle	4.3	4.3	4.4	4.5	4.8	4.9	5.1	5.4	5.3
Beef Cattle	1.1	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3
Swine	7.9	8.3	8.7	9.6	10.8	11.6	12.1	13.5	14.2
Sheep	+	+	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+	+
Poultry	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.8
Horses	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**3.4**	**3.6**	**3.5**	**3.7**	**3.8**	**3.7**	**3.8**	**3.9**	**4.0**
Dairy Cattle	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Beef Cattle	1.4	1.6	1.5	1.5	1.6	1.5	1.5	1.5	1.6
Swine	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Sheep	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Goats	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Poultry	1.6	1.7	1.7	1.8	1.8	1.9	1.9	2.0	2.0
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**18.3**	**19.1**	**19.6**	**20.8**	**22.6**	**23.5**	**24.3**	**26.0**	**26.9**

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

Table 5-7: CH_4 Emissions from Manure Management (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Dairy Cattle	747	751	762	791	843	864	896	941	933
Beef Cattle	200	205	206	212	219	221	229	229	233
Swine	1,371	1,451	1,523	1,668	1,894	2,031	2,106	2,349	2,475
Sheep	4	4	4	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1	1	1
Poultry	261	268	275	284	292	297	301	308	314
Horses	29	29	30	30	31	31	31	31	31
Total	**2,613**	**2,708**	**2,801**	**2,990**	**3,283**	**3,447**	**3,567**	**3,861**	**3,990**

Note: Totals may not sum due to independent rounding.

Table 5-8: N_2O Emissions from Manure Management (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Dairy Cattle	1.0	1.0	1.0	1.0	1.1	1.1	1.2	1.2	1.2
Beef Cattle	16.7	18.4	17.2	18.1	18.5	17.6	18.0	18.3	18.9
Swine	1.7	1.8	1.9	1.9	2.0	2.0	1.9	2.0	2.1
Sheep	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3
Goats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	19.1	19.8	20.4	21.0	21.7	22.3	23.0	23.5	23.9
Horses	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8
Total	**39.8**	**42.1**	**41.7**	**43.3**	**44.4**	**44.2**	**45.3**	**46.3**	**47.3**

Note: Totals may not sum due to independent rounding.

- Extent to which the methane producing potential is realized for each type of manure management system (by state and manure management system)
- Portion of manure managed in each manure management system (by state and animal type)

For swine and dairy cattle —the two largest emitters of methane—estimates were developed using state-level animal population data and average weighted MCFs for each state. These weighted MCFs were determined for each farm size category based on the general relationship between farm sizes and manure system usage, where larger facilities will tend to use liquid systems. These values were further adjusted to harmonize with emissions reported in EPA (1993). For other animal types, 1990 state-level emission estimates from the detailed analysis presented in EPA (1993) were scaled by the change in the state population.

Nitrous oxide emissions were estimated by first determining manure management system usage. Manure system usage for swine and dairy cows were based on assumptions of system usage for the respective populations' farm size distribution. Total Kjeldahl nitrogen[3] production was calculated for all livestock using livestock population data and nitrogen excretion rates. Nitrous oxide emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate N_2O emissions.

See Annex I for more detailed information on the methodology and data used to calculate methane emissions from manure management. The same activity data were also used to calculate N_2O emissions.

Data Sources

Annual livestock population data for all livestock types except horses were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a, 1995 a-e, 1996a-b, 1997a-b, 1998a-d, 1999a-k). Horse population data were obtained from the FAOSTAT database (FAO 1999). Data on farm size distribution for dairy cows and swine were taken from the U.S. Department of Commerce (DOC 1995, 1987). Manure management system usage data for other livestock were taken from EPA (1992). Nitrogen excretion rate data were developed by the American Society of Agricultural Engineers (ASAE 1999). Nitrous oxide emission factors were taken from IPCC/UNEP/OECD/IEA (1997). Manure management systems characterized as "Other" generally refers to deep pit and litter systems. The IPCC N_2O emission factor for "other" systems (0.005 kg N_2O/kg N excreted), was determined to be inconsistent with the characteristics of these management systems. Therefore, in its place the solid storage/drylot emission factor was used.

Uncertainty

The primary factors contributing to the uncertainty in emission estimates are a lack of information on the usage of various manure management systems in each state and the exact methane generating characteristics of each type of manure management system. Because of significant shifts in the swine and dairy sectors toward larger farms, it is believed that increasing amounts of manure are being managed in liquid manure management systems. The existing estimates reflect these shifts in the weighted MCFs based on the 1997 farm-size data. However, the assumption of a direct relationship between farm-size and liquid system usage may not apply in all cases. In addition, the methane generating characteristics of each manure management system type are based on relatively few laboratory and field measurements, and may not match the diversity of conditions under which manure is managed nationally.

The N_2O emission factors published in IPCC/UNEP/OECD/IEA (1997) were also derived using limited information. The IPCC factors are global averages; U.S.-specific emission factors may be significantly different. Manure and urine in anaerobic lagoons and liquid/slurry management systems produce methane at different rates, and would in all likelihood produce N_2O at different rates, although a single emission factor was used for both system types.

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[3] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

Rice Cultivation

Most of the world's rice, and all rice in the United States, is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions in the soil to develop. Once the environment becomes anaerobic, methane is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the methane produced, however, is oxidized by aerobic methanotrophic bacteria in the soil (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the methane is also leached away as dissolved methane in floodwater that percolates from the field. The remaining un-oxidized methane is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Some methane also escapes from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is one of the most important factors affecting methane emissions. Upland rice fields are not flooded, and therefore are not believed to produce methane. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants are dead so the primary methane transport pathway to the atmosphere is blocked. The quantities of methane released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with more shallow flooding depths. Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, methane emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil methane to oxidize but also inhibits further methane production in soils. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions.

Other factors that influence methane emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers,) soil temperature, soil type, cultivar selection, and cultivation practices (e.g., tillage, and seeding and weeding practices). The factors that determine the amount of organic material that is available to decompose, i.e., organic fertilizer use, soil type, cultivar type[4], and cultivation practices, are the most important variables influencing methane emissions over an entire growing season because the total amount of methane released depends primarily on the amount of organic substrate available. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of methane production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to methane, that time is short relative to a growing season, so the dependence of emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence methane emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate, and ammonium sulfate) appear to inhibit methane formation. In the United States, soil types, soil temperatures, cultivar types, and cultivation practices for rice vary from region to region, and even from farm to farm. However, most rice farmers utilize organic fertilizers in the form of rice residue from the previous crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields, usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of Arkansas, southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop. This second rice crop is produced on the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, the amount of organic material that is available for decomposition is considerably higher than with the first (i.e., primary) crop. Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop.

Rice cultivation is a small source of methane emissions in the United States (2 percent). Rice is cultivated

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[4] The roots of rice plants shed organic material. The amount of root exudates produced varies among cultivar types.

in seven states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Estimates of total annual CH_4 emissions from rice cultivation range from 2.3 to 2.7 MMTCE (404 to 476 Gg CH_4) for the years 1990 to 1998 (Table 5-9 and Table 5-10). There was no apparent trend over the nine year period, although total emissions increased by 15 percent between 1990 and 1998 due to an increase in harvested area.

The factors that affect the rice area harvested vary from state to state.[5] In Florida, the state having the smallest harvested rice area, rice acreage is largely a function of sugarcane acreage. Sugarcane fields are flooded each year to control pests, and on this flooded land a rice crop is grown along with a ratoon crop of sugarcane (Schueneman 1997). In Missouri, rice acreage is affected by weather (e.g., rain during the planting season may prevent the planting of rice), the price differential between soybeans and rice (e.g., if soybean prices are higher, then soybeans may be planted on some of the land which would otherwise have been planted in rice), and government support programs (Stevens 1997). The price differential between soybeans and rice also affects rice acreage in Mississippi. Rice in Mississippi is usually rotated with soybeans, but if soybean prices increase relative to rice prices, then some of the acreage that would have been planted in rice, is instead planted in soybeans (Street 1997). In Texas, rice production, and thus, harvested area, are affected by both government programs and the cost of production (Klosterboer 1997). California rice area is influenced by water availability as well as government programs and commodity prices. In Louisiana, rice area is influenced by government programs, weather conditions (e.g., rainfall during the planting season), as well as the price differential between rice and corn and other crops (Saichuk 1997). Arkansas rice area has been influenced in the past by government programs. However,

Table 5-9: CH_4 Emissions from Rice Cultivation (MMTCE)

State	1990	1991	1992	1993	1994	1995	1996	1997	1998
Arkansas	0.7	0.7	0.8	0.7	0.8	0.8	0.7	0.8	0.9
California	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
Florida	+	+	+	+	+	+	+	+	+
Louisiana	0.7	0.7	0.8	0.7	0.8	0.8	0.7	0.8	0.8
Mississippi	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Missouri	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Texas	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3
Total	**2.4**	**2.3**	**2.6**	**2.4**	**2.7**	**2.6**	**2.4**	**2.6**	**2.7**

+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding.

Table 5-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1991	1992	1993	1994	1995	1996	1997	1998
Arkansas	121	127	139	124	143	135	118	140	154
California	72	65	72	80	89	85	91	94	87
Florida	3	4	5	5	5	5	5	4	4
Louisiana	127	119	145	124	145	133	125	136	145
Mississippi	26	23	23	23	23	23	23	23	23
Missouri	10	12	14	12	16	14	12	15	18
Texas	55	54	55	47	55	50	47	40	44
Total	**414**	**404**	**453**	**414**	**476**	**445**	**420**	**453**	**476**

Note: Totals may not sum due to independent rounding.

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[5] The statistic "area harvested" accounts for double cropping, i.e., if one hectare is cultivated twice in one year, then that hectare is counted as two hectares harvested.

due to the phase-out of these programs nationally, which began in 1996, spring commodity prices have had a greater effect on the amount of land planted in rice in recent years (Mayhew 1997).

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) recommend applying a seasonal emission factor to the annual harvested rice area to estimate annual CH_4 emissions. This methodology assumes that a seasonal emission factor is available for all growing conditions. Because season lengths are quite variable both within and among states in the United States, and because flux measurements have not been taken under all growing conditions in the United States, an earlier IPCC methodology (IPCC/UNEP/OECD/IEA 1995) has been applied here, using season lengths that vary slightly from the recommended approach. The 1995 *IPCC Guidelines* recommend multiplying a daily average emission factor by growing season length and annual harvested area. The *IPCC Guidelines* suggest that the "growing" season be used to calculate emissions based on the assumption that emission factors are derived from measurements over the whole growing season rather than just the flooding season. Applying this assumption to the United States, however, would result in an overestimate of emissions because the emission factors developed for the United States are based on measurements over the flooding, rather than the growing, season. Therefore, the method used here is based on the number of days of flooding during the growing season and a daily average emission factor, which is multiplied by the harvested area. Agricultural extension agents in each of the seven states in the United States that produce rice were contacted to determine water management practices and flooding season lengths in each state. Although all contacts reported that rice growing areas were continuously flooded, flooding season lengths varied considerably among states; therefore, emissions were calculated separately for each state.

Emissions from ratooned and primary areas are estimated separately. Information on ratoon flooding season lengths was collected from agricultural extension agents in the states that practice ratooning, and emission factors for both the primary season and the ratoon season were derived from published results of field experiments in the United States.

Data Sources

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 5-11. Data for all states except Florida for 1990 through 1995 were taken from *U.S. Department of Agriculture's National Agriculture Statistics Data—Historical Data* (USDA 1999b). The data for 1996 through 1998 were obtained from the *Crop Production 1998 Summary* (USDA 1999a). Harvested rice areas in Florida from 1990 to 1998 were obtained from Tom Schueneman (1999b, 1999c), a Florida Agricultural Extension Agent. Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998, when the ratooned area was less than 1 percent of the primary area (Slaton 1999a). In the other three states in which ratooning is practiced (i.e., Florida, Louisiana, and Texas), the percentage of the primary area that was ratooned was constant over the entire 1990 to 1998 period. In Florida, the ratooned area was 50 percent of the primary area (Schueneman 1999a), in Louisiana it was 30 percent (Linscombe 1999a), and in Texas it was 40 percent (Klosterboer 1999a).

Information about flooding season lengths was obtained from agricultural extension agents in each state (Beck 1999, Guethle 1999, Klosterboer 1999b, Linscombe 1999b, Scardaci 1999a and 1999b, Schueneman 1999b, Slaton 1999b, Street 1999a and 1999b). These data are presented in Table 5-12.

To determine what daily methane emission factors should be used for the primary and ratoon crops, methane flux information from all the rice field measurements made in the United States was collected. Experiments in which nitrate and sulfate fertilizers, or other substances known to suppress methane formation, were applied, as well as experiments in which measurements were not made over an entire flooding season or in which floodwaters were drained mid-season, were excluded from the analysis. This left ten field experiments from California (Cicerone et al. 1992), Texas (Sass et al. 1990, 1991a, 1991b, 1992), and Louisiana (Lindau et al. 1991, Lindau and Bollich 1993, Lindau et al. 1993, Lindau et al. 1995, Lindau et al. 1998).[6] These experimental results were then sorted by season and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The results for the primary crop showed no consistent correlation between emission rate and type or magnitude of fertilizer application. Although individual experiments have shown a significant increase in emissions when organic fertilizers are added, when the results were combined, emissions from fields that receive organic fertilizers were not found to be, on average, higher that those from fields that receive synthetic fertilizer only. In addition, there appeared to be no correlation between fertilizer application rate and emission rate, either for synthetic or organic fertilizers. These somewhat surprising results are probably due to other variables that have not been taken into account, such as timing and mode of fertilizer application, soil type, cultivar type, and other cultivation practices. There were limited results from ratooned fields. Of those that received synthetic fertilizers, there was no consistent correlation between emission rate and amount of fertilizer applied, however, the type of synthetic fertilizer did not vary among experiments. In contrast, all the ratooned fields that received synthetic fertilizer had emission rates that were higher than the one ratoon experiment in which no synthetic fertilizer was applied. Given these results, the highest and lowest emission rates measured in primary fields that received synthetic fertilizer only—which bounded the results from fields that

Table 5-12: Rice Flooding Season Lengths (Days)

State/Crop	Low	High
Arkansas		
Primary	60	80
Ratoon	30	40
California	100	145
Florida		
Primary	90	110
Ratoon	40	60
Louisiana		
Primary	90	120
Ratoon	70	75
Mississippi	68	82
Missouri	80	100
Texas		
Primary	60	80
Ratoon	40	60

Table 5-11: Rice Areas Harvested (Hectares)

State/Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998
Arkansas									
Primary	485,633	509,915	558,478	497,774	574,666	542,291	473,493	562,525	617,159
Ratoon*	NA	NA	NA	NA	NA	NA	NA	NA	202
California	159,854	144,071	159,450	176,851	196,277	188,183	202,347	208,822	193,444
Florida									
Primary	4,978	8,580	9,308	9,308	9,713	9,713	8,903	7,689	8,094
Ratoon	2,489	4,290	4,654	4,654	4,856	4,856	4,452	3,845	4,047
Louisiana									
Primary	220,558	206,394	250,911	214,488	250,911	230,676	215,702	235,937	250,911
Ratoon	66,168	61,918	75,273	64,346	75,273	69,203	64,711	70,781	75,273
Mississippi	101,174	89,033	111,291	99,150	126,669	116,552	84,176	96,317	108,458
Missouri	32,376	37,232	45,326	37,637	50,182	45,326	38,446	47,349	57,871
Texas									
Primary	142,857	138,810	142,048	120,599	143,262	128,693	120,599	104,816	114,529
Ratoon	57,143	55,524	56,819	48,240	57,305	51,477	48,240	41,926	45,811
Total	**1,273,229**	**1,255,767**	**1,413,557**	**1,273,047**	**1,489,114**	**1,386,969**	**1,261,068**	**1,380,008**	**1,475,799**

Note: Totals may not sum due to independent rounding.
* Arkansas ratooning only occurred in 1998.

