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

1990 – 2001

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U.S. Environmental Protection Agency
1200 Pennsylvania Ave., N.W.
Washington, DC 20460
U.S.A.

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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 decision 3/CP.5 of the UNFCCC Conference of the Parties, national inventories for 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 site.[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.

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[1] See Article 4(1)(a) of the United Nations Framework Convention on Climate Change <http://www.unfccc.int>.

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

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The annexes are contained on the accompanying CD or can be found at <http://www.epa.gov/globalwarming/inventory>.

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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 gases. 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 1992, the United States signed and ratified 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. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[2]

Parties to the Convention, by ratifying, committed "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.

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2001. To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC Parties, 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) and the *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). For most source categories, the IPCC 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 contain bromine are

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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.int>.

[3] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12). See <http://unfccc.int>.

referred to as bromofluorocarbons (i.e., halons). Because CFCs, HCFCs, and halons are stratospheric ozone depleting substances, they are covered under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. The UNFCCC defers to this earlier international treaty; consequently these gases are not included in national greenhouse gas inventories.[4] Some other fluorine containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several gases that do not have a direct global warming effect but indirectly affect terrestrial and/or solar radiation absorption by influencing the formation or destruction of other greenhouse gases, including tropospheric and stratospheric ozone. These gases include carbon monoxide (CO), oxides of nitrogen (NO_x), and non-methane volatile organic compounds (NMVOCs). Aerosols, which are extremely small particles or liquid droplets, such as those produced by sulfur dioxide (SO_2) or elemental carbon emissions, can also affect the absorptive characteristics of the atmosphere.

Although the direct greenhouse gases CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. Since the pre-industrial era (i.e., ending about 1750), concentrations of these greenhouse gases have increased by 31, 150, and 16 percent, respectively (IPCC 2001).

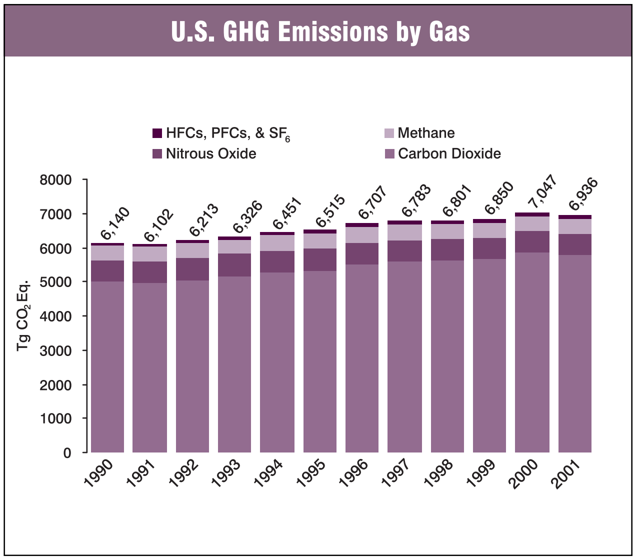
Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODSs) increased by nearly 10 percent per year until the mid-1980s, when international concern about ozone depletion led to the entry into force of the *Montreal Protocol*. Since then, the production of ODSs is being phased out. In recent years, use of ODS substitutes such as HFCs and PFCs has grown as they begin to be phased in as replacements for CFCs and HCFCs. Accordingly, atmospheric concentrations of these substitutes have been growing (IPCC 2001).

Recent Trends in U.S. Greenhouse Gas Emissions

In 2001, total U.S. greenhouse gas emissions were 6,936.2 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.)[5] (13.0 percent above 1990 emissions). Emissions declined for the second time since the base year 1990, decreasing by 1.6 percent (111.2 Tg CO_2 Eq.) from 2000 to 2001, driven primarily by decreases in CO_2 emissions from fossil fuel combustion. The following factors were primary contributors to this decrease: 1) slow economic growth in 2001, leading to decreased demand for electricity fuels, 2) a considerable reduction in industrial output, leading to decreased demand for electricity and fossil fuel, 3) warmer winter conditions compared to 2000, and 4) increased output from nuclear facilities. (See the following section for an analysis of emission trends by general economic sectors.)

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 detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2001.

Figure ES-1



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[4] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

[5] Estimates are presented in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.), which weight each gas by its Global Warming Potential, or GWP, value. (See section on Global Warming Potentials, Chapter 1.)

Table ES-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**5,003.7**	**5,334.4**	**5,514.8**	**5,595.4**	**5,614.2**	**5,680.7**	**5,883.1**	**5,794.8**
Fossil Fuel Combustion	4,814.8	5,141.5	5,325.8	5,400.0	5,420.5	5,488.8	5,692.2	5,614.9
Iron and Steel Production	85.4	74.4	68.3	71.9	67.4	64.4	65.8	59.1
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.2	41.4
Waste Combustion	14.1	18.5	19.4	21.2	22.5	23.9	25.4	26.9
Ammonia Manufacture & Urea Application	19.3	20.5	20.3	20.7	21.9	20.6	19.6	16.6
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3	12.9
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	5.5	5.2
Limestone and Dolomite Use	5.5	7.0	7.6	7.1	7.3	7.7	5.8	5.3
Aluminum Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4	4.1
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2	4.1
Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	1.9	1.9
Carbon Dioxide Consumption	0.9	1.1	1.1	1.2	1.2	1.2	1.2	1.3
Ferroalloys	2.0	1.9	2.0	2.0	2.0	2.0	1.7	1.3
Land-Use Change and Forestry (Sink)[a]	(1,072.8)	(1,064.2)	(1,061.0)	(840.6)	(830.5)	(841.1)	(834.6)	(838.1)
International Bunker Fuels[b]	*113.9*	*101.0*	*102.3*	*109.9*	*112.9*	*105.3*	*99.3*	*97.3*
CH_4	**644.0**	**650.0**	**636.8**	**629.5**	**622.7**	**615.5**	**613.4**	**605.9**
Landfills	212.1	216.1	212.1	207.5	202.4	203.7	205.8	202.9
Natural Gas Systems	122.0	127.2	127.4	126.0	124.0	120.3	121.2	117.3
Enteric Fermentation	117.9	123.0	120.5	118.3	116.7	116.6	115.7	114.8
Coal Mining	87.1	73.5	68.4	68.1	67.9	63.7	60.9	60.7
Manure Management	31.3	36.2	34.9	36.6	39.0	38.9	38.2	38.9
Wastewater Treatment	24.1	26.6	26.8	27.3	27.7	28.2	28.3	28.3
Petroleum Systems	27.5	24.2	23.9	23.6	22.9	21.6	21.2	21.2
Rice Cultivation	7.1	7.6	7.0	7.5	7.9	8.3	7.5	7.6
Stationary Sources	8.1	8.5	8.7	7.5	7.2	7.4	7.6	7.4
Mobile Sources	5.0	4.9	4.8	4.7	4.6	4.5	4.4	4.3
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7	1.7	1.5
Field Burning of Agricultural Residues	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8
Silicon Carbide Production	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**397.6**	**430.9**	**441.7**	**440.9**	**436.8**	**430.0**	**429.9**	**424.6**
Agricultural Soil Management	267.5	284.1	293.2	298.2	299.2	297.0	294.6	294.3
Mobile Sources	50.6	60.9	60.7	60.3	59.7	58.8	57.5	54.8
Manure Management	16.2	16.6	17.0	17.3	17.3	17.4	17.9	18.0
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.1	19.1	17.6
Human Sewage	12.7	13.9	14.1	14.4	14.6	15.1	15.1	15.3
Stationary Combustion	12.5	13.2	13.8	13.7	13.7	13.7	14.3	14.2
Adipic Acid	15.2	17.2	17.0	10.3	6.0	5.5	6.0	4.9
N_2O Product Usage	4.3	4.5	4.5	4.8	4.8	4.8	4.8	4.8
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.5
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
International Bunker Fuels[b]	*1.0*	*0.9*	*0.9*	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*
HFCs, PFCs, and SF_6	**94.4**	**99.5**	**113.6**	**116.8**	**127.6**	**120.3**	**121.0**	**111.0**
Substitution of Ozone Depleting Substances	0.9	21.7	30.4	37.7	44.5	50.9	57.3	63.7
HCFC-22 Production	35.0	27.0	31.1	30.0	40.2	30.4	29.8	19.8
Electrical Transmission and Distribution	32.1	27.5	27.7	25.2	20.9	16.4	15.4	15.3
Semiconductor Manufacture	2.9	5.9	5.4	6.5	7.3	7.7	7.4	5.5
Aluminum Production	18.1	11.8	12.5	11.0	9.0	8.9	7.9	4.1
Magnesium Production and Processing	5.4	5.6	6.5	6.3	5.8	6.0	3.2	2.5
Total	**6,139.6**	**6,514.9**	**6,707.0**	**6,782.6**	**6,801.3**	**6,849.5**	**7,047.4**	**6,936.2**
Net Emissions (Sources and Sinks)	**5,066.8**	**5,450.7**	**5,646.0**	**5,942.0**	**5,970.9**	**6,008.5**	**6,212.7**	**6,098.1**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] For the most recent years, a portion of the sink estimate is based on historical and projected data; see Chapter 6, Table 6-1 for a complete breakdown. Parentheses indicate negative values (or sequestration).

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

Note: Totals may not sum due to independent rounding.

Figure ES-2

Annual Percent Change in U.S. GHG Emissions

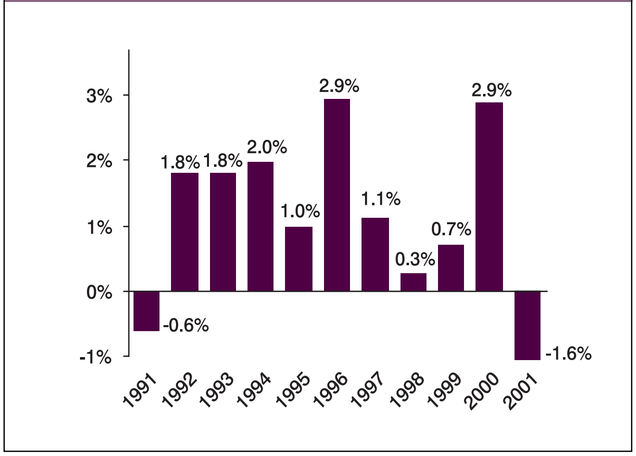

Figure ES-4

2001 Greenhouse Gas Emissions by Gas

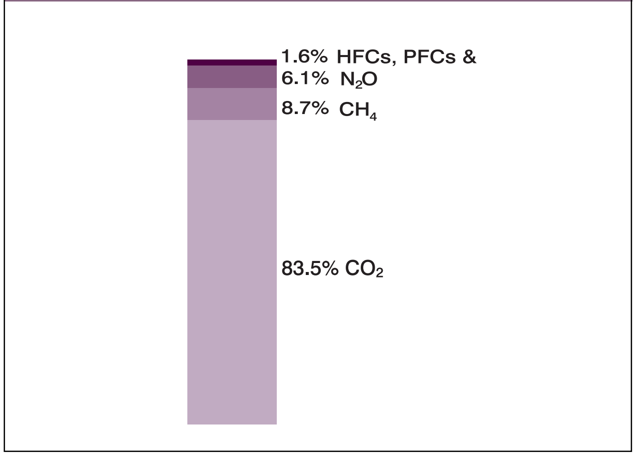

Figure ES-3

Absolute Change in U.S. GHG Emissions Since 1990

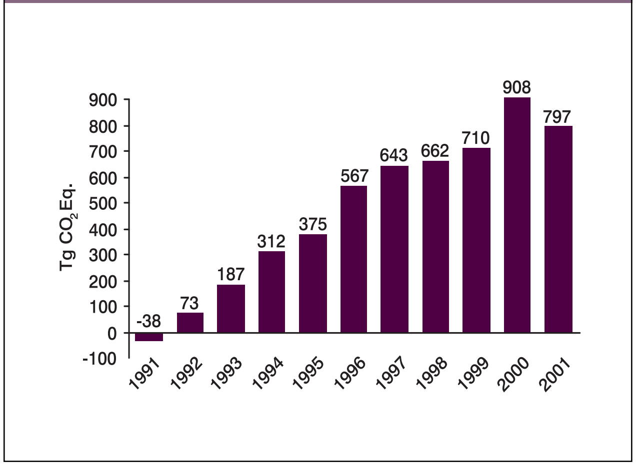

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2001. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing approximately 84 percent of total greenhouse gas emissions. The largest source of CO_2, and of overall greenhouse gas emissions, was fossil fuel combustion. Methane emissions resulted primarily from decomposition of wastes in landfills, natural gas systems, and enteric fermentation associated with domestic livestock. Agricultural soil management and mobile source fossil fuel combustion were the major sources of N_2O emissions. The emissions of substitutes for ozone depleting substances and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate HFC emissions. Electrical transmission and distribution systems accounted for most SF_6 emissions, while the majority of PFC emissions resulted as a by-product of primary aluminum production.

As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion accounted for a nearly constant 80 percent of global warming potential (GWP) weighted emissions in the 1990s. Emissions from this source category grew by 17 percent (800.1 Tg CO_2 Eq.) from 1990 to 2001 and were responsible for most of the increase in national emissions during this period. The most recent annual change in CO_2 emissions from fossil fuel combustion was a reduction of 77.3 Tg CO_2 Eq. (1.4 percent), which is the first decrease in emissions since a decrease from 1990 to 1991; the source's average annual growth rate was 1.3 percent from 1990 through 2001. Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. On an annual basis, the overall consumption of fossil fuels in the United States generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

In the longer-term energy consumption patterns respond to changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs) and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Energy-related CO_2 emissions also depend on the type of fuel or energy consumed and its carbon intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 emissions because of the lower carbon content of natural gas. Table ES-2 shows annual changes in emissions during the last six years for coal, petroleum, and natural gas in selected sectors.

Milder weather conditions in summer and winter of 1997 (compared to 1996) moderated the growth of CO_2 emissions from fossil fuel combustion. The shutdown of several nuclear power plants, however, lead electric utilities to increase their consumption of coal and other fuels to offset the lost nuclear capacity.