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[6] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the reasons just mentioned. In addition, one measurement from the ratooned fields (i.e., the flux of 2.041 $g/m^2/day$ in Lindau and Bollich 1993) was excluded since this emission rate is unusually high compared to other flux measurements in the United States, as well as in Europe and Asia (IPCC/UNEP/OECD/IEA 1997).

received both synthetic and organic fertilizers—was used as the emission factor range for the primary crop, and the lowest and highest emission rates measured in all the ratooned fields was used as the emission factor range for the ratoon crop. These ranges are 0.020 to 0.609 g/m^2-day for the primary crop, and 0.301 to 0.933 g/m^2-day for the ratoon crop.

Uncertainty

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors applied. Daily average emissions, derived from field measurements in the United States, vary by more than one order of magnitude (IPCC/UNEP/OECD/IEA 1997). This variability is due to differences in cultivation practices, particularly the type, amount, and mode of fertilizer application; differences in cultivar type; and differences in soil and climatic conditions. By separating primary from ratooned areas, this Inventory has accounted for more of this variability than previous inventories. However, a range for both the primary (0.315 g/m^2day ±93 percent) and ratoon crop (0.617 g/m^2day ±51 percent) has been used in these calculations to reflect the remaining uncertainty. Based on this range, total methane emissions from rice cultivation in 1998 were estimated to have been approximately 0.43 to 5.0 MMTCE (75 to 876 Gg CH_4), or 2.7 MMTCE ±84 percent.

Another source of uncertainty is in the flooding season lengths used for each state. Flooding seasons in each state may fluctuate from year to year, and thus a range has been used to reflect this uncertainty. Even within a state, flooding seasons can vary by county and cultivar type (Linscombe 1999a).

The last source of uncertainty is in the practice of flooding outside of the normal rice season. According to the agriculture extension agents, all of the rice-growing states practice this on some part of their rice acreage, ranging from 5 to 33 percent of the rice acreage. Fields are flooded for a variety of reasons: to provide habitat for waterfowl, to provide ponds for crawfish production, and to aid in rice straw decomposition. To date, methane flux measurements have not been undertaken in these flooded areas.

As scientific understanding improves, these emission estimates will be adjusted to better reflect these variables.

Agricultural Soil Management

Nitrous oxide (N_2O) is produced naturally in soils through the microbial processes of nitrification and denitrification.[7] A number of agricultural activities add nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities may add nitrogen to soils either directly or indirectly. Direct additions occur through various soil management practices (i.e., application of synthetic and organic fertilizers, application of sewage sludge, application of animal wastes, production of nitrogen-fixing crops, application of crop residues, and cultivation of high organic content soils, which are also called histosols), and through animal grazing (i.e., direct deposition of animal wastes on pastures, range, and paddocks by grazing animals). Indirect additions occur through two mechanisms: 1) volatilization of applied nitrogen (i.e., fertilizer, sewage sludge and animal waste) as ammonia (NH_3) and oxides of nitrogen (NO_x) and subsequent atmospheric deposition of that nitrogen in the form of ammonium (NH_4) and oxides of nitrogen (NO_x); and 2) surface runoff and leaching of applied nitrogen into aquatic systems. Figure 5-2 illustrates these sources and pathways of nitrogen additions to soils in the United States. Other agricultural soil management practices, such as irrigation, drainage, tillage practices, and fallowing of land, can affect fluxes of N_2O, as well as other greenhouse gases, to and from soils. However, because there are significant uncertainties associated with these other fluxes, they have not been estimated.

Estimates of annual N_2O emissions from agricultural soil management range from 75.3 to 83.9 MMTCE

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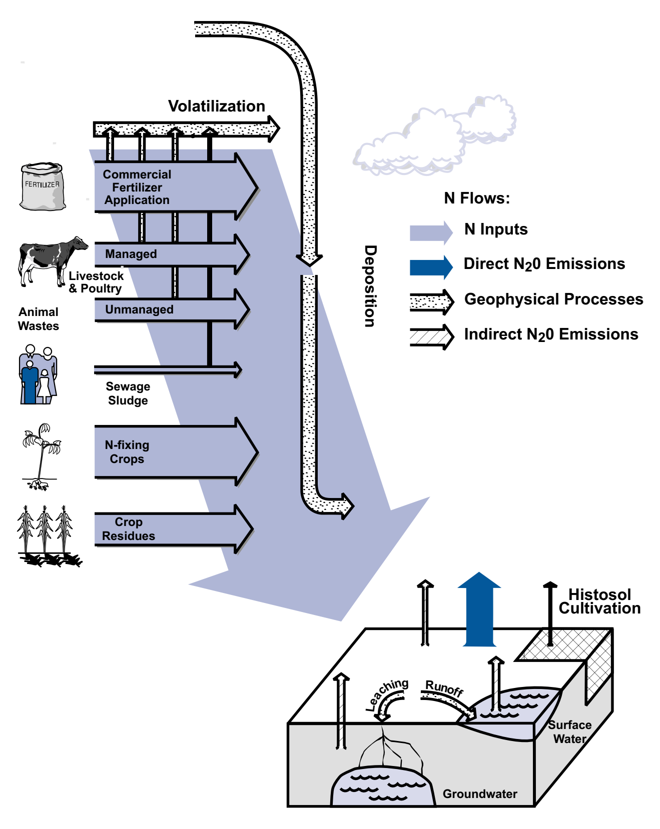
[7] Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to dinitrogen gas (IPCC/UNEP/OECD/IEA 1997). Nitrous oxide is a gaseous intermediate product in the reaction sequences of both processes, which leaks from microbial cells into the soil atmosphere.

Figure 5-2

Sources of N_2O Emissions from Agricultural Soils



(891 to 992 Gg) for the years 1990 to 1998 (Table 5-13 and Table 5-14).[8] Emission levels fluctuated moderately during the 1990 to 1993 period, increased sharply in 1994, and fluctuated again through 1998. These fluctuations are largely a reflection of annual variations in synthetic nitrogen fertilizer consumption and crop production. Synthetic nitrogen fertilizer consumption, and production of corn and most beans and pulses, increased in 1994 due to the 1993 flooding of the North Central region and the intensive cultivation that followed. From 1997 to 1998, N_2O emission estimates decreased by 0.4 percent. Over the nine-year period, total emissions of N_2O increased by approximately 11 percent.

This N_2O source category is divided into three components: (1) direct emissions from managed soils due to N applications and cultivation of histosols; (2) direct emissions from managed soils due to grazing animals; and (3) emissions from soils indirectly induced by applications of nitrogen. Except where specifically noted, the emission estimates for all three components follow the methodologies in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Direct N_2O Emissions from Agricultural Soils

Estimates of N_2O emissions from this component are based on the total amount of nitrogen that is applied to, or made available to—in the case of histosol cultivation—soils through various practices. The practices are: (1) the application of synthetic and organic fertilizers, (2) the application of sewage sludge, (3) the application of livestock and poultry waste through both daily spread and eventual application of wastes that had been managed in waste management systems (e.g., lagoons), (4) the production of nitrogen-fixing crops, (5) the application of crop residues, and (6) the cultivation of histosols.

Annual synthetic and organic fertilizer consumption data for the United States were taken from annual publications on commercial fertilizer statistics (AAPFCO 1995, 1996, 1997, 1998; TVA 1990, 1992a,b, 1994). Organic fertilizers included in these publications are manure, compost, dried blood, sewage sludge, tankage[9], and “other”. The manure portion of the organic fertilizers was subtracted from the total organic fertilizer consumption data to avoid double counting[10]. Fertilizer consumption data are recorded in “fertilizer year” totals (i.e., July to June), which were converted to calendar year totals by assuming that approximately 35 percent

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[8] Note that these emission estimates include applications of N to all soils, but the phrase “Agricultural Soil Management” is kept for consistency with the reporting structure of the *Revised 1996 IPCC Guidelines*.

[9] Tankage is dried animal residue, usually freed from fat and gelatin.

[10] The manure used in commercial fertilizer is accounted for when estimating the total amount of animal waste nitrogen applied to soils.

Table 5-13: N_2O Emissions from Agricultural Soil Methodology and Data Sources Management (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Direct									
Agricultural Soils	42.7	43.3	44.7	43.0	48.3	45.3	47.1	49.3	49.2
Grazing Animals	10.3	10.3	10.6	10.7	10.9	11.1	11.0	10.7	10.5
Indirect	22.4	22.7	23.0	23.6	24.3	24.0	24.3	24.3	24.2
Total	**75.3**	**76.3**	**78.2**	**77.3**	**83.5**	**80.4**	**82.4**	**84.2**	**83.9**

Note: Totals may not sum due to independent rounding.

Table 5-14: N_2O Emissions from Agricultural Soil Management (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Direct									
Agricultural Soils	505	512	528	509	571	536	557	583	581
Grazing Animals	121	122	125	126	129	131	130	126	124
Indirect	265	269	272	279	287	284	288	287	287
Total	**891**	**903**	**925**	**914**	**988**	**951**	**975**	**996**	**992**

Note: Totals may not sum due to independent rounding.

of fertilizer usage occurred from July to December (TVA 1992b). July to December values were not available for calendar year 1998, so a "least squares line" statistical test using the past eight data points was used to arrive at an approximate total. Data on the nitrogen content of synthetic fertilizers were available in the published fertilizer reports; however, these reports did not include nitrogen content information for organic fertilizers. It was assumed that 4.1 percent of non-manure organic fertilizers on a mass basis was nitrogen (Terry 1997). Annual consumption of commercial fertilizers—synthetic and non-manure organic—in units of nitrogen are presented in Table 5-15. The total amount of nitrogen consumed from synthetic and non-manure organic fertilizers was reduced by 10 percent and 20 percent, respectively, to account for the portion that volatilizes to NH_3 and NO_x (IPCC/UNEP/OECD/IEA 1997).

Data collected by the U.S. Environmental Protection Agency (EPA) were used to derive annual estimates of nitrogen additions from land application of sewage sludge. Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment works. Based on a 1988 questionnaire returned from 600 publicly owned treatment works (POTWs), the EPA estimated that 5.4 million metric tons of dry sewage sludge were generated in the United States in that year (EPA 1993). Of this total, 36 percent was applied to land—including agricultural applications, compost manufacture, forest land application, and the reclamation of mining areas—34.0 percent was disposed in landfills, 10.3 percent was surface-disposed (in open dumps), 16.1 percent was incinerated, and 6.3 percent was dumped into the oceans (EPA 1993). In 1997, the EPA conducted a nationwide state-by-state study that estimated that approximately 7 million metric tons of dry sewage sludge were generated by 12,000 POTWs (Bastian 1999). The same study concluded that 54 percent of sewage sludge generated that year was applied to land. Sewage sludge production increased between 1988 and 1997 due to increases in the number of treatment plants and the magnitude of industrial wastewater treated, as well as changes in sewage treatment techniques. The proportion of sewage sludge applied to land increased due to the passage of legislation in 1989 that banned all ocean dumping of sewage, as well as stricter laws regulating the use of landfills for sewage disposal (Bastian 1999). To estimate sewage sludge production for the 1990 to 1998 period, the values for 1988 and 1997 were linearly interpolated. To estimate the proportion of sewage sludge that was applied to land, the values for 1988 and 1992 were linearly interpolated; the 1992 value was estimated by assuming all sewage sludge dumped in the ocean before 1992 was land applied that year (i.e., 1991 was the last year ocean dumping of sludge occurred). A second interpolation was then calculated for the period 1992 to 1997 using the 1997 value and the 1992 estimate. The rate of sewage sludge production destined for land application is currently leveling off (Bastian 1999); in the absence of more precise data for 1998, the 1997 estimate was used for 1998. Anywhere between 1 to 6 percent of dry weight sewage sludge is nitrogen, both in organic and inorganic form (National Research Council 1996); 4 percent was used as a conservative average estimate of the nitrogen content in sewage sludge. Annual land application of sewage sludge in units of nitrogen is presented in Table 5-15. As with non-manure organic fertilizer applications to managed soils, it was assumed that 20 percent of the sewage sludge nitrogen volatilizes. A portion of sewage sludge is used as commercial fertilizer; application of this nitrogen and associated N_2O emissions are accounted for under the organic fertilizer application category.

To estimate the amount of livestock and poultry waste nitrogen applied to soils, it was assumed that all of it will eventually be applied to soils with two exceptions. These exceptions are (1) the nitrogen in the poultry waste that is used as feed for ruminants (i.e., approximately 10 percent of the poultry waste), and (2) the nitrogen in the waste that is directly deposited onto fields by grazing animals.[11] Annual animal population data for all livestock types, except horses, were obtained from the USDA National Agricultural Statistics Service (USDA 1994b,c, 1995a,b, 1996a,b, 1997a,b, 1998a,b; 1999a-g,i-m). Horse population data were obtained from the FAOSTAT database (FAO 1999). Population data by animal type were multiplied by an average animal mass constant (ASAE 1999) to derive total animal mass for each animal type. Total Kjeldahl nitrogen[12] excreted per year (i.e., manure and urine) was then calculated using daily rates of nitrogen excretion per unit of animal mass (ASAE 1999) (Table 5-16). The amount of animal waste nitrogen directly deposited by grazing animals—derived using manure management system usage data and farm size (Safely et al. 1992, DOC 1995) as described in the "Direct N_2O Emissions from Grazing Animals" section—was then subtracted from the total nitrogen. Ten percent of the poultry waste nitrogen produced in managed systems and used as feed for ruminants was then subtracted. Finally, the total amount of nitrogen from livestock and poultry waste applied to soils was then reduced by 20 percent to account for the portion that volatilizes to NH_3 and NO_x (IPCC/UNEP/OECD/IEA 1997).

Table 5-15: Commercial Fertilizer Consumption & Land Application of Sewage Sludge (Thousand Metric Tons of Nitrogen)

Fertilizer Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Synthetic	10,104	10,261	10,324	10,718	11,161	10,799	11,158	11,172	11,156
Non-Manure Organics	8	12	13	11	11	14	15	15	16
Sewage Sludge	94	103	112	120	127	135	143	151	151

Note: The sewage sludge figures do not include sewage sludge used as commercial fertilizer.

Table 5-16: Animal Excretion from Livestock and Poultry (Thousand Metric Tons of Nitrogen)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Applied to Soils	3,695	3,804	3,812	3,864	3,933	3,913	3,890	3,972	3,890
Pasture, Range, & Paddock	4,830	4,850	4,972	5,021	5,132	5,221	5,170	5,029	4,923

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[11] An additional exception is the nitrogen in the waste that will runoff from waste management systems due to inadequate management. There is insufficient information with which to estimate this fraction of waste nitrogen.

[12] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

Annual production statistics for some of the nitrogen-fixing crops (i.e., beans, pulses, and alfalfa) were taken from U.S. Department of Agriculture reports (USDA 1994a, 1997c, 1998c, 1999h). These statistics are presented in Table 5-17. Crop product values for beans and pulses were expanded to total crop dry biomass, in mass units of dry matter, by applying residue to crop ratios and dry matter fractions for residue from Strehler and Stützle (1987). Crop production for the alfalfa were converted to dry matter mass units by applying a dry matter fraction value estimated at 80 percent (Mosier 1998). To convert to units of nitrogen, it was assumed that 3 percent of the total crop dry mass for all crops was nitrogen (IPCC/UNEP/OECD/IEA 1997).

There are no published annual production statistics for non-alfalfa legumes used as forage in the United States (i.e., red clover, white clover, birdsfoot trefoil, arrowleaf clover, crimson clover, hairy vetch). Estimates of average annual crop coverage density and crop area were obtained through personal communications with agricultural extension agents or faculty at agronomy and soil science departments of universities. The estimates of dry matter crop coverage density were obtained through on-site experiment and measurement results (Smith 1999, Peterson 1999, Mosjidis 1999). Estimates of average annual crop areas at the national level are reported in Taylor and Smith (1995). Estimates of annual crop production were derived by multiplying the crop coverage densities by the crop areas. Total nitrogen content was estimated in the same manner as for alfalfa. Annual production estimates for non-alfalfa forage legumes are presented in Table 5-17.

To estimate the amount of nitrogen applied to soils as crop residue, it was assumed that all residues from corn, wheat, bean, and pulse production, except the fractions that are burned in the field after harvest, were either plowed under or left on the field.[13] Annual production statistics were taken from U.S. Department of Agriculture (USDA 1994a, 1997c, 1998c, 1999h). These statistics are presented in Table 5-17 and Table 5-18. Crop residue biomass, in dry matter mass units, was calculated from the production statistics by applying residue

Table 5-17: Nitrogen Fixing Crop Production (Thousand Metric Tons of Product)

Product Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Soybeans	52,416	54,065	59,612	50,885	68,444	59,174	64,780	73,176	75,028
Peanuts	1,635	2,235	1,943	1,539	1,927	1,570	1,661	1,605	1,783
Dry Edible Beans	1,469	1,532	1,026	994	1,324	1,398	1,268	1,332	1,398
Dry Edible Peas	108	169	115	149	102	209	121	264	269
Austrian Winter Peas	6	6	4	7	2	5	5	5	5
Lentils	66	104	71	91	84	97	60	108	88
Wrinkled Seed Peas	42	42	24	39	34	48	25	31	31
Alfalfa	75,671	75,585	71,795	72,851	73,787	76,671	72,137	71,887	74,398
Red Clover	62,438	62,438	62,438	62,438	62,438	62,438	62,438	62,438	62,438
White Clover	40,700	40,700	40,700	40,700	40,700	40,700	40,700	40,700	40,700
Birdsfoot Trefoil	12,375	12,375	12,375	12,375	12,375	12,375	12,375	12,375	12,375
Arrowleaf Clover	2,044	2,044	2,044	2,044	2,044	2,044	2,044	2,044	2,044
Crimson Clover	818	818	818	818	818	818	818	818	818
Hairy Vetch	500	500	500	500	500	500	500	500	500

Table 5-18: Corn and Wheat Production (Thousand Metric Tons of Product)

Product Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Corn for Grain	201,534	189,868	240,719	160,986	255,295	187,970	234,518	233,864	247,943
Wheat	74,292	53,891	67,135	65,220	63,167	59,404	61,980	67,534	69,410

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[13] Although residue application mode would probably affect the magnitude of emissions, a methodology for estimating N_2O emissions for these two practices separately has not been developed yet.

to crop mass ratios and dry matter fractions for residue from Strehler and Stützle (1987). For wheat and corn, nitrogen contents were taken from Barnard and Kristoferson (1985). For beans and pulses, it was assumed that 3 percent of the total crop residue was nitrogen (IPCC/UNEP/OECD/IEA 1997). The crops whose residues were burned in the field are corn, wheat, soybeans, and peanuts. For these crop types, the total residue nitrogen was reduced by 3 percent to subtract the fractions burned in the field (see the Agricultural Residue Burning section).

Total crop nitrogen in the residues returned to soils was then added to the unvolatilized applied nitrogen from commercial fertilizers, sewage sludge, and animal wastes, and the nitrogen fixation from bean, pulse, alfalfa and non-alfalfa forage legume cultivation. The sum was multiplied by the IPCC default emission factor (0.0125 kg N_2O-N/kg N applied) to estimate annual N_2O emissions from nitrogen applied to soils.

Statistics on the area of histosols cultivated each year were not available; however, estimates for the years 1982 and 1992 were available from *National Resources Inventory* (USDA 1994d). The area statistics for 1982 and 1992 were linearly interpolated to obtain area estimates for 1990 and 1991, and linearly extrapolated to obtain area estimates for 1993 to 1998 (Table 5-19). To estimate annual N_2O emissions from histosol cultivation, the histosol areas were multiplied by the default emission factor (8 kg N_2O-N/ha cultivated) recommended in the draft IPCC paper on "good practice" in implementing the *Revised 1996 IPCC Guidelines* (IPCC 1999a). This recommended emission factor is based on the results of recent measurements that indicate that nitrous oxide emissions from cultivated organic soils in mid-latitudes are higher than previously estimated.

Table 5-19: Histosol Area Cultivated (Thousand Hectares)

Year	Area
1990	1,013
1991	1,005
1992	998
1993	991
1994	984
1995	976
1996	969
1997	962
1998	955

Annual N_2O emissions from nitrogen applied to soils were then added to annual N_2O emissions from histosol cultivation to estimate total annual direct N_2O emissions from agricultural cropping practices (Table 5-20).

Direct N_2O Emissions from Grazing Animals

Estimates of N_2O emissions from this component were based on animal wastes that are not used as animal feed, or applied to soils, or managed in manure management systems, but instead are deposited directly on soils by animals in pastures, range, and paddocks.[14] It was assumed that all unmanaged wastes fall into this cat-

Table 5-20: Direct N_2O Emissions from Agricultural Cropping Practices (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Comm. Fertilizers & Sew. Sludge	15.2	15.5	15.6	16.2	16.9	16.3	16.9	16.9	16.9
Animal Waste	4.9	5.1	5.1	5.1	5.2	5.2	5.2	5.3	5.2
N Fixation	15.1	15.3	15.8	14.7	17.1	16.0	16.5	17.6	18.0
Crop Residue	6.4	6.3	7.1	6.0	8.0	6.8	7.5	8.4	8.1
Histosol Cultivation	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0
Total	**42.7**	**43.3**	**44.7**	**43.0**	**48.3**	**45.4**	**47.2**	**49.3**	**49.2**

Note: Totals may not sum due to independent rounding.

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[14] The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) indicate that emissions from animal wastes managed in solid storage and drylot should also be included in the emissions from soils (see footnote "c" in Table 4-22 in the Reference Manual); however, this instruction appeared to be an error (and footnote "b" should have been listed next to "Solid storage and drylot" in Table 4-22). Therefore, N_2O emissions from livestock wastes managed in solid storage and drylot are reported under Manure Management, rather than here. (See Annex H for a discussion of the activity data used to calculate emissions from the manure management source category.)

egory (Safely et al. 1992), except for unmanaged dairy cow wastes. Although it is known that there is a small portion of dairy cattle that graze, there are no available statistics for this category, and therefore the simplifying assumption is made that all unmanaged dairy cow wastes fall into the daily spread category. Estimates of nitrogen excretion by the remaining animals were derived from animal population and weight statistics, information on manure management system usage in the United States, and nitrogen excretion values for each animal type.

Annual animal population data for all the remaining livestock types, except horses, were obtained from the USDA National Agricultural Statistics Service (USDA 1994b,c; 1995a,b; 1996a,b; 1997a,b; 1998a,b; 1999a-g,i-m). Horse population data were obtained from the FAOSTAT database (FAO 1999). Manure management system utilization data for all livestock types except for diary cattle and swine was taken from Safely et al (1992). In the last few years, there has been a significant shift in the dairy and swine industries toward larger, consolidated facilities, which use manure management systems. Based on the assumption that larger facilities have a higher chance of using manure management systems, farm-size distribution data reported in the 1992 and 1997 Census of Agriculture (DOC 1995, USDA 1999n) were used to assess system utilization in the dairy and swine industries. Populations in the larger farm categories were assumed to utilize manure collection and storage systems; all the wastes from smaller farms were assumed to be managed as pasture, range, and paddock. As stated earlier, waste from manure collection and storage systems is covered under the manure management section. Waste from pasture, range, and paddock is considered direct depositing of waste, and is covered in this section.

For each animal type, the population of animals within pasture, range, and paddock systems was multiplied by an average animal mass constant (ASAE 1999) to derive total animal mass for each animal type. Total Kjeldahl nitrogen excreted per year was then calculated for each animal type using daily rates of nitrogen excretion per unit of animal mass (ASAE 1999). Annual nitrogen excretion was then summed over all animal types (see Table 5-21), and reduced by 20 percent to account for the portion that volatilizes to NH_3 and NO_x. The remainder was multiplied by the IPCC default emission factor (0.02 kg N_2O-N/kg N excreted) to estimate N_2O emissions (see Table 5-21).

Indirect N_2O Emissions from Nitrogen Applied to Managed Soils

This component accounts for N_2O that is emitted indirectly from nitrogen applied as commercial fertilizer, sewage sludge, and animal waste. Through volatilization, some of this nitrogen enters the atmosphere as NH_3 and NO_x, and subsequently returns to soils through atmospheric deposition, thereby enhancing N_2O production. Additional nitrogen is lost from soils through leaching and runoff, and enters groundwater and surface water systems, from which a portion is emitted as N_2O. These two indirect emission pathways are treated separately, although the activity data used are identical.

Estimates of total nitrogen applied as commercial fertilizer, sewage sludge, and animal waste were derived using the same approach as was employed to estimate the direct soil emissions. Annual application rates for synthetic and non-manure organic fertilizer nitrogen were derived from commercial fertilizer statistics as described above (AAPFCO 1995, 1996, 1997, 1998; TVA 1990, 1992a and b, 1994). Annual application rates for sewage sludge were also derived as described above. Annual total nitrogen excretion data for livestock and poultry by animal type were derived from EPA data, also as described above, using population statistics (USDA 1994b,c; 1995a,b; 1996a,b; 1997a,b; 1998a,b; 1999a-g,i-m; DOC 1987; and FAO 1999), average animal mass constants (ASAE 1999), and daily rates of nitrogen excretion per unit of animal mass (ASAE 1999). Annual nitrogen excretion was then summed over all animal types.

To estimate N_2O emissions from volatilization and subsequent atmospheric deposition, the methodology described in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) was followed, where it is assumed that 10 percent of the synthetic fertilizer nitrogen and 20 percent of animal waste (i.e., livestock and poultry) nitrogen applied as fertilizer are volatilized to NH_3 and NO_x. It was then assumed that 1 percent of the total deposited nitrogen is emitted as N_2O. The same NH_3 and NO_x volatilization and N_2O emission rates as those used for animal waste fertilizer were used for nitrogen applied to land as non-manure organic fertilizer and as sewage sludge. These emission estimates are presented in Table 5-22.

To estimate N_2O emissions from leaching and runoff, it was assumed that 30 percent of the total nitrogen applied to managed soils was lost to leaching and surface runoff, and 2.5 percent of the lost nitrogen was emitted as N_2O (IPCC/UNEP/OECD/IEA 1997). These emission estimates are also presented in Table 5-22.

Uncertainty

A number of conditions can affect nitrification and denitrification rates in soils. These conditions vary greatly by soil type, climate, cropping system, and soil management regime, and their combined effect on the processes leading to N_2O emissions are not fully understood. Moreover, the amount of added nitrogen from each source that is not absorbed by crops or wild vegetation, but remains in the soil and is available for production of N_2O, is uncertain. Therefore, it is not yet possible to develop statistically valid estimates of emission factors for all possible combinations of soil, climate, and management conditions. The emission factors used were midpoint estimates based on measurements described in the scientific literature, and as such, are representative of current scientific understanding. Nevertheless, estimated ranges around each midpoint estimate are wide; most are an order of magnitude or larger (IPCC/UNEP/OECD/IEA 1997; IPCC 1999a,b).

Uncertainties also exist in the activity data used to derive emission estimates. In particular, the fertilizer statistics include only those organic fertilizers that enter the commercial market, so some non-commercial fertilizer uses have not been captured. Statistics on sewage sludge applied to soils were not available on an annual basis; annual production and application estimates were based on two data points that were calculated from surveys that yielded uncertainty levels as high as 14 percent (Bastian 1999). Also, the nitrogen content of organic fertilizers varies by type, as well as within individual types; however, average values were used to estimate total organic fertilizer nitrogen consumed. Similar uncertainty levels are associated with the nitrogen content of sewage sludge. Conversion factors for the bean,

Table 5-21: Direct N_2O Emissions from Pasture, Range, and Paddock Animals (MMTCE)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
Beef Cattle	9.0	9.1	9.3	9.5	9.8	10.0	10.0	9.7	9.5
Swine	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.2	0.2
Sheep	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Goats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+	+
Poultry	+	+	+	+	+	+	+	+	+
Horses	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total	**10.3**	**10.3**	**10.6**	**10.7**	**10.9**	**11.1**	**11.0**	**10.7**	**10.5**

+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding.

Table 5-22: Indirect N_2O Emissions (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
Volatilization & Atm. Deposition	**3.7**	**3.7**	**3.8**	**3.8**	**3.9**	**3.9**	**4.0**	**3.9**	**3.9**
Comm. Fertilizers & Sew. Sludge	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5
Animal Waste	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Surface Run-off & Leaching	**18.7**	**19.0**	**19.2**	**19.7**	**20.4**	**20.1**	**20.4**	**20.3**	**20.3**
Comm. Fertilizer & Sew. Sludge	10.2	10.3	10.4	10.8	11.3	10.9	11.3	11.3	11.3
Animal Waste	8.6	8.7	8.8	8.9	9.1	9.2	9.1	9.0	9.0
Total	**22.4**	**22.7**	**23.0**	**23.6**	**24.3**	**24.0**	**24.3**	**24.3**	**24.2**

Note: Totals may not sum due to independent rounding.

pulse, alfalfa, and non-alfalfa legume production statistics were based on a limited number of studies, and may not be representative of all conditions in the United States. It was assumed that the entire crop residue for corn, wheat, beans, and pulses was returned to the soils, with the exception of the fraction burned. A portion of this residue may be disposed of through other practices, such as composting or landfilling; however, data on these practices are not available. The point estimates of yearly production yields for non-alfalfa forage legumes carry a high degree of uncertainty; many of the estimated average coverage densities and cover areas are based on a combination of on-field experimentation and expert judgment. Also, the amount of nitrogen that is added to soils from non-alfalfa forage will depend at least in part on grazing intensity, which has not been taken into account. Lastly, the livestock excretion values, while based on detailed population and weight statistics, were derived using simplifying assumptions concerning the types of management systems employed; for example, emissions due to grazing dairy cattle are probably underestimated, while emissions due to soil application of dairy cattle waste are overestimated.