In 1998, warm winter temperatures contributed to a significant drop in residential and commercial natural gas consumption. This drop in emissions from natural gas used for heating was 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.

In 1999, the increase in emissions from fossil fuel combustion was driven largely by growth in petroleum consumption for transportation. In addition, residential and commercial heating fuel demand partially recovered as winter temperatures dropped relative to 1998, although temperatures were still warmer than normal.[6] These increases were offset, in part, by a decline in emissions from electric power producers due primarily to: 1) an increase in net generation of electricity by nuclear plants which reduced demand from fossil fuel plants; and 2) moderated summer temperatures compared to the previous year—thereby reducing electricity demand for air conditioning.

Emissions from fuel combustion increased considerably in 2000, due to several factors. The primary reason for the increase was the robust U.S. economy, which produced a high demand for fuels—especially for petroleum in the transportation sector—despite increases in the price of both natural gas and petroleum. Colder winter conditions relative to the previous year triggered a rise in residential and commercial demand for heating. Structural and other economic changes taking place within U.S. industry—especially manufacturing—lead to lower coal consumption. Additionally, electricity generation became more carbon intensive as coal and natural gas consumption offset reduced hydropower output.

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

Sector	Fuel Type	1996 to 1997		1997 to 1998		1998 to 1999		1999 to 2000		2000 to 2001	
Electricity Generation	Coal	44.1	3%	30.6	2%	8.7	0%	89.4	5%	(50.1)	(3%)
Electricity Generation	Natural Gas	13.9	7%	29.1	13%	12.0	5%	20.6	8%	4.3	2%
Electricity Generation	Petroleum	9.0	14%	29.7	40%	(7.6)	(7%)	(5.7)	(6%)	10.7	12%
Transportation[a]	Petroleum	7.3	0%	33.0	2%	58.7	4%	49.8	3%	19.7	1%
Residential	Natural Gas	(14.0)	(3%)	(23.7)	(9%)	10.0	9%	13.9	3%	(9.6)	(1%)
Commercial	Natural Gas	3.1	2%	(10.8)	(6%)	1.7	1%	9.1	5%	1.6	1%
Industrial	Coal	1.2	1%	(8.7)	(6%)	(6.1)	(4%)	2.3	2%	(7.7)	(6%)
Industrial	Natural Gas	1.1	0%	(11.7)	(2%)	(17.6)	(4%)	12.5	3%	(33.5)	(7%)
All Sectors[b]	**All Fuels[b]**	**74.2**	**1%**	**20.5**	**0%**	**68.3**	**1%**	**202.8**	**4%**	**(77.9)**	**(1%)**

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

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[6] Normals are based on data from 1961 through 1990. Source: NOAA (2002)

In 2001, economic growth in the U.S. slowed considerably for the second time since 1990, contributing to a decrease in CO_2 emissions from fossil fuel combustion, also for the second time since 1990. A significant reduction in industrial output contributed to weak economic growth, primarily in manufacturing, and led to lower emissions from the industrial sector. Several other factors also played a role in this decrease in emissions. Warmer winter conditions compared to 2000, along with higher natural gas prices, reduced demand for heating fuels. Additionally, nuclear facilities operated at their highest capacity on record, offsetting electricity produced from fossil fuels. Since there are no greenhouse gas emissions associated with electricity production from nuclear plants, this substitution reduces the overall carbon intensity of electricity generation.

Other significant trends in emissions from additional source categories over the twelve-year period from 1990 through 2001 included the following:

- Carbon dioxide emissions from waste combustion increased by 12.8 Tg CO_2 Eq. (91 percent), as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.
- Net CO_2 flux from land use change and forestry decreased by 234.7 Tg CO_2 Eq. (22 percent), primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks.
- Methane emissions from coal mining dropped by 26.4 Tg CO_2 Eq. (30 percent) as a result of the mining of less gassy coal from underground mines and the increased use of methane collected from degasification systems.
- By 1998, all of the three major adipic acid producing plants had voluntarily implemented N_2O abatement technology, and as a result, emissions fell by 10.3 Tg CO_2 Eq. (68 percent). The majority of this decline occurred from 1996 to 1998, despite increased production.
- Nitrous oxide emissions from agricultural soil management increased by 26.8 Tg CO_2 Eq. (10 percent) as crop and forage production, manure production, and fertilizer consumption rose.
- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 62.7 Tg CO_2 Eq. This increase was significantly offset, however, by reductions in PFC emissions from aluminum production (14.0 Tg CO_2 Eq. or 77 percent), reductions in emissions of HFC-23 from the production of HCFC-22 (15.2 Tg CO_2 Eq. or 43 percent), and reductions of SF_6 from electric power transmission and distribution systems (16.8 Tg CO_2 Eq. or 52 percent). Reductions in PFC emissions from aluminum production resulted from both industry emission reduction efforts and lower domestic aluminum production. HFC-23 emissions from the production of HCFC-22 decreased because a reduction in the intensity of emissions from that source offset an increase in HCFC-22 production. Reduced emissions of SF_6 from electric power transmission and distribution systems are primarily the result of higher purchase prices for SF_6 and efforts by industry to reduce emissions.

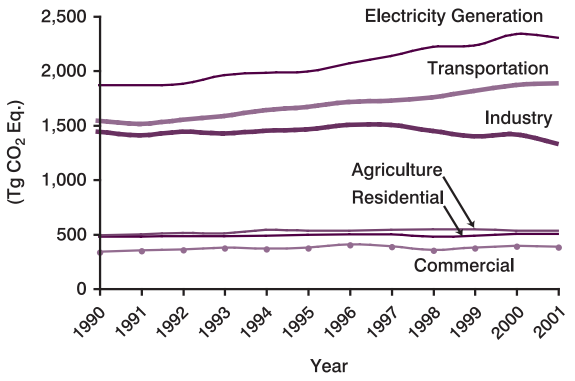
Overall, from 1990 to 2001, total emissions of CO_2 and N_2O increased by 791.1 (16 percent) and 27.0 Tg CO_2 Eq. (7 percent), respectively, while CH_4 emissions decreased by 38.1 Tg CO_2 Eq. (6 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 16.6 Tg CO_2 Eq. (18 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because many of them have 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, trees in urban areas, agricultural soils, and landfilled yard trimmings, which was estimated to be 12 percent of total emissions in 2001.

Emissions by Economic Sector

Throughout this report, emission estimates are grouped into six sectors (i.e., chapters) defined by the IPCC: Energy, Industrial Processes, Solvent Use, Agriculture, Land-Use Change and Forestry, and Waste. While it is important to use this characterization for consistency with UNFCCC reporting guidelines, it is also useful to allocate emissions into more commonly used sectoral categories. This section reports emissions by the following economic sectors: Residential, Commercial, Industry, Transportation, Electricity Generation, and Agriculture, and U.S. Territories. Table ES-3 summarizes emissions from each of these sectors. Figure ES-5 shows the trend in emissions by sector from 1990 to 2001.

Figure ES-5

Emissions Allocated to Economic Sectors



Note: Does not include U.S. territories

Using this categorization, emissions from electricity generation accounted for the largest portion (33 percent) of U.S. greenhouse gas emissions in 2001. Transportation activities, in aggregate, accounted for the second largest portion (27 percent). Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2001. In contrast to electricity generation and transportation, emissions from industry have declined over the past decade, as structural changes have occurred in the U.S. economy (i.e., shifts from a manufacturing based to a service-based economy), fuel switching has occurred, and efficiency improvements have been made. The remaining 21 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, and commercial economic sectors, plus emissions from U.S. Territories. Residences accounted for about 5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 8 percent of U.S. emissions, but unlike all other economic sectors, these emissions were dominated by N_2O emissions from agricultural soils instead of CO_2 from fossil fuel combustion. The commercial sector accounted for about 7 percent of emissions, while U.S. territories accounted for 1 percent.

Table ES-3: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq.)

Sector	1990	1995	1996	1997	1998	1999	2000	2001
Electricity Generation	1,862	1,990	2,064	2,130	2,217	2,227	2,332	2,298
Transportation	1,526	1,651	1,694	1,707	1,736	1,798	1,849	1,867
Industry	1,423	1,445	1,485	1,485	1,433	1,381	1,401	1,316
Agriculture	488	526	526	538	539	540	526	526
Residential	335	371	402	385	353	372	390	379
Commercial	472	488	495	494	474	481	498	497
U.S. Territories	34	44	40	43	48	50	52	54
Total	**6,140**	**6,515**	**6,707**	**6,783**	**6,801**	**6,850**	**7,047**	**6,936**
Sinks	(1,073)	(1,064)	(1,061)	(841)	(830)	(841)	(835)	(838)
Net Emissions (Sources and Sinks)	**5,067**	**5,451**	**5,646**	**5,942**	**5,971**	**6,008**	**6,213**	**6,098**

Note: Totals may not sum. Emissions include CO_2, CH_4, HFCs, PFCs, and SF_6.
See Table 1-13 for more detailed data.

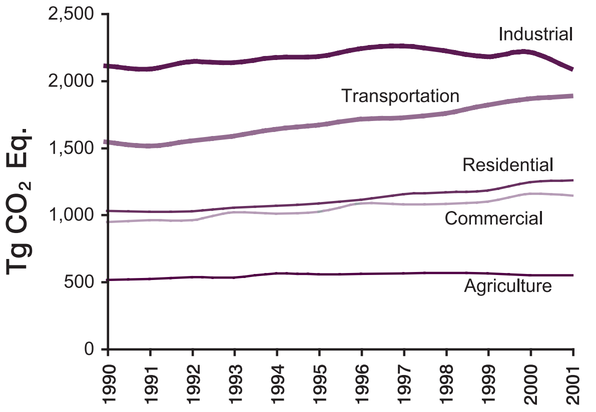
Carbon dioxide was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, and landfilling of yard trimmings.

Electricity is ultimately consumed in the economic sectors described above. Table ES-4 presents greenhouse gas emissions from economic sectors with emissions related to electricity generation distributed into end-use categories (i.e., emissions from electricity generation are allocated to the economic sectors in which the electricity is consumed). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electricity generation were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity.[7] These source categories include CO_2 from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO_2 and N_2O from waste combustion, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution systems.

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (30 percent) in 2001. Emissions from the residential and commercial sectors also increase substantially due to their relatively large share of electricity consumption (e.g., lighting, appliances, etc.). Transportation activities remain the second largest contributor to emissions. In all sectors except agriculture, CO_2 accounts for more than 75 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Figure ES-6 shows the trend in these emissions by sector from 1990 to 2001.

Figure ES-6

Emissions with Electricity Distributed to Economic Sectors



Note: Does not include U.S. territories.

Table ES-4: U.S Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq.)

Sector	1990	1995	1996	1997	1998	1999	2000	2001
Industry	2,097	2,164	2,224	2,245	2,209	2,165	2,201	2,074
Transportation	1,529	1,654	1,697	1,710	1,740	1,801	1,852	1,870
Residential	943	1,020	1,081	1,074	1,076	1,095	1,155	1,139
Commercial	1,025	1,081	1,110	1,151	1,164	1,178	1,241	1,253
Agriculture	512	553	555	560	564	560	547	546
US Territories	34	44	40	43	48	50	52	54
Total	**6,140**	**6,515**	**6,707**	**6,783**	**6,801**	**6,850**	**7,047**	**6,936**
Sinks	(1,073)	(1,064)	(1,061)	(841)	(830)	(841)	(835)	(838)
Net Emissions (Sources and Sinks)	**5,067**	**5,451**	**5,646**	**5,942**	**5,971**	**6,008**	**6,213**	**6,098**

See Table 1-11 for more detailed data.

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[7] Emissions were not distributed to U.S. territories, since the electricity generation sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

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

Total emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: 1) emissions per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; 2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; 3) emissions per unit of electricity consumption, because the electric power industry—utilities and nonutilities combined—was the largest source of U.S. greenhouse gas emissions in 2001; 4) emissions per unit of total gross domestic product as a measure of national economic activity; or 5) emissions per capita.

Table ES-5 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 1.1 percent since 1990. This rate is slower than that for total energy or fossil fuel consumption and much slower than that for either electricity consumption or overall gross domestic product. At the same time, total U.S. greenhouse gas emissions have grown at about the same rate as national population during the last decade (see Figure ES-7). Overall, global atmospheric CO_2 concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

Table ES-5: Recent Trends in Various U.S. Data (Index 1990 = 100) and Global Atmospheric CO_2 Concentration

Variable	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Growth Rate[f]
Greenhouse Gas Emissions[a]	99	101	103	105	106	109	110	111	112	115	113	1.1%
Energy Consumption[b]	100	102	104	106	108	112	112	113	115	118	115	1.3%
Fossil Fuel Consumption[b]	100	102	104	106	107	111	112	113	114	118	115	1.3%
Electricity Consumption[b]	102	102	106	109	112	115	117	121	124	128	127	2.2%
GDP[c]	100	103	105	110	112	116	122	127	132	137	137	2.9%
Population[d]	101	103	104	105	107	108	109	111	112	113	114	1.2%
Atmospheric CO_2 Concentration[e]	100	101	101	101	102	102	103	104	104	104	105	0.4%

[a] GWP weighted values

[b] Energy content weighted values (EIA 2002a)

[c] Gross Domestic Product in chained 1996 dollars (BEA 2002)

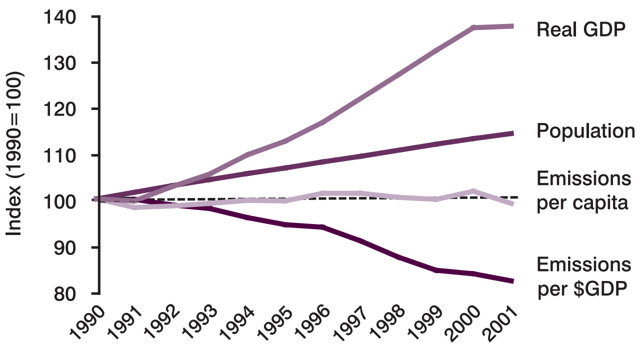
[d] (U.S. Census Bureau 2002)

[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 2002)

[f] Average annual growth rate

Figure ES-7

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



Source: BEA (2002), U.S. Census Bureau (2002), and emission estimates in this report

Global Warming Potentials

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations of the substance produce other greenhouse gases, when a gas influences the atmospheric lifetimes of other gases, and/or when a gas affects atmospheric processes that alter the radiative balance of the Earth (e.g., affect cloud formation or albedo).[8] The IPCC developed the Global Warming Potential (GWP) concept to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas.