Agricultural Residue Burning

Large quantities of agricultural crop residues are produced by farming activities. There are a variety of ways to dispose of these residues. For example, agricultural residues can be plowed back into the field, composted and then applied to soils, landfilled, or burned in the field. Alternatively, they can be collected and used as a fuel or sold in supplemental feed markets. Field burning of crop residues is not considered a net source of carbon dioxide (CO_2) because the carbon released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), and nitrogen oxides (NO_x), which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States; therefore, emissions from this source are minor. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, corn, barley, soybeans, and peanuts, and of these residues, less than 5 percent is burned each year, except for rice.[15] Annual emissions

Table 5-23: Emissions from Agricultural Residue Burning (MMTCE)

Gas/Crop Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**0.2**	**0.2**	**0.2**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Wheat	+	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+	+	+
Soybeans	+	+	+	+	0.1	+	+	0.1	0.1
Peanuts	+	+	+	+	+	+	+	+	+
N_2O	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Wheat	+	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+	+
Soybeans	0.1	0.1	0.1	+	0.1	0.1	0.1	0.1	0.1
Peanuts	+	+	+	+	+	+	+	+	+
Total	**0.3**	**0.2**	**0.3**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

\+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding.

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[15] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Data Sources" discussion below).

from this source over the period 1990 through 1998 averaged approximately 0.2 MMTCE (31 Gg) of CH_4, 0.1 MMTCE (1 Gg) of N_2O, 650 Gg of CO, and 29 Gg of NO_x (see Table 5-23 and Table 5-24).

Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). In order to estimate the amounts of carbon and nitrogen released during burning, the following equations were used:

Carbon Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues Burned *in situ*) × (Dry Matter content of the Residue) × (Burning Efficiency) × (Carbon Content of the Residue) × (Combustion Efficiency)[16]

Nitrogen Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues

Table 5-24: Emissions from Agricultural Residue Burning (Gg)

Gas/Crop Type	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**30**	**28**	**33**	**26**	**34**	**28**	**32**	**34**	**35**
Wheat	7	5	6	6	6	5	5	6	6
Rice	2	2	3	2	2	2	2	2	2
Sugarcane	1	1	1	1	1	1	1	1	1
Corn	12	11	14	10	15	11	14	14	15
Barley	1	1	1	1	1	1	1	1	1
Soybeans	7	7	8	7	9	8	9	10	10
Peanuts	+	+	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Wheat	+	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+	+
CO	**623**	**578**	**688**	**544**	**717**	**590**	**675**	**704**	**733**
Wheat	137	99	124	120	116	109	114	124	128
Rice	48	47	54	40	49	41	47	42	44
Sugarcane	18	20	20	20	20	20	19	21	22
Corn	254	240	304	203	322	237	296	295	313
Barley	15	16	16	14	13	13	14	13	12
Soybeans	148	153	168	144	193	167	183	207	212
Peanuts	2	3	3	2	3	2	2	2	2
NO_x	**26**	**26**	**29**	**23**	**32**	**27**	**30**	**32**	**34**
Wheat	1	1	1	1	1	1	1	1	1
Rice	1	1	2	1	1	1	1	1	1
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	8	8	10	6	10	8	9	9	10
Barley	+	+	+	+	+	+	+	+	+
Soybeans	14	14	16	14	18	16	17	20	20
Peanuts	+	+	+	+	+	+	+	+	+

+ Does not exceed 0.5 Gg

Note: Totals may not sum due to independent rounding.

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[16] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to CO_2. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" was added to the calculations.

Burned *in situ*) × (Dry Matter Content of the Residue) · (Burning Efficiency) × (Nitrogen Content of the Residue) × (Combustion Efficiency)

Emissions of CH_4 and CO were calculated by multiplying the amount of carbon released by the appropriate IPCC default emission ratio (i.e., CH_4-C/C or CO-C/C). Similarly, N_2O and NO_x emissions were calculated by multiplying the amount of nitrogen released by the appropriate IPCC default emission ratio (i.e., N_2O-N/N or NO_x-N/N).

Data Sources

The crop residues that are burned in the United States were determined from various state level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

Crop production data were taken from the USDA's *Field Crops, Final Estimates 1987-1992, 1992-1997* (USDA 1994, 1998) and *Crop Production 1998 Summary* (USDA 1999), except data on the production of rice in Florida, which USDA does not estimate. To estimate Florida rice production, an average 1998 value for ice productivity (i.e., metric tons rice/acre) was obtained from Sem-Chi Rice, which produces the majority of rice in Florida (Smith 1999), and multiplied by total Florida rice acreage each year (Schueneman 1999c). The production data for the crop types whose residues are burned are presented in Table 5-25.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice acreage on which residue burning took place were obtained on a state-by-state basis from agricultural extension agents in each of the seven rice-producing states (Guethle 1999, Fife 1999, Klosterboer 1999a and 1999b, Slaton 1999a and 1999b, Linscombe 1999a and 1999b, Schueneman 1999a and 1999b, Street 1999a and 1999b) (see Table 5-26 and Table 5-27). The estimates provided for each state remained the same from year to year for all states, with the exception of California. For California, it was assumed that the annual percents of rice acreage burned in Sacramento Valley are representative of burning in the entire state, because the Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). The annual percents of rice acreage burned in Sacramento

Table 5-26: Percentage of Rice Area Burned By State

State	Percent Burned
Arkansas	10
California	variable[a]
Florida[b]	0
Louisiana	6
Mississippi	10
Missouri	3.5
Texas	2

[a] Values provided in Table 5-27.

[b] Burning of crop residues is illegal in Florida.

Table 5-25: Agricultural Crop Production (Thousand Metric Tons of Product)

Crop	1990	1991	1992	1993	1994	1995	1996	1997	1998
Wheat	74,292	53,891	67,135	65,220	63,167	59,404	61,980	67,534	69,410
Rice	7,105	7,271	8,196	7,127	9,019	7,935	7,828	8,339	8,570
Sugarcane	25,525	27,444	27,545	28,188	28,057	27,922	26,729	28,766	30,588
Corn*	201,534	189,868	240,719	160,986	255,295	187,970	234,518	233,864	247,943
Barley	9,192	10,110	9,908	8,666	8,162	7,824	8,544	7,835	7,674
Soybeans	52,416	54,065	59,612	50,885	68,444	59,174	64,780	73,176	75,028
Peanuts	1,635	2,235	1,943	1,539	1,927	1,570	1,661	1,605	1,783
Total	**371,698**	**344,883**	**415,058**	**322,612**	**434,069**	**351,799**	**406,041**	**421,120**	**440,995**

*Corn for grain (i.e., excludes corn for silage).

Valley were obtained from Fife (1999). These values declined over the 1990-1998 period because of a legislated reduction in agricultural burning (see Table 5-27). Because the percentage of rice acreage burned varied from state to state, and from year to year within California, a weighted average national "percent burned" factor was derived for rice for each year (Table 5-27). The weighting was based on rice area in each state.

Residue/crop product mass ratios, residue dry matter contents, residue carbon contents, and residue nitrogen contents for all crops except sugarcane, peanuts, and soybeans were taken from Strehler and Stützle (1987). These data for sugarcane were taken from University of California (1977) and Turn et al. (1997). Residue/crop product mass ratios and residue dry matter contents for peanuts and soybeans were taken from Strehler and Stützle (1987); residue carbon contents for these crops were set at 0.45 and residue nitrogen contents were taken from Barnard and Kristoferson (1985). The value for peanuts was set equal to the soybean value. These assumptions are listed in Table 5-28. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent for all crop types (EPA 1994). Emission ratios for all gases (see Table 5-29) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Uncertainty

The largest source of uncertainty in the calculation of non-CO_2 emissions from field burning of agricultural residues is in the estimates of the fraction of residue of each crop type burned each year. Data on the fraction burned, as well as the gross amount of residue burned each year, are not collected at either the national or state level. In addition, burning practices are highly variable among crops, as well as among states. The fractions of residue burned used in these calculations were based upon information collected by state agencies and in pub-

Table 5-27: Percentage of Rice Area Burned

Year	California	U.S. (weighted average)
1990	43	12
1991	43	12
1992	43	12
1993	26	10
1994	24	10
1995	20	9
1996	27	11
1997	16	9
1998	19	9

Table 5-29: Greenhouse Gas Emission Ratios

Gas	Emission Ratio
CH_4[a]	0.005
CO[a]	0.060
N_2O[b]	0.007
NO_x[b]	0.121

[a] Mass of carbon compound released (units of C) relative to mass of total carbon released from burning (units of C)
[b] Mass of nitrogen compound released (units of N) relative to mass of total nitrogen released from burning (units of N)

Table 5-28: Key Assumptions for Estimating Emissions from Agricultural Residue Burning[a]

Crop	Residue/ Crop Ratio	Fraction of Residue Burned	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction
Wheat	1.3	0.03	0.85	0.4853	0.0028
Rice	1.4	variable[b]	0.85	0.4144	0.0067
Sugarcane	0.8	0.03	0.62	0.4235	0.0040
Corn	1.0	0.03	0.78	0.4709	0.0081
Barley	1.2	0.03	0.85	0.4567	0.0043
Soybeans	2.1	0.03	0.87	0.4500	0.0230
Peanuts	1.0	0.03	0.90	0.4500	0.0230

[a] The burning efficiency and combustion efficiency for all crops were assumed to be 0.93 and 0.88, respectively.
[b] See Table 5-27.

lished literature. It is likely that these emission estimates will continue to change as more information becomes available in the future.

Other sources of uncertainty include the residue/crop product mass ratios, residue dry matter contents, burning and combustion efficiencies, and emission ratios. A residue/crop product ratio for a specific crop can vary among cultivars, and for all crops except sugarcane, generic residue/crop product ratios, rather than ratios specific to the United States, have been used. Residue dry matter contents, burning and combustion efficiencies, and emission ratios, all can vary due to weather and other combustion conditions, such as fuel geometry. Values for these variables were taken from literature on agricultural biomass burning.

6. Land-Use Change and Forestry

This chapter provides an assessment of the net carbon dioxide (CO_2) flux caused by (1) changes in forest carbon stocks, (2) changes in non-forest soil carbon stocks, and (3) changes in non-forest carbon stocks in landfills. Six components of forest carbon stocks are analyzed: trees, understory, forest floor, forest soil, wood products, and landfilled wood. The estimated CO_2 flux from each of these forest components is based on carbon stock estimates developed by the U.S. Forest Service, using methodologies that are consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Changes in non-forest soil carbon stocks include mineral and organic soil carbon stock changes due to agricultural land use and land management, and emissions of CO_2 due to the application of crushed limestone and dolomite to agricultural soils. The methods in the *Revised 1996 IPCC Guidelines* were used to estimate all three components of changes in non-forest soil carbon stocks. Changes in non-forest carbon stocks in landfills are estimated for yard trimmings disposed in landfills using EPA's method of analyzing life cycle GHG emissions and sinks associated with solid waste management (EPA 1998).

Unlike the assessments in other chapters, which are based on annual activity data, the flux estimates in this chapter, with the exception of emissions from liming and carbon storage associated with yard trimmings disposed in landfills, are based on periodic activity data in the form of forest and soil surveys. Carbon dioxide fluxes from forest carbon stocks and from non-forest mineral and organic soils are calculated on an average annual basis over five- or ten-year periods. The resulting annual averages are applied to years between surveys. As a result of this data structure, estimated CO_2 fluxes are constant over multi-year intervals. In addition, because the most recent national forest survey was completed for the year 1992, the estimates of the CO_2 flux from forest carbon stocks are based in part on modeled projections of stock estimates for the year 2000.[1]

The previous U.S. Inventory included only a preliminary assessment of the net CO_2 flux from two non-forest soil components: use and management of organic soils and liming of agricultural soils. In the current Inventory, revised estimates of flux from organic soils—based on revised activity data—updated flux estimates for liming of agricultural soils—based on updated activity data—and flux estimates for non-forest mineral soils are included. However, due to the lack of a national soil survey more recent than 1992, carbon flux estimates for non-forest mineral and organic soils were not calculated for the 1993 through 1998 period. Therefore, the non-forest soil carbon flux estimates are not included in the total fluxes reported for this chapter.

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[1] The national forest survey for 1997 is expected to be completed this year. This survey will be used to develop revised forest carbon flux estimates, which will be presented in the 1990-1999 version of the U.S. Inventory.

Estimates of total annual net CO_2 flux from land-use change and forestry decline from 316 to 211 MMTCE (1,160,000 to 773,000 Gg) net sequestration between 1990 and 1998 (Table 6-1 and Table 6-2). The decrease in annual net CO_2 sequestration is due to a maturation and slowed expansion of the U.S. forest cover and a gradual decrease in the rate of yard trimmings disposed in landfills; the abrupt shift between 1992 and 1993 is a result of the use of methodologies that incorporate periodic activity data and decadal, rather than annual, stock estimates.

Changes in Forest Carbon Stocks

Globally, the most important human activity that affects forest carbon fluxes is deforestation, particularly the clearing of tropical forests for agricultural use. Tropical deforestation is estimated to have released nearly 6 billion metric tons of CO_2 per year during the 1980s, or about 23 percent of global CO_2 emissions from anthropogenic activities. Conversely, during this period about 7 percent of global CO_2 emissions were offset by CO_2 uptake due to forest regrowth in the Northern Hemisphere (Houghton et al. 1995).

Table 6-1: Net CO_2 Flux from Land-Use Change and Forestry (MMTCE)*

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Forests	**(274.2)**	**(274.2)**	**(274.2)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**
Trees	(95.6)	(95.6)	(95.6)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)
Understory	(2.4)	(2.4)	(2.4)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Forest Floor	(20.8)	(20.8)	(20.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)
Soil	(155.2)	(155.2)	(155.2)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)
Harvested Wood	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**
Wood Products	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)
Landfilled Wood	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)
Landfilled Yard Trimmings	(4.9)	(4.8)	(4.7)	(4.2)	(3.7)	(3.3)	(2.7)	(2.6)	(2.3)
Total Net Flux	**(316.4)**	**(316.1)**	**(316.2)**	**(213.3)**	**(212.8)**	**(211.9)**	**(211.3)**	**(211.2)**	**(210.9)**

Note: Parentheses indicate sequestration. Totals may not sum due to independent rounding. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
*The total net flux excludes flux estimates for non-forest soils due to incomplete flux estimates for organic and mineral soils for the 1990 through 1998 period.

Table 6-2: Net CO_2 Flux from Land-Use Change and Forestry (Gg)*

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Forests	**(1,005,400)**	**(1,005,400)**	**(1,005,400)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**
Trees	(350,500)	(350,500)	(350,500)	(271,300)	(271,300)	(271,300)	(271,300)	(271,300)	(271,300)
Understory	(8,800)	(8,800)	(8,800)	(4,600)	(4,600)	(4,600)	(4,600)	(4,600)	(4,600)
Forest Floor	(76,300)	(76,300)	(76,300)	(35,800)	(35,800)	(35,800)	(35,800)	(35,800)	(35,800)
Soil	(569,100)	(569,100)	(569,100)	(316,300)	(316,300)	(316,300)	(316,300)	(316,300)	(316,300)
Harvested Wood	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**
Wood Products	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)
Landfilled Wood	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)
Landfilled Yard Trimmings	(17,800)	(17,500)	(17,100)	(15,300)	(13,600)	(12,000)	(10,000)	(9,400)	(8,300)
Total Net Flux	**(1,160,000)**	**(1,159,700)**	**(1,159,300)**	**(780,000)**	**(778,300)**	**(776,700)**	**(774,700)**	**(774,100)**	**(773,000)**

Note: Parentheses indicate sequestration. Totals may not sum due to independent rounding. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
*The total net flux excludes flux estimates for non-forest soils due to incomplete flux estimates for organic and mineral soils for the 1990 through 1998 period.

In the United States, the amount of forest land has remained fairly constant during the last several decades. The United States covers roughly 2,263 million acres, of which 33 percent (737 million acres) is forest land (Powell et al. 1993). The amount of forest land declined by approximately 5.2 million acres between 1977 and 1987 (USFS 1990, Waddell et al. 1989), and increased by about 5.3 million acres between 1987 and 1992 (Powell et al. 1993). These changes represent average fluctuations of only about 0.1 percent per year. Other major land-use categories in the United States include range and pasture lands (29 percent), cropland (17 percent), urban areas (3 percent), and other lands (18 percent) (Daugherty 1995).

Given the low rate of change in U.S. forest land area, the major influences on the current net carbon flux from forest land are management activities and ongoing impacts of previous land-use changes. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems. For example, intensified management of forests can increase both the rate of growth and the eventual biomass density of the forest, thereby increasing the uptake of carbon. The reversion of cropland to forest land through natural regeneration also will, over decades, result in increased carbon storage in biomass and soils.

Forests are complex ecosystems with several interrelated components, each of which acts as a carbon storage pool, including:

- Trees (i.e., living trees, standing dead trees, roots, stems, branches, and foliage)
- Understory vegetation (i.e., shrubs and bushes)
- The forest floor (i.e., woody debris, tree litter, and humus)
- Soil

As a result of biological processes in forests (e.g., growth and mortality) and anthropogenic activities (e.g., harvesting, thinning, and replanting), carbon is continuously cycled through these ecosystem components, as well as between the forest ecosystem and the atmosphere. For example, the growth of trees results in the uptake of carbon from the atmosphere and storage of carbon in living biomass. As trees age, they continue to accumulate carbon until they reach maturity, at which point they are relatively constant carbon stores. As trees die and otherwise deposit litter and debris on the forest floor, decay processes release carbon to the atmosphere and also increase soil carbon. The net change in forest carbon is the sum of the net changes in the total amount of carbon stored in each of the forest carbon pools over time.

The net change in forest carbon, however, may not be equivalent to the net flux between forests and the atmosphere because timber harvests may not always result in an immediate flux of carbon to the atmosphere.[2] Harvesting in effect transfers carbon from one of the "forest pools" to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 if the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested for energy use, combustion results in an immediate release of carbon. Conversely, if timber is harvested and subsequently used as lumber in a house, it may be many decades or even centuries before the lumber is allowed to decay and carbon is released to the atmosphere. If wood products are disposed of in landfills, the carbon contained in the wood may be released years or decades later, or may even be stored permanently in the landfill.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in an annual net uptake (i.e., sequestration) of carbon. Also, due to improvements in U.S. agricultural productivity, the rate of forest land clearing for crop cultivation and pasture slowed in the late 19th century, and by 1920 this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were brought out of crop production, primarily between 1920 and 1950, and were allowed to revert to forest land or were actively reforested. The impacts of these land-use changes are still affecting carbon fluxes from forests in the East. In addition to land-use changes in the early part of this century, in recent

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[2] For this reason, the term "apparent flux" is used in this chapter.

decades carbon fluxes from Eastern forests were affected by a trend toward managed growth on private land, resulting in a near doubling of the biomass density in eastern forests since the early 1950s. More recently, the 1970s and 1980s saw a resurgence of federally sponsored tree-planting programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on reforesting previously harvested lands, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net carbon fluxes. Because most of the timber that is harvested from U.S. forests is used in wood products and much of the discarded wood products are disposed of by landfilling—rather than incineration—significant quantities of this harvested carbon are transferred to long-term storage pools rather than being released to the atmosphere. The size of these long-term carbon storage pools has also increased over the last century.

As shown in Table 6-3 and Table 6-4, U.S. forest components, wood product pools, and landfilled wood were estimated to account for an average annual net sequestration of 311.5 MMTCE (1,142,200 Gg CO_2) from 1990 through 1992, and 208.6 MMTCE (764,700 Gg CO_2) from 1993 through 1998. The net carbon sequestration reported for 1998 represents an offset of about 14 percent of the 1998 CO_2 emissions from fossil fuel com-

Table 6-3: Net CO_2 Flux from U.S. Forests (MMTCE)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Apparent Forest Flux	**(274.2)**	**(274.2)**	**(274.2)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**
Trees	(95.6)	(95.6)	(95.6)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)
Understory	(2.4)	(2.4)	(2.4)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Forest Floor	(20.8)	(20.8)	(20.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)
Forest Soils	(155.2)	(155.2)	(155.2)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)
Apparent Harvested Wood Flux	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**
Apparent Wood Product Flux	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)
Apparent Landfilled Wood Flux	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)
Total Net Flux	**(311.5)**	**(311.5)**	**(311.5)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**

Note: Parentheses indicate net carbon “sequestration” (i.e., sequestration or accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word “apparent” is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 6-4: Net CO_2 Flux from U.S. Forests (Gg)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Apparent Forest Flux	**(1,005,400)**	**(1,005,400)**	**(1,005,400)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**
Trees	(350,500)	(350,500)	(350,500)	(271,300)	(271,300)	(271,300)	(271,300)	(271,300)	(271,300)
Understory	(8,800)	(8,800)	(8,800)	(4,600)	(4,600)	(4,600)	(4,600)	(4,600)	(4,600)
Forest Floor	(76,300)	(76,300)	(76,300)	(35,800)	(35,800)	(35,800)	(35,800)	(35,800)	(35,800)
Soil	(569,100)	(569,100)	(569,100)	(316,300)	(316,300)	(316,300)	(316,300)	(316,300)	(316,300)
Apparent Harvested Wood Flux	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**
Wood Products	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)
Landfilled Wood	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)
Total Net Flux	**(1,142,200)**	**(1,142,200)**	**(1,142,200)**	**(764,700)**	**(764,700)**	**(764,700)**	**(764,700)**	**(764,700)**	**(764,700)**

Note: Parentheses indicate net carbon “sequestration” (i.e., sequestration or accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word “apparent” is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

bustion. The average annual net carbon sequestration reported for 1993 through 1998 represents a 33 percent decrease relative to the average annual net carbon sequestration reported for 1990 through 1992. This overall decrease in annual net sequestration is due to changes in the aggregate age structure of U.S. forests caused by the maturation of existing forests and the slowed expansion of Eastern forest cover. The abrupt shift in annual net sequestration from 1992 to 1993 is the result of calculating average annual fluxes using periodic activity data as well as models that estimate and project decadal rather than annual stock estimates.

Methodology

The methodology for estimating annual forest carbon flux in the United States differs from the methodologies employed for other activities because the forest carbon flux estimates were derived from periodic surveys rather than annual activity data. In addition, because the most recent survey was completed for 1992, a combination of survey data and projected data, rather than complete historical data, was used to derive some of the annual flux estimates.

Timber stock data from national forest surveys were used to derive estimates of carbon contained in the four forest ecosystem components (i.e., trees, understory, forest floor, and soil) for the survey years. The apparent annual forest carbon flux for a specific year was estimated as the average annual change in the total forest carbon stocks between the preceding and succeeding forest survey years. The most recent national forest surveys were conducted for the years 1987 and 1992. Therefore, the apparent annual forest carbon flux estimate for the years 1990 through 1992 was calculated from forest carbon stocks derived from the 1987 and 1992 surveys. To estimate the apparent annual forest carbon flux estimate for the years 1993 through 1998, the 1992 forest carbon stocks and forest carbon stocks for 2000, which were derived from a projection of timber stocks, were used.[3]

Carbon stocks contained in the wood product and landfilled wood pools were estimated for 1990 using historical forest harvest data, and were estimated for 2000 using projections of forest harvest. Therefore, apparent annual wood product and landfilled wood fluxes for the years 1990 through 1998 were calculated from a 1990 historical estimate and a 2000 projection.[4]

The total annual net carbon flux from forests was obtained by summing the apparent carbon fluxes associated with changes in forest stocks, wood product pools, and landfilled wood pools.

The inventory methodology described above is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The IPCC identifies two approaches to developing estimates of net carbon flux from Land-Use Change and Forestry: (1) using average annual statistics on land-use change and forest management activities, and applying carbon density and flux rate data to these activity estimates to derive total flux values; or (2) using carbon stock estimates derived from periodic inventories of forest stocks, and measuring net changes in carbon stocks over time. The latter approach was employed because the United States conducts periodic surveys of national forest stocks. In addition, the IPCC identifies two approaches to accounting for carbon emissions from harvested wood: (1) assuming that all of the harvested wood replaces wood products that decay in the inventory year so that the amount of carbon in annual harvests equals annual emissions from harvests; or (2) accounting for the variable rate of decay of harvested wood according to its disposition (e.g., product pool, landfill, combustion). The latter approach was applied for this inventory using estimates of carbon stored in wood products and landfilled wood.[5] Although there are large uncertainties associated with the data used to develop the flux estimates presented here, the use of direct measurements from forest surveys and associated estimates of product and landfilled wood pools is likely

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[3] Once the 1997 national forest survey is released, new annual estimates of forest carbon flux will be developed. These new estimates will be reported in the 1990-1999 U.S. Inventory.

[4] These values will also be revised once the 1997 national forest survey is released.

[5] This calculation does not account for carbon stored in imported wood products. It does include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

to result in more accurate flux estimates than the alternative IPCC methodology.

Data Sources

The estimates of forest, product, and landfill carbon stocks used in this inventory to derive forest carbon fluxes were obtained from Birdsey and Heath (1995), Heath et al. (1996), and Heath (1997). The amount of carbon in trees, understory vegetation, the forest floor, and forest soil in 1987 and 1992 was estimated using timber volume data collected by the U.S. Forest Service (USFS) for those years (Waddell et al. 1989; Powell et al. 1993). The timber volume data include timber stocks on forest land classified as timberland, reserved forest land, or other forest land[6] in the contiguous United States, but do not include stocks on forest land in Alaska, Hawaii, U.S. territories, or trees on non-forest land (e.g., urban trees).[7] The timber volume data include estimates by tree species, size class, and other categories.

The amount of carbon in trees, understory vegetation, the forest floor, and forest soil in 2000 was estimated by Birdsey and Heath (1995) using the FORCARB forest carbon model (Plantinga and Birdsey 1993) linked to the TAMM/ATLAS forest sector model (Adams and Haynes 1980; Alig 1985; Haynes and Adams 1985; Mills and Kincaid 1992). The forest stock projections for 2000, therefore, are based on multiple variables, including projections of prices, consumption, and production of timber and wood products; and projections of forest area, forest inventory volume, growth, and removals.

The amount of carbon in aboveground and below ground tree biomass in forests was calculated by multiplying timber volumes by conversion factors derived from studies in the United States (Cost et al. 1990, Koch 1989). Carbon stocks in the forest floor and understory vegetation were estimated based on simple models (Vogt et al. 1986) and review of numerous intensive ecosystem studies (Birdsey 1992). Soil carbon stocks were calculated using a model similar to Burke et al. (1989) based on data from Post et al. (1982).

Carbon stocks in wood products in use and in wood stored in landfills were estimated by applying the HARVCARB model (Row and Phelps 1991) to historical harvest data from the USFS (Powell et al. 1993) and harvest projections for 2000 (Adams and Haynes 1980; Mills and Kincaid 1992). The HARVCARB model allocates harvested carbon to disposition categories (i.e., products, landfills, energy use, and emissions), and tracks the accumulation of carbon in different disposition categories over time.

Table 6-5 presents the carbon stock estimates for forests—including trees, understory, forest floor, and forest soil—wood products, and landfilled wood used in this inventory. The increase in all of these stocks over time indicates that, during the examined periods, forests, forest product pools, and landfilled wood all accumulated carbon (i.e., carbon sequestration by forests was greater than carbon removed in wood harvests and released through decay; and carbon accumulation in product pools and landfills was greater than carbon emissions from these pools by decay and burning).

Uncertainty

There are considerable uncertainties associated with the estimates of the net carbon flux from U.S. forests. The first source of uncertainty stems from the underlying forest survey data. These surveys are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. Therefore, the actual timber volumes contained in forests are represented by average values that are subject to sampling and estimation errors. In addition, the forest survey data that are currently available exclude timber stocks on forest land in Alaska, Hawaii, U.S. territories, and trees

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[6] Forest land in the United States includes all land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, growing at a rate of 20 cubic feet per acre per year or more. In 1992, there were about 490 million acres of Timberlands, which represented 66 percent of all forest lands (Powell et al. 1993). Forest land classified as Timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 34 percent of forest land is classified as Productive Reserved Forest Land, which is withdrawn from timber use by statute or regulation, or Other Forest Land, which includes unreserved and reserved unproductive forest land.

[7] Although forest carbon stocks in Alaska and Hawaii are large compared to the U.S. total, net carbon fluxes from forest stocks in Alaska and Hawaii are believed to be minor. Net carbon fluxes from urban tree growth are also believed to be minor.

Table 6-5: U.S. Forest Carbon Stock Estimates (Gg)

Description	1987	1990	1992	2000
Forests	**36,353,000**	**NA**	**37,724,000**	**39,094,000**
Trees	13,009,000	NA	13,487,000	14,079,000
Understory	558,000	NA	570,000	580,000
Forest Floor	2,778,000	NA	2,882,000	2,960,000
Forest Soil	20,009,000	NA	20,785,000	21,475,000
Harvested Wood	**NA**	**3,739,000**	**NA**	**4,112,000**
Wood Products	NA	2,061,000	NA	2,240,000
Landfilled Wood	NA	1,678,000	NA	1,872,000

NA (Not Available)
Note: Forest carbon stocks do not include forest stocks in Alaska, Hawaii, U.S. territories, or trees on non-forest land (e.g., urban trees); wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Shaded areas indicate values based on projections. All other values are based on historical data. Totals may not sum due to independent rounding.

on non-forest land (e.g., urban trees); however, net carbon fluxes from these stocks are believed to be minor.

The second source of uncertainty results from deriving carbon storage estimates for the forest floor, understory vegetation, and soil from models that are based on data from forest ecosystem studies. In order to extrapolate results of these studies to all forest lands, it was assumed that they adequately describe regional or national averages. This assumption can potentially introduce the following errors: (1) bias from applying data from studies that inadequately represent average forest conditions, (2) modeling errors (e.g., erroneous assumptions), and (3) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). In particular, the impacts of forest management activities, including harvest, on soil carbon are not well understood. Moore et al. (1981) found that harvest may lead to a 20 percent loss of soil carbon, while little or no net change in soil carbon following harvest was reported in another study (Johnson 1992). Since forest soils contain over 50 percent of the total stored forest carbon in the United States, this difference can have a large impact on flux estimates.

The third source of uncertainty results from the use of projections of forest carbon stocks for the year 2000 (Birdsey and Heath 1995) to estimate annual net carbon sequestration from 1993 to 1998. These projections are the product of two linked models (i.e., FORCARB and TAMM/ATLAS) that integrate multiple uncertain variables related to future forest growth and economic forecasts. Because these models project decadal rather than annual carbon fluxes, estimates of annual net carbon sequestration from 1993 to 1998 are calculated as *average* annual estimates based on projected long-term changes in U.S. forest stocks.