The GWP of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). Direct radiative effects occur when the gas itself is a greenhouse gas. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in teragrams of CO_2 equivalents (Tg CO_2 Eq.).[9] All gases in this executive summary are presented in units of Tg CO_2 Eq. The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

$$\text{Tg } CO_2 \text{ Eq} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000\text{Gg}}\right)$$

While any time period can be selected, this report uses the 100 year GWPs recommended by the IPCC, and adopted by the UNFCCC for reporting purposes (IPCC 1996). GWP values are listed in Table ES-6.

Global warming potentials are not provided for CO, NO_x, NMVOCs, SO_2, and aerosols because there is no agreed upon method to estimate the contribution of gases that are short-lived in the atmosphere, spatially variable, and have only indirect effects on radiative forcing (IPCC 1996).

Table ES-6: Global Warming Potentials (100 Year Time Horizon) Used in This Report

Gas	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)*	21
Nitrous oxide (N_2O)	310
HFC-23	11,700
HFC-32	650
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. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, carbon fluxes among these various reservoirs are roughly balanced. Since the Industrial Revolution, this equilibrium of atmospheric carbon has been disrupted. Atmospheric concentrations of CO_2 have risen about 31 percent (IPCC 2001), principally because of fossil fuel combustion, which accounted for 97 percent of total U.S. CO_2 emissions in 2001. Globally, approximately 23,300 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels at the end of the 1990s, of which the United States accounted for about 24 percent (see Figure ES-8).[10] Changes in land

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[8] Albedo is a measure of the Earth's reflectivity; see the Glossary (Annex AB) for definition.

[9] Carbon comprises 12/44$^{\text{ths}}$ of carbon dioxide by weight.

[10] Global CO_2 emissions from fossil fuel combustion were taken from Marland et al. (2002). <http://cdiac.esd.ornl.gov/trends/emis/meth_reg.htm>

Box ES-2: The IPCC Third Assessment Report and Global Warming Potentials

In its Third Assessment Report (TAR), the IPCC updated the global warming potentials (GWPs) of several gases relative to the Second Assessment Report (SAR), and new GWPs were calculated for an expanded set of gases. Since the Second Assessment Report, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function (presented in WMO 1999). The GWPs in the TAR are drawn from WMO (1999) and the Second Assessment Report, with updates for those cases where significantly different new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases were recalculated. Because the revised radiative forcing of CO_2 is about 12 percent lower than that in the Second Assessment Report, the GWPs of the other gases relative to CO_2 tend to be larger, taking into account revisions in lifetimes. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons that were not presented in the Second Assessment Report. Table ES-7 presents the new Global Warming Potentials, relative to those presented in the Second Assessment Report.

Table ES-7: Comparison of 100 Year GWPs

Gas	SAR	TAR	Change	
Carbon dioxide (CO_2)	1	1	NC	NC
Methane (CH_4)*	21	23	2	10%
Nitrous oxide (N_2O)	310	296	(14)	(5%)
HFC-23	11,700	12,000	300	3%
HFC-32	650	550	(100)	(15%)
HFC-125	2,800	3,400	600	21%
HFC-134a	1,300	1,300	NC	NC
HFC-143a	3,800	4,300	500	13%
HFC-152a	140	120	(20)	(14%)
HFC-227ea	2,900	3,500	600	21%
HFC-236fa	6,300	9,400	3,100	49%
HFC-4310mee	1,300	1,500	200	15%
CF_4	6,500	5,700	(800)	(12%)
C_2F_6	9,200	11,900	2,700	29%
C_4F_{10}	7,000	8,600	1,600	23%
C_6F_{14}	7,400	9,000	1,600	22%
SF_6	23,900	22,200	(1,700)	(7%)

Source: (IPCC 2001, 1996)
NC (No Change)
* 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.

Although the GWPs have been updated by the IPCC, estimates of emissions presented in this report use the GWPs from the Second Assessment Report. The UNFCCC reporting guidelines for national inventories[11] were updated in 2002, but continue to require the use of GWPs from the SAR so that current estimates of aggregated greenhouse gas emissions for 1990 through 2001 are consistent with estimates developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, and all estimates are provided throughout this report in both CO_2 equivalents and unweighted units. A comparison of emission values using the SAR GWPs versus the TAR GWPs can be found in Chapter 1 and in more detail in Annex S.

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).

Figure ES-9 and Table ES-8 summarize U.S. sources and sinks of CO_2. The remainder of this section discusses CO_2 emission trends in greater detail.

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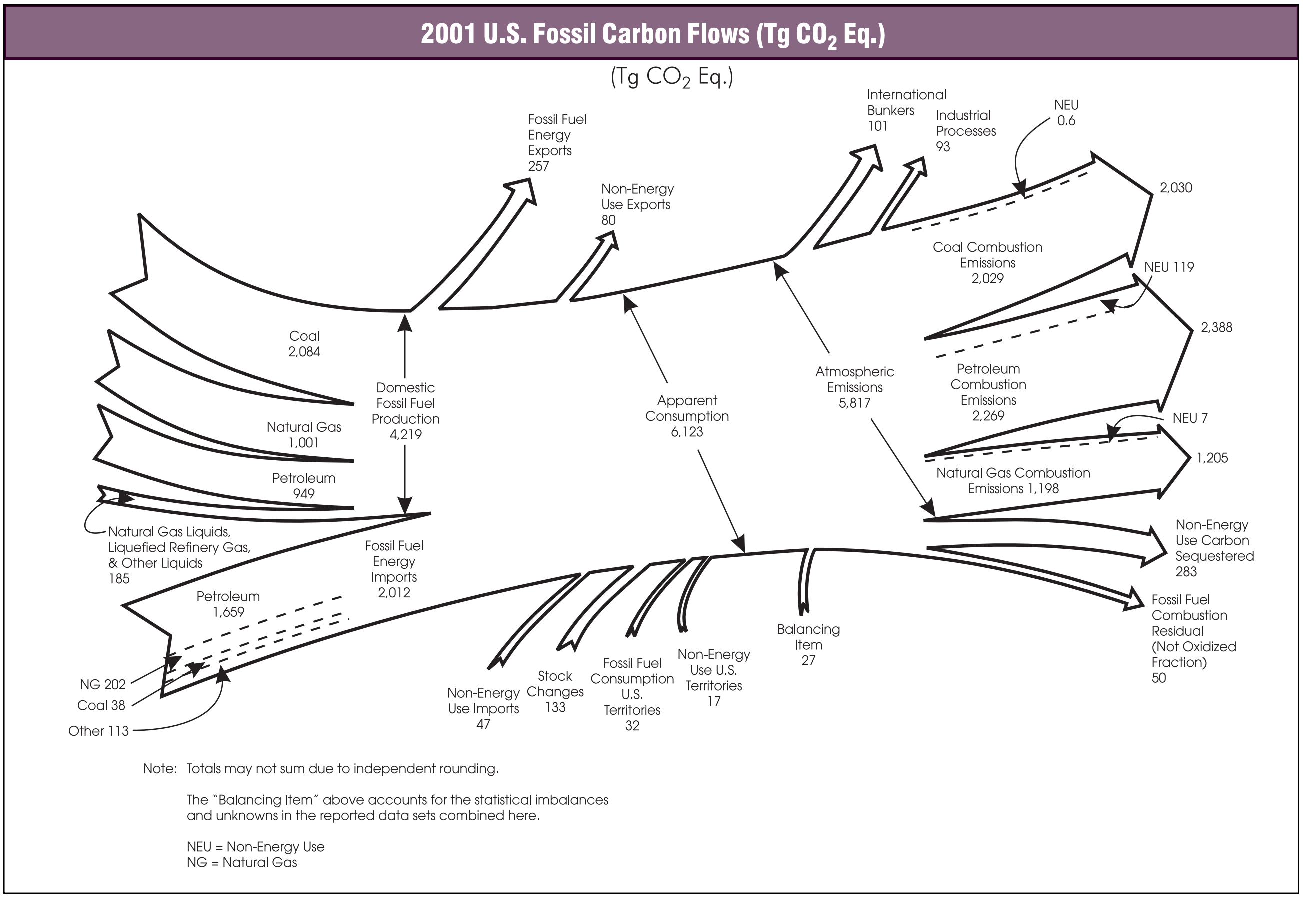
[11] See <http://unfccc.int/cop8/latest/5_sbstal5add1.pdf>.

Figure ES-8

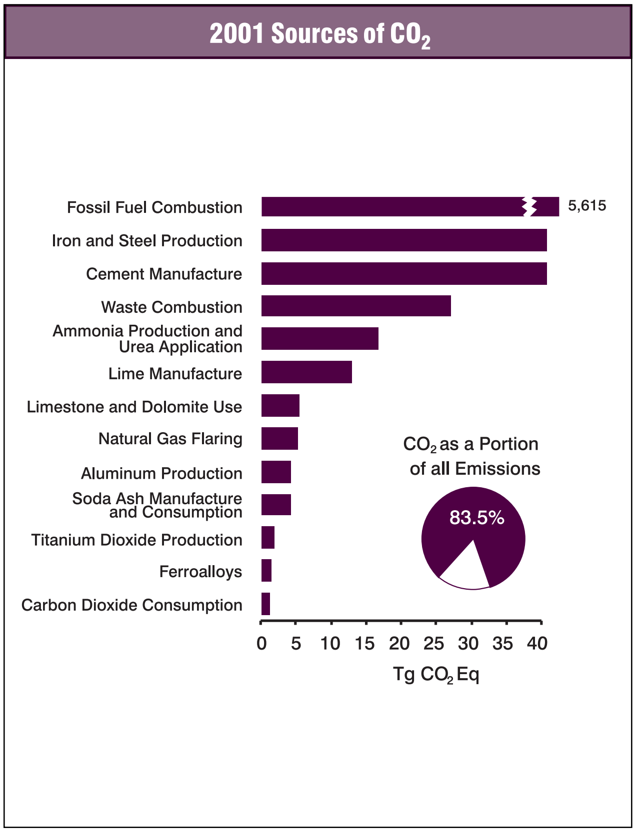


Note: Totals may not sum due to independent rounding.

The "Balancing Item" above accounts for the statistical imbalances and unknowns in the reported data sets combined here.

NEU = Non-Energy Use
NG = Natural Gas

Figure ES-9



Energy

Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2001. In 2001, approximately 86 percent of the energy consumed in the United States was produced through the combustion of fossil fuels. The remaining 14 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-10 and Figure ES-11). A discussion of specific trends related to CO_2 emissions from energy consumption is presented below.

Table ES-8: U.S. Sources of CO_2 Emissions and Sinks (Tg CO_2 Eq.)

Source or Sink	1990	1995	1996	1997	1998	1999	2000	2001
Fossil Fuel Combustion	4,814.8	5,141.5	5,325.8	5,400.0	5,420.5	5,488.8	5,692.2	5,614.9
Electricity Generation	1,805.0	1,931.8	2,003.9	2,070.8	2,160.3	2,173.5	2,277.8	2,242.8
Transportation	1,470.5	1,577.8	1,617.4	1,626.9	1,653.9	1,713.0	1,762.7	1,780.9
Industrial	955.3	1,002.6	1,039.5	1,050.8	1,000.1	973.2	991.1	937.7
Residential	328.9	358.5	388.6	371.7	338.8	357.3	373.9	363.3
Commercial	221.4	226.9	236.4	237.1	219.5	221.7	234.3	235.9
U.S. Territories	33.7	44.0	40.1	42.8	47.9	50.2	52.3	54.4
Iron and Steel Production	85.4	74.4	68.3	71.9	67.4	64.4	65.8	59.1
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.2	41.4
Waste Combustion	14.1	18.5	19.4	21.2	22.5	23.9	25.4	26.9
Ammonia Manufacture & Urea Application	19.3	20.5	20.3	20.7	21.9	20.6	19.6	16.6
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3	12.9
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	5.5	5.2
Limestone and Dolomite Use	5.5	7.0	7.6	7.1	7.3	7.7	5.8	5.3
Aluminum Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4	4.1
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2	4.1
Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	1.9	1.9
Carbon Dioxide Consumption	0.9	1.1	1.1	1.2	1.2	1.2	1.2	1.3
Ferroalloys	2.0	1.9	2.0	2.0	2.0	2.0	1.7	1.3
Land-Use Change and Forestry (Sink)[a]	(1,072.8)	(1,064.2)	(1,061.0)	(840.6)	(830.5)	(841.1)	(834.6)	(838.1)
International Bunker Fuels[b]	*113.9*	*101.0*	*102.3*	*109.9*	*112.9*	*105.3*	*99.3*	*97.3*
Total	**5,003.7**	**5,334.4**	**5,514.8**	**5,595.4**	**5,614.2**	**5,680.7**	**5,883.1**	**5,794.8**
Net Emissions (Sources and Sinks)	**3,930.9**	**4,270.3**	**4,453.8**	**4,754.7**	**4,783.7**	**4,839.6**	**5,048.5**	**4,956.7**

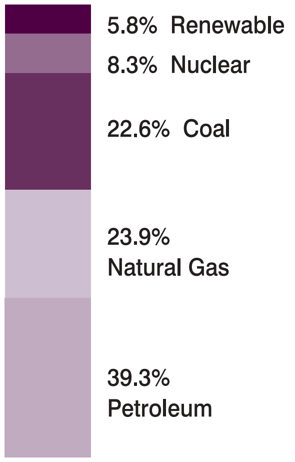
[a] Sinks are only included in net emissions total, and are based partially on projected activity data. Parentheses indicate negative values (or sequestration).