The fourth source of uncertainty results from incomplete accounting of wood products. Because the wood product stocks were estimated using U.S. harvest statistics, these stocks include exports, even if the logs were processed in other countries, and exclude imports. Haynes (1990) estimates that imported timber accounts for about 12 percent of the timber consumed in the United States, and that exports of roundwood and primary products account for about 5 percent of harvested timber.

Changes in Non-Forest Soil Carbon Stocks

The amount of organic carbon contained in soils depends on the balance between inputs of photosynthetically fixed carbon (i.e., organic matter such as decayed detritus and roots) and loss of carbon through decomposition. The quantity and quality of organic matter inputs, and the rate of decomposition, are determined by the combined interaction of climate, soil properties, and land-use. Agricultural practices and other land-use activities, such as clearing, drainage, tillage, planting, crop residue management, fertilization, and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net flux of carbon to or from soils. In addition, the application of carbonate minerals to soils through liming operations results in emissions of CO_2. The IPCC methodology for changes in non-forest soil carbon stocks (IPCC/UNEP/OECD/IEA 1997) is divided into three categories of land-use/land-management activities: (1) agricultural land-use and land management activities on mineral soils, especially land-use change activities; (2) agricultural land-use and land management activities on organic soils, especially cultivation and conversion to pasture and forest; and (3) liming of soils. Organic soils and mineral soils are treated separately because each responds differently to land-use practices.

Organic soils contain extremely deep and rich layers of organic matter. When these soils are cultivated, tilling or mixing of the soil aerates the soil, thereby accelerating the rate of decomposition and CO_2 generation. Because of the depth and richness of the organic layers, carbon loss from cultivated organic soils can continue over long periods of time. Conversion of organic soils to agricultural uses typically involves drainage as well, which also causes soil carbon oxidation. When organic soils are disturbed, through cultivation and/or drainage, the rate at which organic matter decomposes, and therefore the rate at which CO_2 emissions are generated, is determined primarily by climate, the composition (decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for upland crops results in greater carbon loss than conversion to pasture or forests, due to deeper drainage and/or more intensive management practices (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997).

Mineral soils contain considerably less organic carbon than organic soils. Furthermore, much of the organic carbon is concentrated near the soil surface. When mineral soils undergo conversion from their native state to agricultural use, as much as half of the soil organic carbon can be lost to the atmosphere. The rate and ultimate magnitude of carbon loss will depend on native vegetation, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40-60 percent of the carbon loss occurs within the first 10 years following conversion; after that, carbon stocks continue to drop but at a much slower rate. In temperate regions, carbon loss can continue for several decades. Eventually, the soil will reach a new equilibrium that reflects a balance between carbon accumulation from plant biomass and carbon loss through oxidation. Any changes in land-use or management practices that result in increased biomass production or decreased oxidation (e.g., crop rotations, cover crops, application of organic amendments and manure, and reduction or elimination of tillage) will result in a net accumulation of soil organic carbon until a new equilibrium is achieved.

Lime in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) is commonly added to agricultural soils to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating CO_2. The rate of degradation is determined by soil conditions and the type of mineral applied; it can take several years for agriculturally-applied lime to degrade completely.

Of the three activities, use and management of mineral soils was by far the most important in terms of contribution to total flux during the 1990 through 1992 period (see Table 6-6 and Table 6-7). Because the most recent national survey of land-use and management is from 1992, carbon flux estimates for the years 1993 through 1998 for non-forest organic and mineral soils are not included. Annual carbon sequestration on mineral soils for 1990 through 1992 was estimated at 18.2 MMTCE (66,600 Gg CO_2), while annual emissions from organic soils were estimated at 7.4 MMTCE (27,100 Gg CO_2). Between 1990 and 1998, liming accounted for net annual emissions that ranged from 2.1 to 3.0 MMTCE (7,700 to 11,000 Gg CO_2). Total net annual CO_2 flux from all three activities on non-forest soils (use and management of mineral and organic soils, and liming of soils) was negative over the 1990 to 1992 period (i.e., the combined activities resulted in net carbon sequestration each year). While organic soils and liming both accounted for net CO_2 emissions, the sum of emissions from both activities was more than offset by carbon sequestration in mineral soils.

The emission estimates and analysis for this source are restricted to CO_2 fluxes associated with the use and

Table 6-6: Net CO_2 Flux From Non-Forest Soils (MMTCE)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Mineral Soils	(18.2)	(18.2)	(18.2)	NA	NA	NA	NA	NA	NA
Organic Soils	7.4	7.4	7.4	NA	NA	NA	NA	NA	NA
Liming of Soils	2.2	2.8	2.1	2.1	2.3	2.5	2.4	2.4	3.0

Note: Numbers in parentheses indicate net carbon sequestration.
NA: Not available.

Table 6-7: Net CO_2 Flux From Non-Forest Soils (Gg)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Mineral Soils	(66,600)	(66,600)	(66,600)	NA	NA	NA	NA	NA	NA
Organic Soils	27,100	27,100	27,100	NA	NA	NA	NA	NA	NA
Liming of Soils	8,088	10,224	7,687	7,722	8,455	9,191	8,882	8,702	10,943

Note: Numbers in parentheses indicate net carbon sequestration. Totals might not add up due to independent rounding.
NA: Not available.

management of non-forest mineral and organic soils and liming of soils. However, it is important to note that land-use and land-use change activities may also result in fluxes of non-CO_2 greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO), to and from soils. For example, when lands are flooded with freshwater, such as during hydroelectric dam construction, CH_4 is produced and emitted to the atmosphere due to anaerobic decomposition of organic material in the soil and water column. Conversely, when flooded lands, such as lakes and wetlands, are drained, anaerobic decomposition and associated CH_4 emissions will be reduced. Dry soils are a sink of CH_4, so eventually, drainage may result in soils that were once a source of CH_4 becoming a sink of CH_4. However, once the soils become aerobic, oxidation of soil carbon and other organic material will result in elevated emissions of CO_2. Moreover, flooding and drainage may also affect net soil fluxes of N_2O and CO, although these fluxes are highly uncertain. The fluxes of CH_4, and other gases, due to flooding and drainage are not assessed in this inventory due to a lack of activity data on the extent of these practices in the United States as well as scientific uncertainties about the variables that control fluxes.[8]

Methodology and Data Sources

The methodologies used to calculate CO_2 emissions from use and management of mineral and organic soils and from liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), except where noted below.

The estimates of annual net CO_2 flux from mineral soils are based on work by Eve et al. (2000). Eve at al. developed total mineral soil carbon stock estimates for 1982 and 1992 by applying the default IPCC carbon stock and carbon adjustment factors to area estimates derived from U.S. databases on climate (Daly et al. 1994, 1998), soil types and land use and management (USDA 1994), and tillage practices (CTIC 1998). These databases were linked to obtain total area for each combined climate/soil/land-use/tillage category in 1982 and 1992. To derive carbon stock estimates for each year, the areas for each combined category were multiplied by the default IPCC values for soil carbon under native vegetation, and base, tillage, and input factors. The base, tillage, and input factors were adjusted to account for use of a ten-year accounting period, rather than the 20-year period used in the *IPCC Guidelines*. The changes in carbon stocks between 1982 and 1992 for all categories

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[8] However, methane emissions due to flooding of rice fields are included, as are nitrous oxide emissions from agricultural soils. These are addressed under the Rice Cultivation and Agricultural Soil Management sections, respectively, of the Agriculture chapter.

were then summed, and divided by ten, to obtain an estimate of total average annual change in carbon C stocks (i.e., net flux) for that period. The *1997 National Resources Inventory*, which will be a 1997 update of USDA (1994), had not been completed at the time this version of the U.S. Inventory was compiled. Publication of the *1997 National Resources Inventory* will enable mineral soil carbon stock estimates for 1997 to be developed, which will allow for estimation of annual average mineral soil carbon flux for 1993 through 1998.

The estimates of annual CO_2 emissions from organic soils are also based on Eve et al. (2000). The procedure used is similar to that for mineral soils, except that organic soils under native vegetation were excluded from the database under the assumption that they are not significantly affected by human activity. Following the IPCC methodology, only organic soils under intense management were included, and the default IPCC rates of carbon loss were applied to the total 1982 and 1992 areas for the climate/land-use categories defined in the IPCC Guidelines. The area estimates were derived from the same climatic, soil, and land-use/land management databases that were used in the mineral soil calculations (Daly et al. 1994, 1998; USDA 1994). As with mineral soils, producing estimates for 1993 through 1998 will be possible once the *1997 National Resources Inventory* is published.

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were calculated by multiplying the annual amounts of limestone and dolomite applied (see Table 6-8), by CO_2 emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite).[9] These emission factors are based on the assumption that all of the carbon in these materials evolves as CO_2. The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the U.S. Geological Survey's Mineral Resources Program Crushed Stone Reports and Mineral Industry Surveys (USGS 1993; 1995; 1996; 1997a,b; 1998a,b; 1999a,b). To develop these data, the Mineral Resources Program obtained production and use information by surveying crushed stone manufacturers. Because some manufacturers were reluctant to provide information, the estimates of total crushed limestone and dolomite production and use are divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production). To estimate the total amounts of crushed limestone and dolomite applied to agricultural soils, it was assumed that the fractions of "unspecified" and "estimated" production that were applied to agricultural soils were equal to the fraction of "specified" production that was applied to agricultural soils. In addition, data were not available in 1990, 1992, and 1998 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate these data, average annual fractions were derived from data in the other years (i.e., 1991, 1993, and 1994 through 1997) and were applied to the total crushed stone production statistics in 1990, 1992, and 1998.

Table 6-8: Quantities of Applied Minerals (Thousand Metric Tons)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Limestone	15,807	19,820	15,024	15,340	16,730	17,913	17,479	16,539	21,337
Dolomite	2,417	3,154	2,297	2,040	2,294	2,747	2,499	2,989	3,262

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[9] Note: the default emission factor for dolomite provided in the Workbook volume of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) is incorrect. The value provided is 0.122 metric ton carbon/metric ton of dolomite; the correct value is 0.130 metric ton carbon/metric ton of dolomite.

Uncertainty

Uncertainties in the flux estimates for mineral and organic soils result from both the activity data and the carbon stock and adjustment factors. Each of the datasets used in deriving the area estimates has a level of uncertainty that is passed on through the analysis, and the aggregation of data over large areas necessitates a certain degree of generalization. The default IPCC values used for estimates of mineral soil carbon stocks under native vegetation, as well as for the base, tillage and input factors, carry with them high degrees of uncertainty, as these values represent broad regional averages based on expert judgment. Moreover, measured carbon loss rates from cultivated organic soils vary by as much as an order of magnitude. In addition, this methodology does not take into account changes in carbon stocks and land-use trends that occurred over longer time periods.

Uncertainties in the estimates of emissions from liming stem primarily from the methodology, rather than the underlying activity data. It can take several years for agriculturally-applied lime to degrade completely. The IPCC method assumes that the amount of mineral applied in any year is equal to the amount that degrades in that year, so annual application rates can be used to derive annual emissions. Further research is required to determine applied limestone degradation rates. Moreover, soil and climatic conditions are not taken into account in the calculations.

Table 6-9: Net CO_2 Flux from Non-Forest Carbon Stocks in Landfills

Year	MMTCE	Gg
1990	(4.9)	(17,800)
1991	(4.8)	(17,500)
1992	(4.7)	(17,100)
1993	(4.2)	(15,300)
1994	(3.7)	(13,600)
1995	(3.3)	(12,000)
1996	(2.7)	(10,000)
1997	(2.6)	(9,400)
1998	(2.3)	(8,300)

Note: Parentheses indicate sequestration.

Changes in Non-Forest Carbon Stocks in Landfills

As is the case with landfilled forest products, carbon contained in landfilled yard trimmings can be stored indefinitely. In the United States, yard trimmings (i.e., grass clippings, leaves, branches) comprise a significant portion of the municipal waste stream. In 1990, the EPA estimated discards of yard trimmings to landfills at over 21 million metric tons. Since then, programs banning or discouraging disposal, coupled with a dramatic rise in the number of composting facilities, have decreased the disposal rate for yard trimmings; the 1998 landfill disposal was about 10 million metric tons. The decrease in the yard trimmings landfill disposal rate has resulted in a decrease in the rate of landfill carbon storage from about 4.9 MMTCE in 1990 to 2.3 MMTCE in 1998 (see Table 6-9).

Yard trimmings comprise grass, leaves, and branches and have long been a significant component of the U.S. waste stream. In 1990, discards (i.e., landfilling plus combustion) of yard trimmings were about 27.9 million metric tons, representing 17.9 percent of U.S. disposal of municipal solid waste (EPA 1999). Unlike most of the rest of the waste stream, yard trimmings disposal has declined consistently in the 1990s—generation has declined at 3.3 percent per year, and recovery (e.g., composting) has increased at an average annual rate of 15 percent. Laws regulating disposal of yard trimmings now affect over 50 percent of the U.S. population, up from 28 percent in 1992 (EPA 1999). By 1997, discards were about 15 million metric tons, representing 10 percent of U.S. municipal waste disposal.

Methodology

The methodology for estimating carbon storage is based on a life cycle analysis of greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). According to this methodology, carbon storage is the product of the mass of yard trimmings disposed, on a wet weight basis and a storage factor. The storage factor is based on a series of experiments designed to evaluate methane generation and residual organic material in landfills under average conditions

(Barlaz 1997). These experiments analyzed grass, leaves, branches, and other materials, and were designed to promote biodegradation by providing ample moisture and nutrients.

For purposes of this analysis, the composition of yard trimmings was assumed to consist of 50 percent grass clippings, 25 percent leaves, and 25 percent branches. A different storage factor was used for each component. The weighted average carbon storage factor is 0.19 Gg carbon per Gg of yard trimmings, as shown in Table 6-10. Results, in terms of carbon storage, are also shown.

Data Sources

The yard trimmings discard rate was taken from the EPA report *Characterization of Municipal Solid Waste in the U.S.: 1998 Update* (EPA 1999), which provides estimates for 1990 through 1997 and forecasts for 2000 and 2005. Yard trimmings discards for 1998 were projected using the EPA (1999) forecast of generation and recovery rates (decrease of 6 percent per year, increase of 8 percent per year, respectively) for 1997 through 2000. This report does not subdivide discards of individual materials into volumes landfilled and combusted, although it does provide an estimate of the overall distribution of solid waste between these two management methods (76 percent and 24 percent, respectively) for the waste stream as a whole.[10] Thus, yard trimmings disposal to landfills is the product of the quantity discarded and the proportion of discards managed in landfills (see Table 6-11). The carbon storage factors were obtained from EPA (1998).

Uncertainty

The principal source of uncertainty for the landfill carbon storage estimates stem from an incomplete understanding of the long-term fate of carbon in landfill environments. Although there is ample field evidence that many landfilled organic materials remain virtually intact for long periods, the quantitative basis for predicting long-term storage is based on limited laboratory results under experimental conditions. In reality, there is likely to be considerable heterogeneity in storage rates, based on (1) actual composition of yard trimmings (e.g., oak leaves decompose more slowly than grass clippings) and (2) landfill characteristics (e.g., availability of moisture, nitrogen, phosphorus, etc.). Other sources of uncertainty include the estimates of yard trimmings disposal rates—which are based on extrapolations of waste composition surveys, and the extrapolation of a value for 1998 disposal from estimates for the period from 1990 through 1997.