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

Note: Totals may not sum due to independent rounding.

Figure ES-10

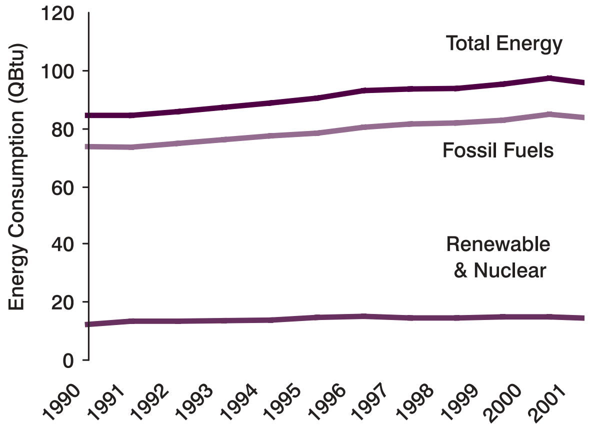
2001 U.S. Energy Consumption by Energy Source



Source: Annual Energy Review 2001, EIA (2002a), Table 1.3

Figure ES-11

U.S. Energy Consumption (Quadrillion Btu)



Note: Expressed as gross calorific values.
Source: Annual Energy Review 2001, EIA (2002a), Table 1.3.

Fossil Fuel Combustion (5,614.9 Tg CO_2 Eq.)

As fossil fuels are combusted, the carbon stored in them is emitted almost entirely 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 and natural gas have about 25 percent and 45 percent less carbon than coal, respectively. From 1990 through 2001, 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 23 percent of total energy consumption, respectively. Most petroleum was consumed in the transportation end-use sector, while the vast majority of coal was used by electric power generators, and natural gas was consumed largely in the industrial and residential end-use sectors.

Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.4 percent from 1990 to 2001. The fundamental factors influencing this trend include (1) a growing domestic economy over the last 11 years, and (2) significant growth in emissions from transportation activities and electricity generation. Between 1990 and 2001, CO_2 emissions from fossil fuel combustion increased from 4,814.8 Tg CO_2 Eq. to 5,614.9 Tg CO_2 Eq.—a 17 percent total increase over the twelve-year period.

The four major end-use sectors contributing to CO_2 emissions from fossil fuel combustion are industrial, transportation, residential, and commercial. Electricity generation also emits 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, electricity generation emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity consumption. This method of distributing emissions assumes that each end-use sector consumes electricity that is generated from the national average mix of fuels according to their carbon intensity. In reality, sources of electricity vary widely in carbon intensity. By assuming the same carbon intensity for each end-use sector's electricity consumption, for example, emissions attributed to the residential end-use sector may be underestimated, while emissions attributed to the industrial end-use sector may be overestimated. Emissions from electricity generation are also addressed separately after the end-use sectors have been discussed.

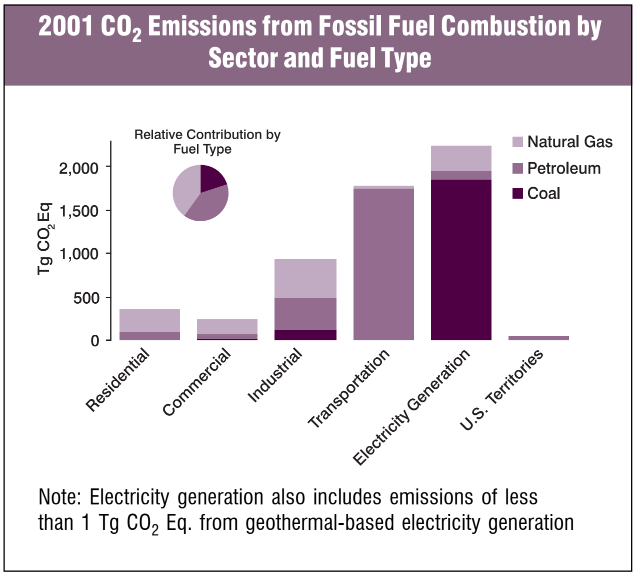
Note that emissions from U.S. territories are calculated separately due to a lack of specific consumption data for the individual end-use sectors. Table ES-9, Figure ES-12, and Figure ES-13 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Table ES-9: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1995	1996	1997	1998	1999	2000	2001
Industrial	**1,632.1**	**1,710.3**	**1,767.4**	**1,796.8**	**1,764.6**	**1,744.8**	**1,779.5**	**1,684.5**
Combustion	955.3	1,002.6	1,039.5	1,050.8	1,000.1	973.2	991.1	937.7
Electricity	676.8	707.7	727.9	746.0	764.5	771.7	788.4	746.8
Transportation	**1,473.5**	**1,580.9**	**1,620.4**	**1,630.0**	**1,657.0**	**1,716.2**	**1,766.1**	**1,784.4**
Combustion	1,470.5	1,577.8	1,617.4	1,626.9	1,653.9	1,713.0	1,762.7	1,780.9
Electricity	3.0	3.0	3.0	3.1	3.1	3.2	3.4	3.6
Residential	**918.8**	**996.4**	**1,056.6**	**1,048.0**	**1,051.6**	**1,069.4**	**1,127.3**	**1,111.1**
Combustion	328.9	358.5	388.6	371.7	338.8	357.3	373.9	363.3
Electricity	589.9	637.8	668.1	676.4	712.8	712.1	753.5	747.8
Commercial	**756.6**	**810.0**	**841.2**	**882.5**	**899.4**	**908.2**	**966.9**	**980.5**
Combustion	221.4	226.9	236.4	237.1	219.5	221.7	234.3	235.9
Electricity	535.2	583.1	604.8	645.4	679.9	686.5	732.6	744.6
U.S. Territories	**33.7**	**44.0**	**40.1**	**42.8**	**47.9**	**50.2**	**52.3**	**54.4**
Total	**4,814.8**	**5,141.5**	**5,325.8**	**5,400.0**	**5,420.5**	**5,488.8**	**5,692.2**	**5,614.9**
Electricity Generation	**1,805.0**	**1,931.8**	**2,003.9**	**2,070.8**	**2,160.3**	**2,173.5**	**2,277.8**	**2,242.8**

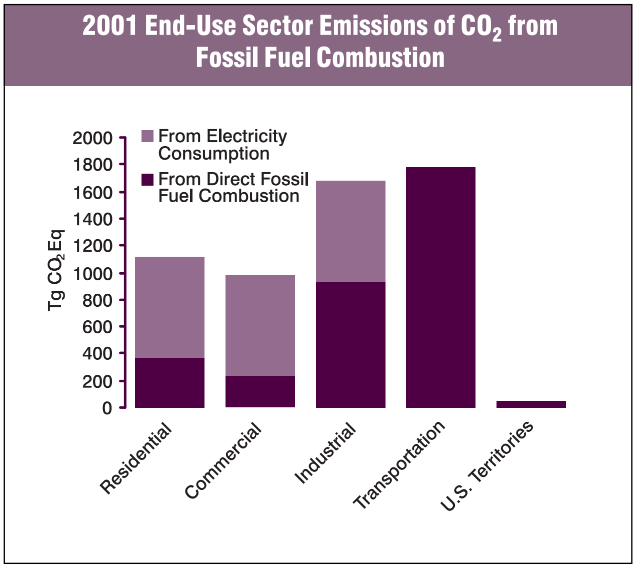
Note: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electricity generation are allocated based on aggregate national electricity consumption by each end-use sector.

Figure ES-12



Note: Electricity generation also includes emissions of less than 1 Tg CO_2 Eq. from geothermal-based electricity generation

Figure ES-13



Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is consumed by industry, accounted for 30 percent of CO_2 from fossil fuel combustion in 2001. About half of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The other half of the emissions resulted from consuming electricity for motors, electric furnaces, ovens, lighting, and other applications.

Transportation End-Use Sector. Transportation activities (excluding international bunker fuels) accounted for 32 percent of CO_2 emissions from fossil fuel combustion in 2001.[12] Virtually all of the energy consumed in this end-use sector came from petroleum products. Just over half of the emissions resulted from gasoline consumption for personal vehicle use. 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 17 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2001. Both sectors relied heavily on electricity for meeting energy demands, with 67 and 76 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking.

Electricity Generation. The United States relies on electricity to meet a significant portion of its energy demands, especially for lighting, electric motors, heating, and air conditioning. Electricity generators consumed 34 percent of U.S. energy from fossil fuels and emitted 40 percent of the CO_2 from fossil fuel combustion in 2001. The type of fuel combusted by electricity generators 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, electricity generators rely on coal for over half of their total energy requirements and accounted for 93 percent of all coal consumed for energy in the United States in 2001. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Waste Combustion (26.9 Tg CO_2 Eq.)

The burning of garbage and non-hazardous solids, referred to as municipal solid waste (MSW), as well as the burning of hazardous waste, is usually performed to recover energy from the waste materials. Carbon dioxide emissions arise from the organic (i.e., carbon) materials found in these

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[12] 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 2001.

wastes. Within MSW, many products contain carbon of biogenic origin, and the CO_2 emissions from their combustion are accounted for under the Land-Use Change and Forestry chapter. Several components of MSW, such as plastics, synthetic rubber, synthetic fibers, and carbon black, are of fossil fuel origin, and are included as sources of CO_2 emissions.

Natural Gas Flaring (5.2 Tg CO_2 Eq.)

Flaring of natural gas from oil wells releases CO_2. Natural gas is flared to relieve rising pressure or to dispose of small quantities of gas that are not commercially marketable. In 2001, flaring accounted for approximately 0.1 percent of U.S. CO_2 emissions.

Biomass Combustion (183.7 Tg CO_2 Eq.)

Biomass refers to organically-based carbon fuels (as opposed to fossil-based). Biomass in the form of fuel wood and wood waste was used primarily in the industrial sector, while the transportation sector was the predominant user of biomass-based fuels, such as ethanol from corn and woody crops.

Although these fuels do emit CO_2, in the long run the CO_2 emitted from biomass 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 croplands are accounted for in the estimates for Land-Use Change and Forestry.

The industrial sector accounted for 69 percent of gross CO_2 emissions from biomass combustion, and the residential sector accounted for 18 percent. Ethanol consumption by the transportation sector accounted for 6 percent.

Industrial Processes

Emissions are produced as a by-product of many non-energy-related activities. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO_2. The major production processes that emit CO_2 include iron and steel production, cement manufacture, lime manufacture, limestone and dolomite use, soda ash manufacture and consumption, CO_2 consumption, titanium dioxide production, ferroalloy production, and ammonia manufacturing and urea application. Carbon dioxide emissions from these sources were approximately 148.0 Tg CO_2 Eq. in 2001, accounting for about 3 percent of total CO_2 emissions.

Iron and Steel Production (59.1 Tg CO_2 Eq.)

Iron is produced by first reducing iron oxide (i.e., iron ore) with metallurgical coke in a blast furnace to produce pig iron. Carbon dioxide is produced as the metallurgical coke used in the blast furnace process is oxidized. Steel, which contains less than 2 percent carbon by weight, is produced from pig iron in a variety of specialized steel making furnaces. The majority of CO_2 emissions from the iron and steel processes come from the use of coke in the production of pig iron, with smaller amounts evolving from the removal of carbon from pig iron used to produce steel.

Cement Manufacture (41.4 Tg CO_2 Eq.)

Clinker is an intermediate product in the formation of finished Portland and masonry cement. Heating calcium carbonate ($CaCO_3$) in a cement kiln forms lime and CO_2. The lime combines with other materials to produce clinker, and the CO_2 is released into the atmosphere.

Ammonia Manufacture and Urea Application (16.6 Tg CO_2 Eq.)

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 (i.e., a petroleum fraction) or the electrolysis of brine at chlorine plants (EPA 1997). The two fossil fuel-based reactions produce carbon monoxide and hydrogen gas. This carbon monoxide is transformed into CO_2 in the presence of a catalyst. The CO_2 is generally released into the atmosphere, but some of the CO_2, together with ammonia, is used as a raw material in the production of urea [$CO(NH_2)_2$], which is a type of nitrogenous fertilizer. The carbon in the urea that is produced and assumed to be subsequently applied to agricultural land as a nitrogenous fertilizer is ultimately released into the environment as CO_2.

Lime Manufacture (12.9 Tg CO_2 Eq.)

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

Limestone and Dolomite Use (5.3 Tg CO_2 Eq.)

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)$) are basic raw materials used in a wide variety of industries, including construction, agriculture, chemical, and metallurgy. 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.

Aluminum Production (4.1 Tg CO_2 Eq.)

Carbon dioxide is emitted when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite. 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.

Soda Ash Manufacture and Consumption (4.1 Tg CO_2 Eq.)

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.

Titanium Dioxide Production (1.9 Tg CO_2 Eq.)

Titanium dioxide (TiO_2) is a metal oxide manufactured from titanium ore, and is principally used as a pigment. It is used in white paint and as a pigment in the manufacture of white paper, foods, and other products. Two processes, the chloride process and the sulfate process, are used for making TiO_2. Carbon dioxide is emitted from the chloride process, which uses petroleum coke and chlorine as raw materials.

Ferroalloy Production (1.3 Tg CO_2 Eq.)

Carbon dioxide is emitted from the production of several ferroalloys through the use of metallurgical coke as a raw material. Ferroalloys are composites of iron and other elements, often including silicon, manganese, and chromium. When incorporated in alloy steels, ferroalloys alter the material properties of the steel.

Carbon Dioxide Consumption (1.3 Tg CO_2 Eq.)

Many segments of the economy consume CO_2, including food processing, beverage manufacturing, chemical processing, and a host of industrial and other miscellaneous applications. Carbon dioxide may be produced as a by-product from the production of certain chemicals (e.g., ammonia), from select natural gas wells, or by separating it from crude oil and natural gas. For the most part, the CO_2 used in these applications is eventually released to the atmosphere.

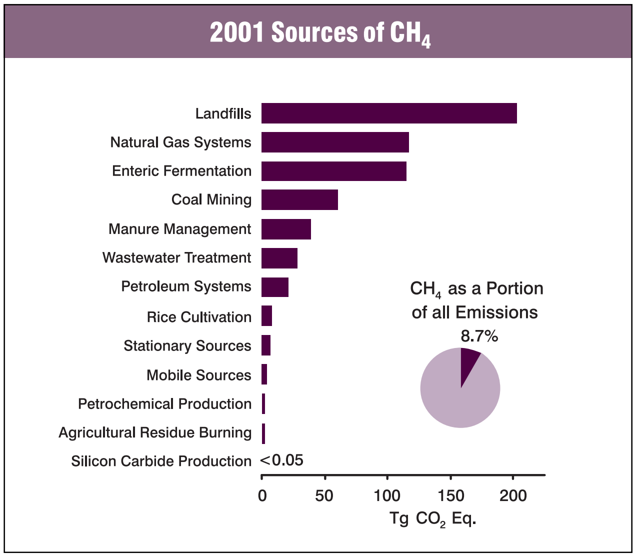
Land-Use Change and Forestry

When humans alter the terrestrial biosphere through land use, changes in land-use, and forest management practices, they also alter the natural carbon fluxes between biomass, soils, and the atmosphere. Forest management practices, tree planting in urban areas, the management of agricultural soils, and landfilling of yard trimmings have resulted in a net uptake (sequestration) of carbon in the United States, which offset about 14 percent of total U.S. gross CO_2 emissions in 2001. Forests (including vegetation, soils, and harvested wood) accounted for approximately 91 percent of total 2001 sequestration, urban trees accounted for 7 percent, agricultural soils (including mineral and organic soils and the application of lime) accounted for 2 percent, and landfilled yard trimmings accounted for 1 percent of the total sequestration in 2001. The net forest sequestration is a result of net forest growth and increasing forest area, as well as a net accumulation of carbon stocks in harvested wood pools. The net sequestration in urban forests is a result of net tree growth in these areas. In agricultural soils, mineral soils account for a net carbon sink that is approximately one and a third time larger than the sum of emissions from organic soils and liming. The mineral soil carbon sequestration is largely due to conversion of cropland to permanent pastures and hay production, a reduction in summer fallow areas in semi-arid areas, an increase in the adoption of conservation tillage practices, and an increase in the amounts of organic fertilizers (i.e., manure and sewage sludge) applied to agriculture lands. The landfilled yard trimmings net sequestration is due to the long-term accumulation of yard trimming carbon in landfills.

Methane Emissions

According to the IPCC, CH_4 is more than 20 times as effective as CO_2 at trapping heat in the atmosphere. Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 150 percent (IPCC 2001). Experts believe that over half of this atmospheric increase was due to 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-14 and Table ES-10).

Figure ES-14



Landfills (202.9 Tg CO_2 Eq.)

Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In an environment where the oxygen content is low or zero, anaerobic bacteria can decompose organic materials, such as yard waste, household waste, food waste, and paper, resulting in the generation of CH_4 and biogenic CO_2. Site-specific factors, such as waste composition, moisture, and landfill size, influence the level of methane generation.

Methane emissions from U.S. landfills have decreased by 4 percent since 1990. The generally declining emission estimates are a result of two offsetting trends: (1) the amount of municipal solid waste in landfills contributing to CH_4 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. Additionally, 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.

Natural Gas and Petroleum Systems (138.6 Tg CO_2 Eq.)

Methane is the major component of natural gas. Fugitive emissions of CH_4 occur throughout the production, processing, transmission, and distribution of natural gas. Because natural gas is often found in conjunction with

Table ES-10: U.S. Sources of Methane Emissions (Tg CO_2 Eq.)

Source	1990	1995	1996	1997	1998	1999	2000	2001
Landfills	212.1	216.1	212.1	207.5	202.4	203.7	205.8	202.9
Natural Gas Systems	122.0	127.2	127.4	126.0	124.0	120.3	121.2	117.3
Enteric Fermentation	117.9	123.0	120.5	118.3	116.7	116.6	115.7	114.8
Coal Mining	87.1	73.5	68.4	68.1	67.9	63.7	60.9	60.7
Manure Management	31.3	36.2	34.9	36.6	39.0	38.9	38.2	38.9
Wastewater Treatment	24.1	26.6	26.8	27.3	27.7	28.2	28.3	28.3
Petroleum Systems	27.5	24.2	23.9	23.6	22.9	21.6	21.2	21.2
Rice Cultivation	7.1	7.6	7.0	7.5	7.9	8.3	7.5	7.6
Stationary Sources	8.1	8.5	8.7	7.5	7.2	7.4	7.6	7.4
Mobile Sources	5.0	4.9	4.8	4.7	4.6	4.5	4.4	4.3
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7	1.7	1.5
Field Burning of Agricultural Residues	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8
Silicon Carbide Production	+	+	+	+	+	+	+	+
*International Bunker Fuels**	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
Total*	**644.0**	**650.0**	**636.8**	**629.5**	**622.7**	**615.5**	**613.4**	**605.9**

+ Does not exceed 0.05 Tg CO_2 Eq.
* Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.

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 2001, CH_4 emissions from U.S. natural gas systems were accounted for approximately 19 percent of U.S. CH_4 emissions.

Petroleum is often found in the same geological structures as natural gas, and the two are often retrieved together. Crude oil is saturated with many lighter hydrocarbons, including methane. When the oil is brought to the surface and processed, many of the dissolved lighter hydrocarbons (as well as water) are removed through a series of high-pressure and low-pressure separators. The remaining hydrocarbons in the oil are emitted at various points along the system. Methane emissions from the components of petroleum systems generally occur as a result of system leaks, disruptions, and routine maintenance. In 2001, emissions from petroleum systems were just under 4 percent of U.S. CH_4 emissions.

Coal Mining (60.7 Tg CO_2 Eq.)

Produced millions of years ago during the formation of coal, CH_4 trapped within coal seams and surrounding rock strata is released when the coal is mined. The quantity of CH_4 released to the atmosphere during coal mining operations depends primarily upon the type of coal and the method and rate of mining.

Methane from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed. Because CH_4 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, CH_4-recovery systems may supplement these ventilation systems. Recovery of CH_4 in the United States has increased in recent years. During 2001, coal mining activities emitted 10 percent of U.S. CH_4 emissions. From 1990 to 2001, emissions from this source decreased by 30 percent due to increased use of the CH_4 collected by mine degasification systems and a general shift toward surface mining.

Stationary and Mobile Combustion (11.7 Tg CO_2 Eq.)

In 2001, stationary and mobile combustion were responsible for CH_4 emissions of 7.4 and 4.3 Tg CO_2 Eq., respectively. The majority of CH_4 emissions from stationary combustion resulted from the burning of wood in the residential end-use sector. The combustion of gasoline in highway vehicles was responsible for the majority of the CH_4 emitted from mobile combustion.

Petrochemical and Silicon Carbide Production (1.5 Tg CO_2 Eq.)

Small amounts of CH_4 are released during the production of five petrochemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol. These production processes resulted in emissions of 1.5 Tg CO_2 Eq. in 2001. Methane is also emitted from the production of silicon carbide, a material used as an industrial abrasive. In 2001, silicon carbide production resulted in emissions of less than 0.1 Tg CO_2 Eq.

Enteric Fermentation (114.8 Tg CO_2 Eq.)

During animal digestion, CH_4 is produced through the process of enteric fermentation, in which microbes residing in animal digestive systems break down food. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest CH_4 emissions among all animal types because they have a rumen, or large fore-stomach, in which CH_4-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have much lower CH_4 emissions. In 2001, enteric fermentation was the source of about 19 percent of U.S. CH_4 emissions, and more than 70 percent of the CH_4 emissions from agriculture. From 1990 to 2001, emissions from this source decreased by 3 percent. Emissions from enteric fermentation have been generally decreasing since 1995, primarily due to declining dairy cow and beef cattle populations.

Manure Management (38.9 Tg CO_2 Eq.)

The decomposition of organic animal waste in an anaerobic environment produces CH_4. The most important factor affecting the amount of CH_4 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 CH_4, whereas solid waste management approaches produce little or no CH_4. Higher temperatures and moist climatic conditions also promote CH_4 production.

Emissions from manure management were about 6 percent of U.S. CH_4 emissions in 2001 and 24 percent of the CH_4 emissions from agriculture. From 1990 to 2001, emissions from this source increased by 24 percent. 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.

Rice Cultivation (7.6 Tg CO_2 Eq.)

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 CH_4 to the atmosphere, primarily through the rice plants. In 2001, rice cultivation was the source of 1 percent of U.S. CH_4 emissions, and about 5 percent of U.S. CH_4 emissions from agriculture. Emission estimates from this source have increased about 7 percent since 1990 due to an increase in the area harvested.

Field Burning of Agricultural Residues (0.8 Tg CO_2 Eq.)

Burning crop residue releases a number of greenhouse gases, including CH_4. Because field burning is not a common debris clearing method used in the United States, it was responsible for only 0.1 percent of U.S. CH_4 emissions in 2001.

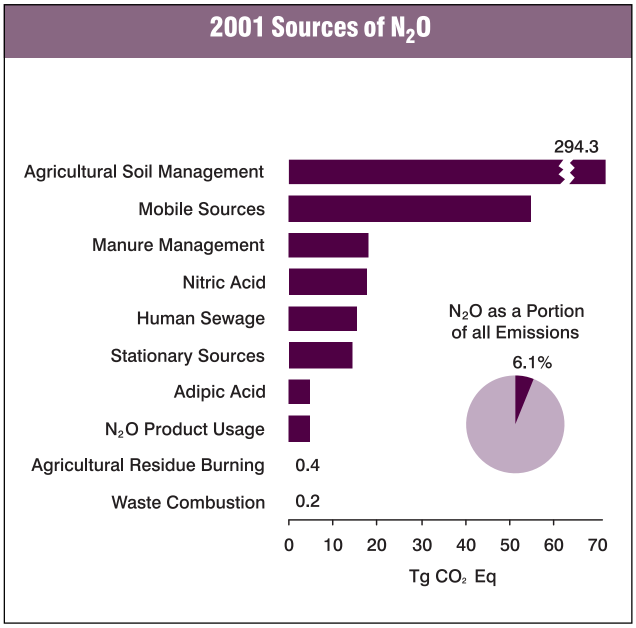
Wastewater Treatment (28.3 Tg CO_2 Eq.)

Wastewater from domestic sources (i.e., municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms and chemical contaminants. Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, with the latter condition producing CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. Untreated wastewater may also produce CH_4 if contained under anaerobic conditions.

Nitrous Oxide Emissions

Nitrous oxide (N_2O) is produced naturally from biological sources in soil and water, and anthropogenically by a variety of agricultural, energy-related, industrial, and waste management activities. While total N_2O emissions are much lower than CO_2 emissions, N_2O is approximately 300 times more powerful than CO_2 at trapping heat in the atmosphere. Since 1750, the atmospheric concentration of N_2O has risen by approximately 16 percent (IPCC 2001). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, fuel combustion in motor vehicles, manure management, nitric acid production, human sewage, and stationary fuel combustion (see Figure ES-15 and Table ES-11).

Figure ES-15



2001 Sources of N_2O

Table ES-11: U.S. Sources of Nitrous Oxide Emissions (Tg CO_2 Eq.)

Source	1990	1995	1996	1997	1998	1999	2000	2001
Agricultural Soil Management	267.5	284.1	293.2	298.2	299.2	297.0	294.6	294.3
Mobile Sources	50.6	60.9	60.7	60.3	59.7	58.8	57.5	54.8
Manure Management	16.2	16.6	17.0	17.3	17.3	17.4	17.9	18.0
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.1	19.1	17.6
Human Sewage	12.7	13.9	14.1	14.4	14.6	15.1	15.1	15.3
Stationary Combustion	12.5	13.2	13.8	13.7	13.7	13.7	14.3	14.2
Adipic Acid	15.2	17.2	17.0	10.3	6.0	5.5	6.0	4.9
N_2O Product Usage	4.3	4.5	4.5	4.8	4.8	4.8	4.8	4.8
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.5
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
International Bunker Fuels*	1.0	0.9	0.9	1.0	1.0	0.9	0.9	0.9
Total*	**397.6**	**430.9**	**441.7**	**440.9**	**436.8**	**433.0**	**429.9**	**424.6**

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

Agricultural Soil Management (294.3 Tg CO_2 Eq.)

Nitrous oxide 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 microbial processes. These activities may add nitrogen to soils either directly or indirectly. Direct additions occur through the application of synthetic and organic fertilizers; production of nitrogen-fixing crops and forages; the application of livestock manure, crop residues, and sewage sludge; cultivation of high-organic-content soils; and direct excretion by animals onto soil. Indirect additions result from volatilization and subsequent atmospheric deposition, and from leaching and surface run-off of some of the nitrogen applied to or deposited on soils as fertilizer, livestock manure, and sewage sludge.

In 2001, agricultural soil management accounted for 69 percent of U.S. N_2O emissions. From 1990 to 2001, emissions from this source increased by 10 percent as fertilizer consumption, manure production, and production of nitrogen-fixing and other crops rose.

Stationary and Mobile Combustion (68.9 Tg CO_2 Eq.)

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 quantity emitted varies according to the type of fuel, technology, and pollution control device used, as well as maintenance and operating practices. For example, some types of catalytic converters installed to reduce motor vehicle pollution can promote the formation of N_2O.

In 2001, N_2O emissions from mobile combustion were 13 percent of U.S. N_2O emissions, while stationary combustion accounted for 3 percent. From 1990 to 2001, combined N_2O emissions from stationary and mobile combustion increased by 9 percent, primarily due to increased rates of N_2O generation in highway vehicles.

Adipic Acid Production (4.9 Tg CO_2 Eq.)

Most 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 2001, U.S. adipic acid plants emitted 1 percent of U.S. N_2O emissions. Even though adipic acid production has increased, by 1998 all three major adipic acid plants in the United States had voluntarily implemented N_2O abatement technology. As a result, emissions have decreased by 68 percent since 1990.

Nitric Acid Production (17.6 Tg CO_2 Eq.)