Table 6-10: Composition of Yard Trimmings (%) in MSW and Carbon Storage Factor (Gg Carbon/Gg Yard Trimmings)

Component	Percent	Storage Factor
Grass	50	0.11
Leaves	25	0.36
Branches	25	0.19
Total/ Weighted Average	**100**	**0.19**

Table 6-11: Yard Trimmings Disposal to Landfills

Year	Metric Tons
1990	21,236,000
1991	20,822,000
1992	20,408,000
1993	18,168,000
1994	16,203,000
1995	14,265,200
1996	11,962,300
1997	11,197,000
1998	9,929,500

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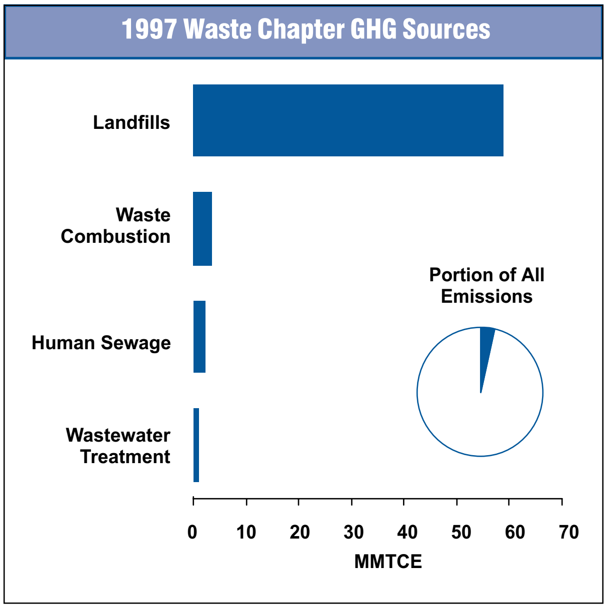
[10] Note that this calculation uses a different proportion for combustion than an earlier calculation in the waste combustion section of Chapter 6. The difference arises from different sources of information with different definitions of what is included in the solid waste stream.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (See Figure 7-1). Landfills are the nation's largest source of anthropogenic methane emissions, accounting for 33 percent of the U.S. total.[1] Waste combustion is the second largest source in this sector, emitting carbon dioxide (CO_2) and nitrous oxide (N_2O). Smaller amounts of methane are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of N_2O emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by each of these sources, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Overall, in 1998, waste activities generated emissions of 65.4 MMTCE, or 3.6 percent of total U.S. greenhouse gas emissions.

Figure 7-1



Landfills

Landfills are the largest anthropogenic source of methane (CH_4) emissions in the United States. In 1998, landfill emissions were approximately 58.8 MMTCE (10,268 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 93 percent of total landfill emissions, while industrial landfills accounted for the remainder. Landfills also emit non-methane volatile organic compounds (NMVOCs). There are over 2,300 landfills in the United States (BioCycle 1999), with the largest landfills receiving most of the waste and generating the majority of the methane.

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[1] Landfills also store carbon from biogenic sources, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in Chapter 6.

Table 7-1: Emissions from Waste (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**59.1**	**59.0**	**60.0**	**60.5**	**60.8**	**61.4**	**61.1**	**61.1**	**59.7**
Landfills	58.2	58.1	59.1	59.6	59.9	60.5	60.2	60.2	58.8
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
N_2O	**2.1**	**2.1**	**2.1**	**2.1**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Human Sewage	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CO_2	**2.8**	**3.0**	**3.0**	**3.1**	**3.1**	**3.0**	**3.1**	**3.4**	**3.5**
Waste Combustion	2.8	3.0	3.0	3.1	3.1	3.0	3.1	3.4	3.5
Total	**64.0**	**64.1**	**65.1**	**65.7**	**66.1**	**66.6**	**66.4**	**66.7**	**65.4**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**10,320**	**10,303**	**10,475**	**10,557**	**10,608**	**10,724**	**10,667**	**10,671**	**10,430**
Landfills	10,170	10,151	10,321	10,401	10,451	10,566	10,507	10,509	10,267
Wastewater Treatment	150	151	153	155	156	158	159	161	162
N_2O	**24**	**24**	**25**	**25**	**26**	**25**	**26**	**26**	**26**
Human Sewage	23	24	24	24	25	25	25	25	25
Waste Combustion	1	1	1	1	1	1	1	1	1
CO_2	**10,344**	**10,931**	**10,992**	**11,295**	**11,307**	**11,104**	**11,504**	**12,531**	**12,889**
Waste Combustion	10,344	10,931	10,992	11,295	11,307	11,104	11,504	12,531	12,889

Note: Totals may not sum due to independent rounding.

Methane emissions result from the decomposition of organic landfill materials such as paper, food scraps, and yard trimmings. This decomposition process is a natural mechanism through which microorganisms derive energy. After being placed in a landfill, organic waste is initially digested by aerobic (i.e., in the presence of oxygen) bacteria. After the oxygen supply has been depleted, the remaining waste is attacked by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Methane-producing anaerobic bacteria convert these fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent methane, by volume.[2] Methane production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

Between 1990 and 1998, methane emissions from landfills were relatively constant (see Table 7-3 and Table 7-4). The roughly constant emissions estimates are a result of two offsetting trends: (1) the amount of MSW in landfills contributing to methane emissions increased, thereby increasing the potential for emissions; and (2) the amount of landfill gas collected and combusted by landfill operators also increased, thereby reducing emissions.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of MSW in landfills, which is related to total MSW landfilled annually for the last 30 years; (2) composition of the waste-in-place; (3) the amount of methane that is recovered and either flared or used for energy purposes; and (4) the amount of methane oxidized in landfills instead

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[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987).

Box 7-1: Biogenic Emissions and Sinks of Carbon

For many countries, CO_2 emissions from the combustion or degradation of biogenic materials is important because of the significant amount of energy they derive from biomass (e.g., burning fuelwood). The fate of biogenic materials is also important when evaluating waste management emissions (e.g., the decomposition of grass clippings or combustion of paper). The carbon contained in paper and grass trimmings was originally removed from the atmosphere by photosynthesis, and under natural conditions, it would eventually degrade and cycle back to the atmosphere as CO_2. The quantity of carbon that these degradation processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic greenhouse gas sources. But the focus of the United Nations Framework Convention on Climate Change is on anthropogenic emissions—emissions resulting from human activities and subject to human control—because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and enhancing the atmosphere's natural greenhouse effect.

Thus, if CO_2 emissions from biogenic materials (e.g., paper, wood products, and yard trimmings) result from materials grown on a sustainable basis, then those emissions are considered to mimic the closed loop of the natural carbon cycle —that is, they return to the atmosphere CO_2 that was originally removed by photosynthesis. Conversely, CO_2 emissions from burning fossil fuels or products such as plastics derived from fossil sources would not enter the cycle were it not for human activity (i.e., they were removed from permanent fossil deposits). Likewise, CH_4 emissions from landfilled waste would not be emitted were it not for the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills.

However, the removal of carbon from this cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of sustainable, biogenic origin (e.g., yard trimmings) are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. Landfilling of forest products and yard trimmings results in long-term storage of about 19 MMTCE and 2 to 5 MMTCE per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in Chapter 6 to comport with IPCC inventory reporting guidance regarding the tracking of carbon flows.

Box 7-2: Recycling and Greenhouse Gas Emissions and Sinks

U.S. waste management patterns changed dramatically in the 1990s in response to changes in economic and regulatory factors. Perhaps the most significant change from a greenhouse gas perspective was the increase in the national average recycling rate, which climbed from 16 percent in 1990 to 28 percent in 1997 (EPA 1999).

This change had an important effect on emissions in several areas, primarily in regard to emissions from waste and energy activities, as well as forestry sinks. The impact of increased recycling on greenhouse gas emissions can be best understood when emissions are considered from a life cycle perspective (EPA 1998). When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed and managed as waste. The substitution of recycled inputs for virgin inputs reduces three types of emissions throughout the product life cycle. First, manufacturing processes involving recycled inputs generally require less energy than those using virgin inputs. Second, the use of recycled inputs leads to reductions in process non-energy emissions. Third, recycling reduces disposal and waste management emissions, including methane from landfills and nitrous oxide and non-biogenic carbon dioxide emissions from combustion. In addition to greenhouse gas emission reductions from manufacturing and disposal, recycling of paper products—which are the largest component of the U.S. wastestream—results in increased forest carbon sequestration. When paper is recycled, fewer trees are needed as inputs in the manufacturing process; reduced harvest levels result in older average forest ages, with correspondingly more carbon stored.

of being released into the atmosphere. The estimated total quantity of waste-in-place contributing to emissions increased from about 4,926 Gg in 1990 to 5,907 Gg in 1998, an increase of 20 percent (see Annex J). During this period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 1,110 Gg of methane was recovered and combusted (i.e., used for energy or flared) from landfills. In 1998, the estimated quantity of methane recovered and combusted increased to 3,590 Gg.

Over the next several years, the total amount of MSW generated is expected to increase slightly. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of methane that is recovered and either flared or used for energy purposes is expected to increase, partially as a result of a recently promulgated regulation that requires large landfills to collect and combust landfill gas (Federal Register 1996).

Methodology

Based on available information, methane emissions from landfills were estimated to equal the methane produced from municipal landfills, minus the methane recovered and combusted, minus the methane oxidized before being released into the atmosphere, plus the methane produced by industrial landfills.

The methodology for estimating CH_4 emissions from municipal landfills is based on a model that updates the population of U.S. landfills each year. This model is based on the pattern of actual waste disposal by each individual landfill surveyed by the EPA's Office of Solid Waste in 1987. A second model was employed to estimate emissions from the landfill population (EPA 1993). For each landfill in the data set, the amount of waste-in-place contributing to methane generation was estimated using its year of opening, its waste acceptance rate, year of closure, and design capacity. Data on national waste disposed in landfills each year was apportioned by landfill. Emissions from municipal landfills

Table 7-3: CH_4 Emissions from Landfills (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
MSW Landfills	60.4	61.8	63.6	65.5	67.5	69.5	71.1	72.8	74.3
Industrial Landfills	4.2	4.3	4.4	4.5	4.6	4.8	4.9	5.0	5.1
Recovered									
Gas-to-Energy	(4.6)	(4.9)	(5.2)	(6.0)	(6.8)	(7.1)	(8.0)	(9.2)	(11.6
Flared	(1.7)	(3.0)	(3.6)	(4.4)	(5.5)	(6.7)	(7.8)	(8.3)	(9.0)
Net Emissions	**58.2**	**58.1**	**59.1**	**59.6**	**59.9**	**60.5**	**60.2**	**60.2**	**58.8**

Note: Totals may not sum due to independent rounding.

Table 7-4: CH_4 Emissions from Landfills (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
MSW Landfills	10,550	10,791	11,107	11,431	11,777	12,138	12,419	12,705	12,974
Industrial Landfills	731	746	767	787	809	833	850	868	883
Recovered									
Gas-to-Energy	(811)	(861)	(915)	(1,053)	(1,183)	(1,233)	(1,397)	(1,608)	(2,025)
Flared	(299)	(524)	(637)	(764)	(952)	(1,171)	(1,363)	(1,454)	(1,564)
Net Emissions	**10,171**	**10,152**	**10,321**	**10,402**	**10,452**	**10,566**	**10,508**	**10,510**	**10,268**

Note: Totals may not sum due to independent rounding.

were then estimated by multiplying the quantity of waste contributing to emissions by emission factors (EPA 1993). For further information see Annex J.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, and a database compiled by the EPA's Landfill Methane Outreach Program (LMOP). Based on the information provided by vendors, the methane combusted by the 235 flares in operation from 1990 to 1998 were estimated. This estimate likely underestimates emissions. The EPA believes that more than 700 flares exist in the United States, and so the EPA is working with the Solid Waste Association of North America (SWANA) to better characterize flaring activities. Additionally, the LMOP database provided data on landfill gas flow and energy generation for 237 of the approximately 260 operational landfill gas-to-energy projects.

Emissions from industrial landfills were assumed to be equal to 7 percent of the total methane emissions from municipal landfills. The amount of methane oxidized was assumed to be 10 percent of the methane generated (Liptay et al. 1998). To calculate net methane emissions, methane recovered and oxidized was subtracted from methane generated at municipal and industrial landfills.

Data Sources

The landfill population model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA's Office of Solid Waste (EPA 1988). National landfill waste disposal data for 1991 through 1998 were obtained from *BioCycle* (1999). Documentation on the landfill methane emissions methodology employed is available in the EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993). Information on flares was obtained from vendors, and information on landfill gas-to-energy projects was obtained from the LMOP database.

Uncertainty

Several types of uncertainties are associated with the estimates of methane emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is lacking on the area landfilled and total waste-in-place—the fundamental factors that affect methane production. In addition, the statistical model used to estimate emissions is based upon methane generation at landfills that currently have developed energy recovery projects, and may not precisely capture the relationship between emissions and various physical characteristics of individual landfills. Overall, uncertainty in the landfill methane emission rate is estimated to be roughly ±30 percent.

Waste Combustion

Waste combustion involves the burning of garbage and non-hazardous solids, referred to as municipal solid waste (MSW). In 1996, there were approximately 137 municipal waste combustion plants in operation within the United States (EPA 1999). Most of the organic materials in MSW are of biogenic origin. Net CO_2 emissions resulting from combustion of biogenic materials are accounted for under Land-Use Change and Forestry (see Box 7-1). However, one component—plastics—is of fossil origin, and is included as a source of CO_2 emissions. Plastics in the U.S. wastestream are primarily in the form of containers, packaging, and durable goods. Some other materials in the waste stream (e.g., some textiles and rubber) are of fossil origin, but are not included in this estimate.

In addition, MSW combustion has been identified as a source of nitrous oxide (N_2O) emissions. N_2O emissions are dependent on the types of waste burned and combustion temperatures (De Soete 1993).

Carbon dioxide emissions have risen 25 percent since 1990, to about 3.5 MMTCE (12,900 Gg) in 1998, as the volume of plastics in MSW has increased (see Table 7-5 and Table 7-6). Nitrous oxide emissions from MSW combustion were estimated to be 0.1 MMTCE (1 Gg) in 1998, and have not changed significantly since 1990.

Table 7-5: CO_2 and N_2O Emissions from Waste Combustion (MMTCE)

Year	CO_2	N_2O
1990	2.8	0.1
1991	3.0	0.1
1992	3.0	0.1
1993	3.1	0.1
1994	3.1	0.1
1995	3.0	0.1
1996	3.1	0.1
1997	3.4	0.1
1998	3.5	0.1

Table 7-6: CO_2 and N_2O Emissions from Waste Combustion (Gg)

Year	CO_2	N_2O
1990	10,000	1
1991	10,900	1
1992	11,000	1
1993	11,300	1
1994	11,300	1
1995	11,100	1
1996	11,500	1
1997	12,600	1
1998	12,900	1

Methodology

In the report, *Characterization of Municipal Solid Waste in the United States* (EPA 1999), the flows of plastics in the U.S. wastestream are reported for seven resin categories. The 1997 quantity generated, recovered, and discarded for each resin is shown in Table 7-7. The report does not provide estimates for individual materials landfilled and combusted, although it does provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and combusted, total discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. wastestream (76 percent and 24 percent, respectively).

Fossil CO_2 emissions for 1997 were estimated as the product of plastic combusted, carbon content, and combustion efficiency (see Table 7-8). The carbon content of each of the six types of plastics is listed, with the value for "other plastics" assumed equal the weighted average of the six categories. A combustion efficiency of 98 percent was assumed.