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 2001, N_2O emissions from nitric acid production accounted for 4 percent of U.S. N_2O emissions. From 1990 to 2001, emissions from this source category decreased by 1 percent with the trend in the time series closely tracking the changes in production.

N_2O from Product Usage (4.8 Tg CO2 Eq.)

Nitrous oxide is used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia and as an anesthetic in various dental and veterinary applications. As such, it is used to treat short-term pain, for sedation in minor elective surgeries and as an induction anesthetic. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream.

Manure Management (18.0 Tg CO_2 Eq.)

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 2001 accounted for 4 percent of U.S. N_2O emissions. From 1990 to 2001, emissions from this source category increased by 11 percent, as poultry and swine populations have increased.

Field Burning of Agricultural Residues (0.5 Tg CO_2 Eq.)

Large quantities of agricultural crop residues are produced by farming activities, some of which is disposed by burning in the field. Field burning of crop residues is a source of N_2O, which is released during combustion. Because field burning is not a common method of agricultural residue disposal in the United States, emissions from this source are minor.

Human Sewage (Domestic Wastewater) (15.3 Tg CO_2 Eq.)

Domestic human sewage is usually mixed with other household wastewater, which includes shower drains, sink drains, washing machine effluent, etc., and transported by a collection system to either a direct discharge, an on-site or decentralized or centralized wastewater treatment system. After processing, treated effluent may be discharged to a receiving water environment (e.g., river, lake, estuary, etc.), applied to soils, or disposed of below the surface. Nitrous oxide may be generated during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. Emissions of N_2O from treated human sewage discharged into aquatic environments were estimated to be 15.3 Tg CO_2 Eq. in 2001.

Waste Combustion (0.2 Tg CO_2 Eq.)

Combustion is used to manage about 7 to 17 percent of the municipal solid wastes (MSW) generated in the United States. Almost all combustion of MSW in the United States occurs at waste-to-energy facilities where energy is recovered. Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), with some components, such as plastics, synthetic rubber, and synthetic fibers, of fossil origin, which together accounted for emissions of 0.2 Tg CO_2 Eq. in 2001.

HFC, PFC, and SF_6 Emissions

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are families 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. HFCs and PFCs do not deplete the stratospheric ozone layer, and are therefore acceptable alternatives under 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 PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere once emitted. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated.

Other emissive sources of these gases include aluminum production, HCFC-22 production, semiconductor manufacturing, electrical transmission and distribution systems, and magnesium production and processing. Figure ES-16 and Table ES-12 present emission estimates for HFCs, PFCs, and SF_6, which totaled 111.0 Tg CO_2 Eq. in 2001.

Substitution of Ozone Depleting Substances (63.7 Tg CO_2 Eq.)

The use and subsequent emissions of HFCs and PFCs as substitutes for ozone depleting substances (ODSs) have increased from small amounts in 1990 to account for 57 percent of aggregate HFC, PFC, and SF_6 emissions. This increase was in large part the result of efforts to phase-out chlorofluorocarbons (CFCs) and other ODSs in the United States, especially the introduction of HFC-134a as a CFC substitute in refrigeration and air-conditioning applications.

Table ES-12: Emissions of HFCs, PFCs, and SF_6 (Tg CO_2 Eq.)

Source	1990	1995	1996	1997	1998	1999	2000	2001
Substitution of Ozone Depleting Substances	0.9	21.7	30.4	37.7	44.5	50.9	57.3	63.7
HCFC-22 Production	35.0	27.0	31.1	30.0	40.2	30.4	29.8	19.8
Electrical Transmission and Distribution	32.1	27.5	27.7	25.2	20.9	16.4	15.4	15.3
Semiconductor Manufacture	2.9	5.9	5.4	6.5	7.3	7.7	7.4	5.5
Aluminum Production	18.1	11.8	12.5	11.0	9.0	8.9	7.9	4.1
Magnesium Production and Processing	5.4	5.6	6.5	6.3	5.8	6.0	3.2	2.5
Total	**94.4**	**99.5**	**113.6**	**116.8**	**127.6**	**120.3**	**121.0**	**111.0**

Note: Totals may not sum due to independent rounding.

In the short term, this trend is expected to continue, and will likely accelerate in the next decade as hydrochlorofluoro-carbons (HCFCs), which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

Aluminum Production (4.1 Tg CO_2 Eq.)

During the production of primary aluminum CF_4 and C_2F_6 are emitted as intermittent by-products of the smelting process. These PFCs are formed when fluorine from the cryolite bath combines with carbon from the electrolyte anode. Emissions from aluminum production have decreased by 77 percent between 1990 and 2001 due to emission reduction efforts by the industry and falling domestic aluminum production.

HCFC-22 Production (19.8 Tg CO_2 Eq.)

HFC-23 is a by-product of the production of HCFC-22. Emissions from this source have decreased by 43 percent since 1990. The HFC-23 emission rate (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined significantly since 1990, although production has been increasing.

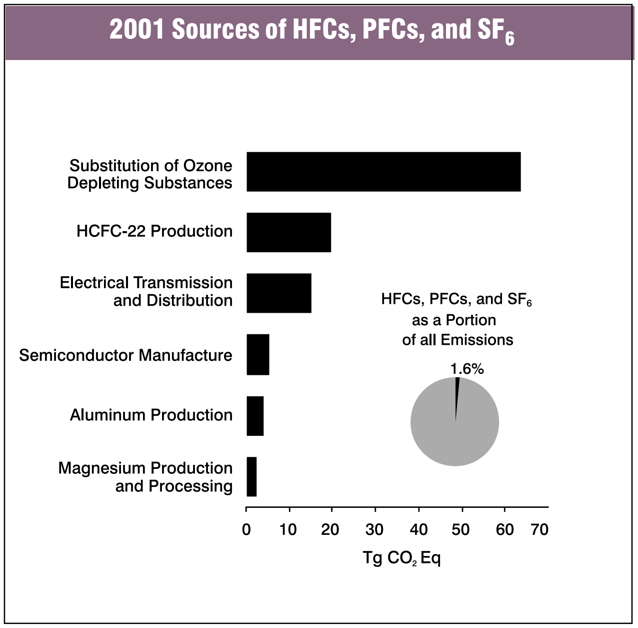
Semiconductor Manufacturing (5.5 Tg CO_2 Eq.)

The semiconductor industry uses combinations of HFCs, PFCs, SF_6, and other gases for plasma etching and to clean chemical vapor deposition tools. Emissions from this source category have increased with the growth in the semiconductor industry and the rising intricacy of chip designs. However, the growth rate in emissions has slowed since 1997, and emissions actually declined between 1999 and 2001. This later reduction is due to the implementation of PFC emission reduction methods, such as process optimization.

Electrical Transmission and Distribution Systems (15.3 Tg CO_2 Eq.)

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 decreased by 52 percent since 1990, primarily due to higher SF_6 prices and industrial efforts to reduce emissions.

Figure ES-16



2001 Sources of HFCs, PFCs, and SF_6

Magnesium Production (2.5 Tg CO_2 Eq.)

Sulfur hexafluoride is also used as a protective cover gas for the casting of molten magnesium. Emissions from primary magnesium production and magnesium casting have decreased by 53 percent since 1990. Emissions have decreased since 1999, due to a decrease in the quantity of magnesium die cast and the closure of a U.S. primary magnesium production facility.

Box ES-3: Emissions of Ozone Depleting Substances

Manmade halogenated compounds were first emitted into the atmosphere in significant quantities during the 20th century. This family of man-made compounds includes CFCs, halons, methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs). These substances have a variety of industrial applications, including refrigeration, air conditioning, foam blowing, solvent cleaning, sterilization, fire extinguishing, agricultural fumigation and sterilization, coatings, paints, and aerosols.

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

Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many countries ratified 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 UNFCCC reporting guidelines do not include reporting instructions for estimating emissions of ODSs because they are tracked under the *Montreal Protocol*. Nevertheless, estimates for several Class I and Class II ODSs are provided in Table ES-13 for informational purposes. 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 the destruction of ozone—also a greenhouse gas—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-13: Emissions of Ozone Depleting Substances (Gg)

Compound	1990	1995	1996	1997	1998	1999	2000	2001
Class I								
CFC-11	53.5	36.2	26.6	25.1	24.9	24.0	22.8	22.8
CFC-12	112.6	51.8	35.5	23.1	21.0	14.0	17.2	21.3
CFC-113	52.7	17.1	+	+	+	+	+	+
CFC-114	4.7	1.6	+	+	+	+	+	+
CFC-115	4.2	3.0	3.2	2.9	2.7	2.6	2.3	1.5
Carbon Tetrachloride	32.3	4.7	+	+	+	+	+	+
Methyl Chloroform	316.6	92.8	+	+	+	+	+	+
Halon-1211	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Halon-1301	1.8	1.4	1.4	1.3	1.3	1.3	1.3	1.2
Class II								
HCFC-22	34.0	39.3	41.0	42.4	43.8	74.1	79.1	80.5
HCFC-123	+	0.6	0.7	0.8	0.9	1.0	1.1	1.2
HCFC-124	+	5.6	5.9	6.2	6.4	6.5	6.5	6.5
HCFC-141b	1.3	9.9	9.9	8.8	9.7	10.9	10.9	10.7
HCFC-142b	0.8	3.6	4.0	4.3	4.7	5.0	5.4	5.8
HCFC-225ca/cb	+	+	+	+	+	+	+	+

Source: EPA, Office of Atmospheric Programs
+ Does not exceed 0.05 Gg

Ambient Air Pollutant Emissions

In the United States, carbon monoxide (CO), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2) are referred to as "ambient air pollutants," as termed in the Clean Air Act. These 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 hundreds of organic compounds that participate in atmospheric chemical reactions (i.e., propane, butane, xylene, toluene, ethane and many others)—are emitted primarily from transportation, industrial processes, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from coal combustion for electric power generation and the metals industry.

Table ES-14: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1995	1996	1997	1998	1999	2000	2001
NO_x	**23,037**	**22,509**	**22,360**	**22,289**	**21,961**	**21,341**	**20,917**	**20,141**
Stationary Fossil Fuel Combustion	9,884	9,822	9,540	9,578	9,419	8,716	8,226	7,826
Mobile Fossil Fuel Combustion	12,134	11,784	11,714	11,768	11,592	11,582	11,395	11,254
Oil and Gas Activities	139	100	126	130	130	113	115	117
Waste Combustion	82	88	135	140	145	142	149	149
Industrial Processes	769	682	808	634	635	748	992	755
Solvent Use	1	3	3	3	3	3	3	3
Field Burning of Agricultural Residues	28	29	32	34	35	34	35	35
Waste	0	1	3	3	3	3	3	3
CO	**130,575**	**109,149**	**104,063**	**101,132**	**98,976**	**95,464**	**93,965**	**100,653**
Stationary Fossil Fuel Combustion	4,999	5,383	3,935	3,927	3,927	4,941	4,163	4,169
Mobile Fossil Fuel Combustion	119,482	97,755	93,409	90,284	87,940	84,574	83,680	90,268
Oil and Gas Activities	302	316	321	333	332	152	152	153
Waste Combustion	978	1,073	2,628	2,668	2,826	2,833	2,914	2,916
Industrial Processes	4,124	3,958	3,016	3,153	3,163	2,145	2,214	2,327
Solvent Use	4	5	1	1	1	46	45	44
Field Burning of Agricultural Residues	685	656	747	761	781	760	784	762
Waste	1	2	5	5	5	14	14	14
NMVOCs	**20,937**	**19,520**	**17,184**	**16,994**	**16,403**	**16,245**	**15,418**	**15,148**
Stationary Fossil Fuel Combustion	912	973	1,018	1,016	1,016	1,312	1,088	1,087
Mobile Fossil Fuel Combustion	10,933	8,744	8,306	7,928	7,742	7,658	7,230	6,800
Oil and Gas Activities	555	582	433	442	440	376	348	357
Waste Combustion	222	237	304	313	326	326	332	333
Industrial Processes	2,426	2,643	1,997	2,038	2,047	1,890	1,845	1,829
Solvent Use	5,217	5,609	4,969	5,100	4,671	4,533	4,422	4,584
Field Burning of Agricultural Residues	NA	NA	NA	NA	NA	NA	NA	NA
Waste	673	731	158	157	161	151	153	158
SO_2	**20,936**	**16,892**	**16,682**	**17,091**	**17,189**	**16,013**	**14,802**	**14,324**
Stationary Fossil Fuel Combustion	18,407	14,724	14,746	15,104	15,191	14,073	12,883	12,367
Mobile Fossil Fuel Combustion	793	673	649	659	665	701	632	636
Oil and Gas Activities	390	334	304	312	310	275	279	281
Waste Combustion	39	42	29	29	30	29	29	30
Industrial Processes	1,306	1,117	953	985	991	933	977	1,008
Solvent Use	0	1	1	1	1	1	1	1
Field Burning of Agricultural Residues	NA	NA	NA	NA	NA	NA	NA	NA
Waste	0	1	1	1	1	1	1	1

Source: (EPA 2003) except for estimates from field burning of agricultural residues.
\+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

Box ES-4: 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 radiation from the sun back to space, thereby reducing the radiation reaching the Earth's surface; (2) affect cloud formation; and (3) affect atmospheric chemical composition (e.g., by providing surfaces for heterogeneous chemical reactions). The indirect effect of sulfur-derived aerosols on radiative forcing can be considered in two parts. The first indirect effect is the aerosols' tendency to decrease water droplet size and increase water droplet concentration in the atmosphere. The second indirect effect is the tendency of the reduction in cloud droplet size to affect precipitation by increasing cloud lifetime and thickness. Although still highly uncertain, the radiative forcing estimates from both the first and the second indirect effect are believed to be negative, as is the combined radiative forcing of the two (IPCC 2001). 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 regional haze, 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.

Electricity generation is the largest anthropogenic source of SO_2 emissions in the United States, accounting for 69 percent in 2001. Coal combustion contributes nearly all of those emissions (approximately 92 percent). Sulfur dioxide emissions have decreased in recent years, primarily as a result of electric power generators switching from high sulfur to low sulfur coal and installing flue gas desulfurization equipment.

Ambient air pollutants are regulated under the Clean Air Act in an effort to protect human health and the environment. These gases also indirectly affect the global climate by either acting as short-lived greenhouse gases or reacting with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Unlike the other ambient air pollutants, sulfur-containing compounds emitted into the atmosphere affect the Earth's radiative budget negatively; therefore, it is discussed separately.

One important indirect climate change effect of NMVOCs and NO_x is their role as precursors for tropospheric ozone formation. They can also alter the atmospheric lifetimes of other greenhouse gases. Another example of ambient air pollutant formation into greenhouse gases is carbon monoxide's interaction 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 ambient air pollutants (EPA 2003).[13] Table ES-14 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.

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, 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 highly accurate. For some 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 UNFCCC reporting guidelines follow the recommendation of the Revised 1996 IPCC Guidelines for National Greeenhouse Gas Inventories (IPCC/UNEP/OECD/IEA 1997) and require that countries provide single point estimates for each gas and emission or removal source category.

Currently, a qualitative discussion of uncertainty is presented for all source and sink categories. Within the discussion of each emission source, specific factors affecting the accuracy of the estimates are discussed. A limited number of sources also contain a quantitative uncertainty assessment. Beginning with the Inventory submission in 2004, the United States will provide quantitative estimates for all source and sink categories, in accordance with the new UNFCCC reporting guidelines.

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[13] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2003).

Changes in This Year's Inventory Report

Each year the U.S. Greenhouse Gas Inventory Program recalculates and revises the emission and sink estimates for all years in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* and attempts to improve both the analyses themselves, through the use of better methods or data, and the overall usefulness of the report. A summary of this year's revisions is presented in this chapter, including both changes in methodology and updates to historical data. The magnitude of each change's impact on emissions is also described. Table Changes-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and Table Changes-2 summarizes the quantitative effect on U.S. sinks, both relative to the previously published U.S. Inventory (i.e., 1990-2000 report). These tables present the magnitude of these changes in units of teragrams of carbon dioxide (CO_2) equivalents (Tg CO_2 Eq.).

For methodological changes, differences between the previous report and this report are explained. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 2000) has been recalculated to reflect the change.

Changes in historical data are generally the result of changes in statistical data supplied by other agencies. References for the data are provided for additional information.

Methodological Changes

CO_2 Emissions from Fossil Fuel Combustion

Storage factors for fossil fuels produced but not combusted (e.g., feedstocks) have been updated. The carbon storage factor for miscellaneous products under other petroleum for U.S. territories was reduced to 10 percent. This revision is based on the assumption that the carbon consumption for miscellaneous products is not used primarily for asphalt and road oil, which had been previously assumed, but for other uses which store much less carbon. The combination of this change, the historical changes described below, and the methodological changes in "Emissions and Storage from Non-Energy Uses of Fossil Fuels" (which affect the emissions from this source), resulted in an average annual increase of 52.0 Tg CO_2 Eq. (1.0 percent) in CO_2 emissions for the period 1990 through 2000.

Table Changes-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000
CO_2	**5.2**	**28.6**	**31.1**	**27.4**	**39.1**	**15.2**	**43.1**
Fossil Fuel Combustion	34.9	56.5	59.2	60.5	64.4	40.2	68.9
Natural Gas Flaring	NC	NC	NC	NC	NC	NC	(0.5)
Cement Manufacture	NC	NC	NC	NC	NC	NC	0.1
Lime Manufacture	NC	NC	NC	NC	NC	NC	+
Limestone and Dolomite Use	0.3	+	0.2	(1.3)	(0.9)	(1.4)	(3.4)
Soda Ash Manufacture and Consumption	+	+	+	+	+	+	+
Carbon Dioxide Consumption	0.1	0.1	+	(0.1)	(0.2)	(0.4)	(0.1)
Waste Combustion	+	(0.1)	(0.2)	(0.2)	2.2	2.1	2.9
Titanium Dioxide Production	NC	NC	NC	NC	NC	NC	+
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production	NC	NC	NC	(4.3)	NC	NC	+
Ferroalloys	NC	NC	NC	NC	NC	NC	NC
Ammonia Manufacture & Urea Application	0.8	1.5	0.8	1.2	1.8	1.7	1.6
International Bunker Fuels	+	+	+	+	(0.1)	(0.1)	(1.0)
CH_4	**(7.3)**	**(7.6)**	**(6.9)**	**(3.8)**	**(4.4)**	**(5.0)**	**(1.2)**
Stationary Sources	0.2	0.3	0.3	+	0.2	+	0.1
Mobile Sources	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Coal Mining	+	NC	NC	NC	NC	NC	+
Natural Gas Systems	0.8	1.6	0.8	3.3	1.8	1.7	4.8
Petroleum Systems	1.1	+	(0.1)	(0.4)	(0.5)	(0.7)	(0.6)
Petrochemical Production	NC	+	+	NC	NC	+	+
Silicon Carbide Production	NC	NC	NC	NC	NC	+	NC
Enteric Fermentation	(10.0)	(10.2)	(9.1)	(8.4)	(8.2)	(7.9)	(8.2)
Manure Management	2.1	1.4	0.7	0.7	1.0	1.3	0.8
Rice Cultivation	NC	NC	NC	NC	NC	NC	+
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	NC	+
Landfills	(1.3)	(0.5)	0.6	1.1	1.4	0.6	2.3
Wastewater Treatment	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.4)
International Bunker Fuels	+	+	+	+	+	+	+
N_2O	**10.3**	**11.2**	**11.3**	**11.1**	**10.5**	**9.4**	**4.6**
Stationary Sources	(0.3)	(0.3)	(0.3)	(0.5)	(0.6)	(0.9)	(0.7)
Mobile Sources	(0.3)	0.5	0.6	0.7	0.5	0.1	(0.8)
Adipic Acid	0.3	(0.7)	(0.7)	(1.2)	(1.7)	(2.2)	(2.1)
Nitric Acid	+	+	+	+	+	+	(0.7)
Manure Management	0.1	0.2	0.2	0.2	0.2	0.2	0.4
Agricultural Soil Management	0.5	0.6	0.6	0.7	0.8	0.7	(3.0)
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	NC	+
Human Sewage	5.7	6.3	6.3	6.5	6.5	6.7	6.7
N_2O Product Usage[a]	4.3	4.5	4.5	4.8	4.8	4.8	4.8
Waste Combustion	NC	NC	NC	NC	NC	NC	+
International Bunker Fuels	+	+	+	+	+	+	+
HFCs, PFCs, and SF_6	**0.7**	**1.0**	**1.8**	**(0.1)**	**+**	**0.4**	**(0.4)**
Substitution of Ozone Depleting Substances	NC	(0.1)	(0.2)	(0.3)	(0.3)	(0.4)	(0.5)
Aluminum Production	NC	NC	NC	NC	NC	NC	+
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Electrical Transmission and Distribution	0.9	1.0	0.9	0.7	0.7	0.9	1.0
Magnesium Production and Processing	(0.1)	0.1	1.1	(0.6)	(0.4)	(0.1)	(0.8)
Net Change in Total Emissions[b]	**8.9**	**33.1**	**37.2**	**34.5**	**45.2**	**20.1**	**46.1**
Percent Change	**0.1%**	**0.5%**	**0.6%**	**0.5%**	**0.7%**	**0.3%**	**0.7%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq.

[a] New source category relative to previous inventory.

[b] Excludes emissions from land-use change and forestry.

NC: (No Change)

Note: Totals may not sum due to independent rounding.

Table Changes-2: Revisions to Net CO_2 Sequestration from Land-Use Change and Forestry (Tg CO_2 Eq.)

Component	1990	1995	1996	1997	1998	1999	2000
Forests	NC	NC	NC	NC	NC	NC	14.7
Urban Trees	NC	NC	NC	NC	NC	NC	NC
Agricultural Soils	24.0	45.3	46.6	46.5	55.7	55.8	53.7
Landfilled Yard Trimmings	0.9	0.6	0.5	0.4	(0.3)	(0.5)	(0.5)
Net Change in Total Flux	**24.9**	**45.8**	**47.1**	**46.9**	**55.4**	**55.3**	**67.9**
Percent Change	**(2.3%)**	**(4.1%)**	**(4.2%)**	**(5.3%)**	**(6.3%)**	**(6.2%)**	**(7.5%)**

NC: (No Change)
Note: Numbers in parentheses indicate an *increase* in estimated net sequestration, or a decrease in net flux of CO_2 to the atmosphere. In the "percent change" row, negative numbers indicate that the sequestration estimate has decreased, and positive numbers indicate that the sequestration estimate has increased. Totals may not sum due to independent rounding.

Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

The methods for estimating CO_2 emissions of non-energy uses (NEU) of fossil fuels were revised in several ways this year. A full time series (1990-2001) of net imports/exports of feedstock-related petrochemicals was incorporated into the NEU analysis. The storage versus emissions balance of NEU carbon was also updated to include the carbon emitted from consumption of personal cleansers (e.g., soaps, shampoo, and detergents) and the carbon flows in refinery wastewaters. These changes, in combination with historical data changes in "CO2 Emissions from Fossil Fuel Combustion" and other modifications to the NEU section, resulted in an average annual decrease in stored carbon of 12.9 Tg CO_2 Eq. (5.0 percent) for the period 1990 through 2000.

Stationary Combustion (excluding CO_2)

The activity data for estimating non-CO_2 emissions from stationary combustion previously included the consumption of some fuels used for non-energy purposes. For the current inventory, consumption for these purposes is now being removed from the activity data. The combination of this change and the historical data changes described below resulted in an average annual increase of 0.2 Tg CO_2 Eq. (2.8 percent) of CH_4 emissions and an average annual decrease of 0.4 Tg CO_2 Eq. (3.0 percent) in N_2O emissions for the period 1990 through 2000.

Mobile Combustion (excluding CO_2)

The methodology for estimating non-CO_2 emissions from mobile combustion was altered significantly. The changes consisted of revisions to the distribution of control technologies for gasoline and diesel highway vehicles, the estimation of emission factors for gasoline and diesel highway vehicles, the estimation of vehicle miles traveled for alternative fuel vehicles, and the development of emission factors for alternative fuel vehicles.

Control technology assignments for light and heavy-duty conventional fuel vehicles for model years 1972 (when regulations began to take effect) through 1995 were estimated in EPA (1998). Assignments for 1998 through 2001 were determined using confidential engine family sales data submitted to the EPA (EPA 2002b). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2002a). This was used to determine the fraction of sales of each class of vehicle that met Tier 0, Tier 1, and LEV standards. Assignments for 1996 and 1997 were estimated based upon the fact that Tier 1 standards for light-duty vehicles were fully phased in by 1996. The previous methodology, which estimated control technology and emissions for California separately from the other 49 states, is no longer used.

Previous emission factors for heavy-duty gasoline vehicles only included Tier 0, oxidation catalyst, non-catalyst control and uncontrolled. In 1996, heavy-duty gasoline engines underwent a significant change with most going to three-way catalysts and multi-point sequential fuel injection systems, and new emission factors for these vehicles were developed. Emission factors for methane (CH_4) for Tier 1 and LEV heavy-duty gasoline vehicles were estimated using emission factors from the California Air Resources Board (CARB 2000). Nitrous oxide emissions were estimated from the ratio of NO_x emissions to N_2O emissions for Tier 0 heavy-duty gasoline trucks. A NO_x to N_2O ratio of 60 was used.

Vehicle Miles Traveled (VMT) for alternative fuel and advanced technology vehicles were calculated from the Energy Information Administration Data Tables (EIA 2002a). The data obtained include vehicle fuel use and total number of vehicles in use from 1992 through 2001. Fuel economy for each vehicle type and calendar year was determined by estimating the gasoline equivalent fuel economy for each technology. Energy economy ratios (the ratio of the gasoline equivalent fuel economy of a given technology to that of conventional gasoline or diesel vehicles) were taken from full fuel cycle studies done for the California Air Resources Board (Unnasch and Browning 2000). These were used to estimate fuel economy in miles per gasoline gallon equivalent for each alternative fuel and vehicle type. Energy use per fuel type was then divided among the various weight categories and vehicle technologies that would use that fuel. Total VMT per vehicle type for each calendar year was then determined by dividing the energy usage by the fuel economy. Average VMT was then calculated by dividing total VMT per vehicle type by the number of vehicles. Average VMT for each vehicle type was checked against the Federal Highway Administration Highway Statistics Series for each calendar year (FHWA 1996 through 2001). Note that for alternative fuel vehicles capable of running on both/either traditional and alternative fuels, the VMT given reflects only those miles driven that were powered by the alternative fuel.

Light-duty alternative fuel vehicle emission factors are estimated in Argonne National Laboratory's GREET 1.5 – Transportation Fuel Cycle Model (Wang 1999). In addition, Lipman and Delucchi estimate emission factors for some light and heavy-duty alternative fuel vehicles (Lipman and Delucchi 2002). The approach taken here is to calculate CH_4 emissions from actual test data and determine N_2O emissions from NO_x emissions from the same tests. Since it is likely that most alternative fuel vehicles use the same or similar catalysts to their conventional counterpart, the amount of N_2O emissions will depend upon the amount of oxides of nitrogen emissions that the engine produces. Based upon gasoline data for Tier 1 cars, the tailpipe NO_x to N_2O ratio is 5.75. Lipman and Delucchi (2002) found NO_x to N_2O ratios for light-duty alternative fuel vehicles with three-way catalyst systems to vary from 3 to 5.5 for older technology.

- Methane emission factors for light-duty vehicles were taken from the Auto/Oil Air Quality Improvement Research Program dataset (CRC 1997). This dataset provided CH_4 emission factors for all light-duty vehicle technologies except for propane (LPG). Light-duty propane emission factors were determined from reports on propane-vehicle emissions from the California Air Resources Board (Brasil and McMahon 1999) and the University of California Riverside (Norbeck et al 1998).
- Heavy-duty emission factors for alternative fuel vehicles were determined from test data using the West Virginia University mobile dynamometer (DOE 2002). Emission factors were determined based on the ratio of total hydrocarbon emissions to CH_4 emissions found for light-duty vehicles using the same fuel. Nitrous oxide emissions for heavy-duty engines were calculated from NO_x emission results using a NO_x to N_2O ratio of 50, which is more typical for heavy-duty engines with oxidation catalysts.