Emissions for 1990 through 1996 were calculated using the same approach. Estimates of the portion of

Table 7-7: 1997 Plastics in the Municipal Solid Waste Stream by Resin (Thousand Metric Tons)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	1,724	4,200	1,198	4,881	2,531	1,905	3,030	**19,469**
Recovery	327	381	0	91	109	9	91	**1,007**
Discard	1,397	3,819	1,198	4,790	2,422	1,896	2,939	**18,462**
Landfill	1,061	2,903	910	3,641	1,841	1,441	2,234	**14,030**
Combustion	336	916	288	1,149	582	455	706	**4,432**
Recovery*	19%	9%	0%	2%	4%	0.5%	3%	**5%**
Discard*	81%	91%	100%	98%	96%	99.5%	97%	**95%**
Landfill*	62%	69%	76%	75%	73%	76%	74%	**72%**
Combustion*	19%	22%	24%	24%	23%	24%	23%	**23%**

* As a percent of waste generation.

Note: Totals may not sum due to independent rounding. PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE/LLDPE ((linear) low density polyethylene), PP (polypropylene), PS (polystyrene).

Table 7-8: 1997 Plastics Combusted (Thousand Metric Tons), Carbon Content (%), and Carbon Equivalent Combusted (Thousand Metric Tons)

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Quantity Combusted	336	916	288	1,149	582	455	706	**4,432**
Carbon Content of Resin	62.5	85.7	38.1	85.7	85.7	92.3	67.9[a]	–
Carbon Equivalent Combusted	210	785	110	985	498	420	479	**3,487**
Emissions (MMTCE)[b]	**0.2**	**0.8**	**0.1**	**1.0**	**0.5**	**0.4**	**0.5**	**3.4**

[a] Weighted average of other plastics.
[b] Assumes 98 percent combustion efficiency.

plastics in the wastestream in 1998 were not available; therefore, they were projected by assuming 3 percent annual growth rate in generation and a 5.4 percent growth rate for recovery, based on reported trends (EPA 1999).

Estimates of N_2O emissions from MSW combustion in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1997). According to this methodology, emissions of N_2O from MSW combustion is the product of the mass of MSW combusted, an emission factor of N_2O emitted per unit mass of waste combusted, and an N_2O emissions control removal efficiency. For MSW combustion in the United States, an emission factor of 30 g N_2O/metric ton MSW, and an estimated emissions control removal efficiency of zero percent were used.

Data Sources

The estimates of CO_2 emissions and N_2O emissions are based on different data sources. The fossil CO_2 emissions are a function of a specific material—plastics—as reported by EPA (1999) in its characterization of the municipal wastestream. The N_2O emissions are a function of total waste combusted, as reported in the April 1999 issue of *BioCycle* (Glenn 1999). Table 7-9 provides MSW generation and percentage combustion data for the total wastestream. The emission factor of N_2O emissions per quantity of MSW combusted was taken from Olivier (1993).

Table 7-9: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted

Year	Waste Generation	Combusted (%)
1990	266,541,881	11.5
1991	254,796,765	10.0
1992	264,843,388	11.0
1993	278,572,955	10.0
1994	293,109,556	10.0
1995	296,586,430	10.0
1996	297,268,188	10.0
1997	309,075,035	9.0
1998	340,090,022	7.5

As noted above, CO_2 emissions from plastics are based on (1) the carbon content of the various plastic resins, and (2) an assumption of 98 percent combustion efficiency, as reported in the EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 1998).

Uncertainty

A source of uncertainty affecting both fossil CO_2 and N_2O emissions is the estimate of the MSW combustion rate. The EPA (1999) estimates of plastics generation, discards, and combustion are subject to considerable error. Similarly, the *BioCycle* (Glenn 1999) estimate of total waste combustion—used for the N_2O estimate—is based on a survey of state officials, who use differing definitions of solid waste and who draw from a variety of sources of varying reliability and accuracy. Despite the differences in methodology and data sources, the two references—EPA's Office of Solid Waste (EPA 1999) and *BioCycle* (Glenn 1999)—provide estimates of total solid waste combusted that are relatively consistent (see Table 7-10).

The other principal source of uncertainty for the carbon dioxide estimate is combustion efficiency. Municipal waste combustors vary considerably in their efficiency as a function of waste type, moisture content, combustion conditions, and other factors. The value of 98 percent assumed here may not be representative of typical conditions.

As with other combustion-related sources of N_2O, emissions are affected by combustion conditions (De Soete 1993). In part, because insufficient data exists to provide detailed estimates of N_2O emissions for individual combustion facilities, the estimates presented are highly uncertain. The emission factor for N_2O from MSW combustion facilities used in the analysis is a default used to estimate N_2O emissions from facilities worldwide (Olivier 1993). As such, it has a range of uncertainty of an order of magnitude (between 25 and 293 g N_2O/metric ton MSW combusted) (Watanabe, et al. 1992). Due to a lack of relevant information on the control of N_2O emissions from MSW combustion facilities in the United States, the estimate of zero percent for N_2O emissions control removal efficiency is also uncertain.

Table 7-10: U.S. Municipal Solid Waste Combusted by Data Source (Metric Tons)

Year	EPA	BioCycle
1990	28,939,680	30,652,316
1991	30,236,976	25,479,677
1992	29,656,638	29,132,773
1993	29,865,024	27,857,295
1994	29,474,928	29,310,956
1995	32,241,888	29,658,643
1996	32,740,848	29,726,819
1997	32,294,240	27,816,753
1998	NA	25,506,752

NA (Not Available)

Wastewater Treatment

The breakdown of organic material in wastewater treatment systems produces methane when it occurs under anaerobic conditions. The amount of methane produced is driven by the extent to which the organic material is broken down under anaerobic versus aerobic conditions. During collection and treatment, wastewater may be incidentally or deliberately managed under anaerobic conditions. The methane produced during deliberate anaerobic treatment is typically collected and flared or combusted for energy. However, whenever anaerobic conditions develop, some of the methane generated is incidentally released to the atmosphere. Untreated wastewater may also produce methane if contained under anaerobic conditions.

The organic content, expressed in terms of biochemical oxygen demand (BOD), determines the methane producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. Under anaerobic conditions, wastewater with higher BOD concentrations will produce more methane than wastewater with lower BOD.

In 1998, methane emissions from municipal wastewater were 0.9 MMTCE (163 Gg). Emissions have increased since 1990 reflecting the increase in the U.S. human population. Table 7-11 provides emission estimates from domestic wastewater treatment.

Table 7-11: CH_4 Emissions from Domestic Wastewater Treatment

Year	MMTCE	Gg
1990	0.9	150
1991	0.9	152
1992	0.9	154
1993	0.9	155
1994	0.9	157
1995	0.9	158
1996	0.9	160
1997	0.9	161
1998	0.9	163

At this time, data are not sufficient to estimate methane emissions from industrial wastewater sources. Further research is ongoing to quantify emissions from this source.

Methodology

Wastewater methane emissions are estimated using the default IPCC methodology (IPCC/UNEP/OECD/IEA 1997). The total population for each year was multiplied by a per capita wastewater BOD production rate to determine total wastewater BOD produced. It was assumed that, per capita, 0.05 kilograms of wastewater BOD5[3] is produced per day and that 15 percent of wastewater BOD5 is anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.22 Gg CH_4/Gg BOD5.

Data Sources

National population data for 1990 to 1998 were supplied by the U.S. Census Bureau (1999). The emission factor employed was taken from Metcalf and Eddy (1972). Table 7-12 provides U.S. population and wastewater BOD data.

Uncertainty

Domestic wastewater emissions estimates are highly uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, especially incidental occurrences. It is also believed that industrial wastewater is responsible for significantly more methane emissions than domestic wastewater treatment.

Human Sewage

Sewage is disposed on land or discharged into aquatic environments such as rivers and estuaries. Prior to being disposed on land or in water, it may be deposited in septic systems or treated in wastewater treatment facilities. Nitrous oxide (N_2O) may be generated during each of these stages through nitrification and denitrification of the nitrogen that is present in sewage. Nitrification occurs aerobically and converts ammonium into nitrate, while denitrification occurs anaerobically, and converts nitrate into dinitrogen gas. Nitrous oxide is a gaseous intermediate product in the reaction sequences of both processes. In general, temperature, pH, biochemical oxygen demand (BOD), and nitrogen concentration affect N_2O generation from human sewage. BOD is the amount of dissolved oxygen used by aerobic microorganisms to completely consume the available organic matter (Metcalf and Eddy 1972). The amount of protein consumed by humans determines the quantity of nitrogen contained in sewage.

Nitrous oxide emission from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) with one exception. The IPCC methodology assumes that N_2O emissions associated with land disposal and sewage treatment are negligible and all sewage nitrogen is discharged directly into aquatic environments. In the United States, however, a certain amount of sewage nitrogen is applied to soils via sewage sludge applications and therefore, not all sewage nitrogen enters aquatic environments.[4] The N_2O estimates presented here account for the amount of nitrogen in sewage sludge applied to soils.

Table 7-12: U.S. Population (Millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD5
1990	249.3	4,554
1991	252.0	4,602
1992	254.9	4,655
1993	257.7	4,706
1994	260.2	4,752
1995	262.7	4,797
1996	265.1	4,842
1997	267.7	4,888
1998	270.2	4,935

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[3] The 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972).

[4] The IPCC methodology is based on the total amount of nitrogen in sewage, which is in turn based on human protein consumption and the fraction of nitrogen in protein (i.e., $Frac_{NPR}$). A portion of the total nitrogen in sewage in the United States is applied to soils in the form of sewage sludge each year. This amount is estimated as part of agricultural soil management (see Chapter 6) and is subtracted here from total nitrogen in human sewage to estimate sewage N_2O emissions.

Table 7-13: N_2O Emissions from Human Sewage

Year	MMTCE	Gg
1990	2.0	23
1991	2.0	24
1992	2.0	24
1993	2.0	24
1994	2.1	25
1995	2.1	25
1996	2.1	25
1997	2.1	25
1998	2.2	25

Emissions of N_2O from sewage nitrogen discharged into aquatic environments were estimated to be 2.2 MMTCE (25 Gg N_2O) in 1998. An increase in the U.S. population and the per capita protein intake resulted in an overall increase of 10 percent in N_2O emissions from human sewage between 1990 and 1998 (see Table 7-13).

Methodology

With the exception described above, N_2O emissions from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This is illustrated below:

$$N_2O(s) = [(\text{Protein}) \times (\text{Frac}_{NPR}) \times (\text{NR People})] \times [1-\text{Frac}_{N\text{-}SOIL}] \times (EF) \times ({}^{44}/_{28})$$

Where:

$N_2O(s)$ = N_2O emissions from human sewage

Protein = Annual, per capita protein consumption

Frac_{NPR} = Fraction of nitrogen in protein

NR People = U.S. population

$\text{Frac}_{N\text{-}SOIL}$ = Fraction of sewage sludge N applied to soils

EF = Emission factor (kg N_20-N/kg sewage-N produced)

(44/28) = The molecular weight ratio of N_2O to N_2

Data Sources

U.S. population data were taken from the U.S. Census Bureau (1999). Data on the annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 1999) (see Table 7-14). Because data on protein intake were unavailable for 1998, the value of per capita protein consumption for the previous year was used. An emission factor has not been specifically estimated for the United States, so the default IPCC value (0.01 kg N_2O-N/kg sewage-N produced) was applied. Similarly, the fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Uncertainty

The U.S. population (NR people), per capita protein intake data (Protein), and fraction of nitrogen in protein (Frac_{NPR}) are believed to be fairly accurate. There is significant uncertainty, however, in the emission factor (EF) employed due to regional differences that would likely affect N_2O emissions but are not accounted for in the default IPCC factor. Moreover, the underlying methodological assumption that negligible N_2O emissions result from sewage treatment may be incorrect. In addition N_2O emissions from industrial wastewater, which have not been addressed in the IPCC Guidelines, have not been estimated.

Table 7-14: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year)

Year	Population	Protein
1990	249.3	39.2
1991	252.0	39.8
1992	254.9	40.1
1993	257.7	40.1
1994	260.2	41.0
1995	262.7	40.4
1996	265.1	40.8
1997	267.7	41.0
1998	270.2	41.0

Waste Sources of Criteria Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of criteria air pollutant emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 1998 are provided in Table 7-15.

Methodology and Data Sources

These emission estimates were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1998* (EPA 1999). This EPA report provides emission estimates of these gases by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA data bases.

Uncertainty

Uncertainties in these estimates are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

Table 7-15: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
NO_x	**83**	**86**	**87**	**112**	**103**	**89**	**87**	**89**	**90**
Landfills	+	+	+	1	1	1	1	1	1
Wastewater Treatment	+	+	+	+	+	+	+	+	+
Waste Combustion[a]	82	85	86	107	99	88	86	87	88
Miscellaneous[b]	+	1	1	4	3	1	1	1	+
CO	**979**	**1,012**	**1,032**	**1,133**	**1,111**	**1,075**	**1,083**	**1,095**	**1,107**
Landfills	1	1	2	2	2	2	4	4	4
Wastewater Treatment	+	+	+	+	+	+	+	+	+
Waste Combustion[a]	978	1,011	1,030	1,130	1,108	1,073	1,079	1,091	1,103
Miscellaneous[b]	+	+	+	1	1	1	1	1	1
NMVOCs	**895**	**907**	**916**	**949**	**949**	**968**	**388**	**394**	**400**
Landfills	58	60	63	67	73	68	18	19	19
Wastewater Treatment	57	58	61	63	64	61	57	58	59
Waste Combustion[a]	222	227	230	256	248	237	237	240	243
Miscellaneous[b]	558	562	563	563	564	602	76	77	79

+ Does not exceed 0.5 Gg

[a] Includes waste incineration and open burning (EPA 1999)

[b] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

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Mobile Air Conditioning: Air conditioning systems in cars, trucks, buses, and trains primarily use the refrigerant HFC-134a. The quantity of refrigerant in a typical car air conditioner is small, but because of millions of air conditioned vehicles on the road, plus the increasing number of miles those vehicles are being driven, mobile air conditioners are the largest user of HFC-134a in the United States.

Air conditioning equipment: A number of HFCs are used in refrigeration and air conditioning systems, with the result that emissions of HFCs occur during operation and repair of these systems. HFCs have global warming potentials (GWPs) that range from 140 to 11,700 times the warming potential of carbon dioxide. The use of recapture and recycling equipment such as that shown significantly reduces emissions of these refrigerants into the atmosphere.

Refrigeration: Household refrigerators use the refrigerant HFC-134a, and so do many of the processes that allow cold food to arrive fresh on the way to your home. Cold storage refrigeration, refrigerated transport, and retail food refrigerators use HFC-134a or other HFC refrigerant blends. The amount of refrigerant contained in household refrigerators is typically small, but because of the large number of households in the United States, household refrigeration is considered an important HFC-134a end-use. Additionally, HFCs are used in the insulating foam of the refrigerator unit.

Aluminum Production: Primary aluminum smelting from alumina ore results in emissions two PFCs, CF_4 and C_2F_6. These PFCs have global warming potentials of 6,500 and 9,200 times the warming potential of carbon dioxide, respectively. PFCs are intermittent by-products of the smelting process, occurring when the alumina ore content of the electrolytic bath falls below critical levels optimal for the chemical reactions to take place.

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