The combination of these changes and the historical data revisions described below resulted in an average annual increase of 0.1 Tg CO_2 Eq. (1.8 percent) in CH_4 emissions and 0.1 Tg CO_2 Eq. (0.2 percent) in N_2O emissions for the period 1990 through 2000.

Coal Mining

There was a single alteration to the methodology for estimating the emissions from coal mining. The change consisted of incorporating EIA's updated coal production data for the year 2000. The combination of this change and the historical data revisions described below resulted in an average annual increase of 0.1 Tg CO_2 Eq. (0.1 percent) in CH_4 emissions for the period 1990 through 2000.

Natural Gas Systems

The methodology used to estimate the emissions from natural gas systems was modified in two ways. First, data from four additional states were added to the number of north central non-associated wells. These states were left out in previous analyses, because the number of wells in these states was negligible. Second, the reduction in emission factors due to technological improvement was removed. In the past, emission factors were reduced at an annual rate of 0.2 percent such that by year 2020, emission factors would have declined by 5 percent from 1995. These reductions were made to reflect the underlying technological improvements through both innovation and normal replacement of equipment. However, the analysis already incorporates the emission reductions from some of these technological improvements as reported by EPA's Natural Gas STAR Partners. This is done by subtracting emission reductions associated with each stage of the natural gas system (production, processing, transmission and distribution) from the corresponding total emissions estimates for each operating stage. Thus, the emission factors were held constant throughout the time series for this year's inventory to eliminate the possibility of double counting. See Annex G for more detailed information on the methodology and data used to calculate CH_4 emissions from natural gas systems. The combination of these changes and the historical data revisions described below resulted in an average annual increase of 1.3 Tg CO_2 Eq. (1.1 percent) in CH_4 emissions for the period 1990 through 2000.

Petroleum Systems

There were three alterations to the methodology for estimating CH_4 emissions from petroleum systems. First, the emission factor for gas engines in the production sector was adjusted. In the previous report, the emission factor for gas engines, 0.08 scf CH_4/ HP-hr, was based on the 1999 EPA draft report, *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999). The 1996 Radian Study, *Methane Emissions from the U.S. Petroleum Industry* (Radian 1996) cites an emission factor of 0.24 scf CH_4/ HP-hr, which is a more accurate estimate for the emission factor of gas engines. Therefore, the 1996 Radian Study is the basis for the gas engine emission factor used in this year's inventory. Second, in the previous report, the activity data in the CRF table for the refining and crude transportation were based on crude oil production. However, crude production accounts only for the crude that is produced in the country, not the crude that is imported. The total crude refined includes both crude that is produced in the country and crude that is imported. In this year's report, the activity data for refining and crude transportation were based on refinery crude feed data obtained from EIA (2001). The amount of refinery feed accounts for all crude produced and imported that is refined. The activity data for crude oil transport were unavailable. In this case, it was assumed that all the crude that is transported goes to refineries. Therefore, the activity data for refining sector was used also for the transportation sector. Changing the bases from the crude production to refinery feed more accurately estimates the activity data of refining and crude transportation. Third, the estimated emissions in last year's report did not account for any emissions reductions reported by members of EPA's Natural Gas STAR Program. In this year's report, these emission reductions are taken into account by subtracting from tank venting the amount of emission reductions that were reported by the Natural Gas STAR Program partners from installing vapor recovery units for the period 1990 through 2001 (EPA 1995- 2000). Incorporating the reported emission reductions into the estimated CH_4 emissions gives a more accurate inventory estimate. See Annex H for additional detail. These changes resulted in an average annual increase of 0.1 Tg CO_2 Eq. (0.2 percent) in CH_4 emissions for the period 1990 through 2000.

Municipal Solid Waste Combustion

The incorporation of new 2000 data in the municipal solid waste combustion section led to a change in methodology for estimating the activity data for the years 1999 and 2001. Values for 1999 were interpolated between 1998 and 2000 reported data; 2001 values were extrapolated from the 2000 data. The combination of this change and the historical data changes described below resulted in an average annual increase of 0.6 Tg CO_2 Eq. (2.6 percent) in CO_2 emissions for the period 1990 through 2000.

Ammonia Manufacture and Urea Application

The methodology for estimating CO_2 emissions from ammonia production was adjusted to account for the use of some of the CO_2 produced from ammonia production as a raw material in the production of urea. For each ton of urea produced, 8.8 of every 12 tons of CO_2 are consumed and 6.8 of every 12 tons of ammonia is consumed. The CO_2 emissions reported for ammonia production are therefore reduced by a factor of 0.73 multiplied by total annual domestic urea production, and that amount of CO_2 emissions is allocated to urea fertilizer application. Both ammonia production and urea application are included in the same section of the Industrial Processes chapter; therefore total CO_2 emissions resulting from nitrogenous fertilizer production does not change.

In addition to the allocation of some emissions to urea application within this section, urea application data were adjusted to account for imports and exports of urea. Since imports of urea were greater than exports of urea during the years 1990 through 2000, this resulted in a net increase of emissions. The combination of this change and the historical data change discussed below resulted in an average annual increase of 1.2 Tg CO_2 Eq. (6.5 percent) in CO_2 emissions for the period 1990 through 2000.

Nitrous Oxide (N_2O) Product Usage

The N_2O Product Usage source has been added to this year's report to account for emissions produced by the use of nitrous oxide and products containing it. Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia and as an anesthetic in various dental and veterinary applications. The second principal use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Emissions from this source category added an annual average of 4.5 Tg CO_2 Eq. in N_2O emissions over the period 1990 through 2000.

Electrical Transmission and Distribution

The primary change in the methodology for calculating emissions from electrical transmission and distribution was an increase in the assumed emission rate from equipment manufacturers. Previously, the emission rate of U.S. electrical equipment manufacturers was assumed to be 3 percent of the SF_6 charged into new equipment. In light of the final CIGRE paper, this estimate has been increased to 10 percent. This revision resulted in an average annual increase of 0.9 Tg CO_2 Eq. (3.7 percent) in SF_6 emissions for the period 1990 through 2000.

Magnesium Production and Processing

There was a single change to the methodology for estimating the emissions from magnesium production. The emission factor for die casting in 2000 was adjusted downward to reflect the fact that participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry, which have relatively low emission rates, accounted for a greater percentage of die casting (nearly 100 percent) than previously believed (60 percent). The combination of this change and the historical data revisions described below resulted in an average annual decrease of less than 0.1 Tg CO_2 Eq. (1.9 percent) in SF_6 emissions for the period 1990 through 2000.

Enteric Fermentation

The methodology for estimating CH_4 emissions from enteric fermentation now incorporates new diet information for grazing beef cattle and cattle in feedlots. The changes in diet information were based on comments received during the expert review period of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*. To revise the values for digestible energy (DE) and fraction of energy converted to CH_4 (Y_m) for grazing beef cattle (beef cows, beef replacements, heifer stockers, and steer stockers), the diet descriptions developed for the enteric fermentation model were combined with new diet characteristic information found in the Nutrient Requirements of Beef Cattle (NRC 2000). New DE values were estimated for both forage-only and supplemented diets. For forage diets, two separate DE values were used to account for the lower feed quality in the western United States. Where DE values were not available, total digestible nutrients as a percent of dry matter intake was used as a proxy for DE and is considered essentially the

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[1] For example, in California the forage DE of 64.7 percent was used for 95 percent of the grazing cattle diet and a supplemental diet DE of 65.2 percent was used for five percent of the grazing cattle diet, for a total weighted DE of 64.9 percent.

same as the DE value. Weighted averages were developed for DE values for each region using both the supplemental diet and the forage diet.[1] For beef cows, the DE value was adjusted downward by two percent (assumed value) to reflect the reduced diet of the mature beef cow. For feedlot animals, diet characteristics were revised because of abrupt changes in emissions due to changes in DE and Y_m, as a result of the DE and Y_m originally being used for sets of years 1990 through 1992,1993 through 1995, and 1996 through 2000. It was also determined that the values used previously for 1990 through 1992 were too low for the DE and too high for the Y_m. To correct both of these issues, the values previously used for 1993 through 1995 were used for 1990, and this value was extrapolated linearly between the 1990 and the 1996 values. Values remain constant from 1996 onwards. See Annex L for more detailed information on the development of the diet information from cattle. The combination of these changes and the historical data revisions described below resulted in an average annual decrease of 9.3 Tg CO_2 Eq. (7.3 percent) in CH_4 emissions for the period 1990 through 2000.

Manure Management

The primary change in the methodology for estimating CH_4 and N_2O emissions from manure management was a change in the source for volatile solids excretion rates for cattle. This source was updated to be consistent with the results of the Enteric Fermentation Energy model.

In previous years, the method for calculating volatile solids production from dairy cows reflected the relationship between milk production and volatile solids production. Cows that produce more milk per year also produce more volatile solids in their manure due to their increased feed. Figure 4-1 in the *Agricultural Waste Management Field Handbook* (USDA 1996) was used to determine the mathematical relationship between volatile solids production and milk production for a 1,400 pound dairy cow. The resulting best-fit equation was used to estimate the volatile solids excretion rate for dairy cows given the estimated annual milk production data, published by USDA's National Agricultural Statistics Service (USDA 2000). State-specific volatile solids production rates were then calculated for each year of the inventory and used instead of a single national volatile solids excretion rate constant.

The volatile solids excretion rate for other animals were developed from published sources reviewed for U.S.-specific livestock waste characterization data. Data from the National Engineering Handbook, Agricultural Waste Management Field Handbook (USDA 1996) were chosen as the primary source of waste characteristics. In some cases, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1999) were used to supplement the USDA data.

This year, the method for calculating volatile solids production from beef and dairy cows, heifers, and steer is based on the relationship between animal diet and energy utilization, which is modeled in the enteric fermentation portion of the inventory. Volatile solids content of manure is equal to the fraction of the diet consumed by cattle that is not digested and thus is excreted as fecal material. The combination of this fecal material and urinary excretions constitutes manure. The enteric fermentation model requires the estimation of gross energy intake and its fractional digestibility, digestible energy, in the process of estimating enteric CH_4 emissions (see Annex M for details on the enteric energy model). These two inputs were used to calculate the indigestible energy per animal unit as gross energy minus digestive energy plus an additional 2 percent of gross energy for urinary energy excretion per animal unit. This was then converted to volatile solids production per animal unit using the typical conversion of dietary gross energy to dry organic matter of 20.1 MJ/kg (Garrett and Johnson 1983). The combination of this change and the historical data changes described below resulted in an average annual increase of 1.3 Tg CO_2 Eq. (4.0 percent) in CH_4 emissions and an average annual increase of 0.2 Tg CO_2 Eq. (1.2 percent) in N_2O emissions for the period 1990 through 2000.

Land-Use Change and Forestry

The Land-Use Change and Forestry chapter comprises four sections: 1) Forests; 2) Urban Trees; 3) Agricultural Soils; and 4) Landfilled Yard Trimmings. The methodologies used in the first, third, and fourth sections have changed relative to the previous Inventory. The changes to each section are described below.

- *Forests*. In this year's Inventory, revised estimates are reported for the amounts of harvested wood products and landfilled wood for 2000 to correct small errors in the results reported last year.

- *Agricultural Soils*. The current inventory is based on a modified version of the carbon accounting method developed by the Intergovernmental Panel on Climate Change (IPCC/UNEP/OECD/IEA 1997). The default IPCC method is a deterministic approach that provides general global parameters for estimating the impact of land use and management on soil organic carbon storage, and does not directly assess uncertainty in the resulting estimates. Previous years' inventories used the default method. For the current inventory, the method was modified in four ways to improve the method for application to U.S. soils and to assess uncertainty. First, probability density functions were developed for each management factor, instead of using the single values provided in the IPCC documentation (IPCC/UNEP/OECD/IEA 1997). Second, probability density functions were constructed for the activity data that were used in the previous inventory. Third, the mineral soil equation was modified so that the reference carbon stocks were based on soils under agricultural management instead of native vegetation. This was necessary due to the availability of data to construct probability density functions for the reference carbon stocks. Fourth, a Monte Carlo Analysis was used to select values from the probability density functions for repeated calculations of carbon stock change, generating a 95 percent confidence interval for the inventory. Overall, these changes should better reflect the impact of land use and management on soil organic carbon storage in U.S. agricultural lands. Four additional changes were made in the methods from the previous inventory to improve the estimates. First, the effect of wetland restoration in the Northern Great Plains was included, and represented an additional increase in carbon storage for wetlands enrolled in the Conservation Reserve Program and restored through the Partners for Wildlife Program (U.S. Fish and Wildlife Service). Second, changes in carbon stocks were not estimated for lands converted from agricultural uses to urban, miscellaneous non-cropland, and open water. In the previous inventory, carbon stocks were computed for these non-agricultural land uses using the factor values that were intended to represent changes from cultivated cropland to grasslands or forests. Consequently, applying these factor values to represent changes to non-agricultural land uses is highly questionable (e.g., converting a corn field into a subdivision or lake), and so those calculations were not included in the current inventory. Third, the previous inventory only accounted for manure applied to a portion of U.S. grazing lands based upon assumptions by Follett et al. (2001). The current inventory accounts for all of the manure and sewage sludge nitrogen that is available for application to agricultural land, based on information derived for the Agriculture Soil Management section of the Agriculture chapter of this volume. A national average rate of application was assumed, as was a national average rate of soil organic carbon change for croplands and grazing lands. This is a more complete and accurate assessment of manure and sewage sludge impacts on soil organic carbon storage than the previous inventory. Lastly, carbon stock changes for 1993 through 1997 in the previous inventory were based on land use and management differences between 1982 and 1997. To better reflect trends in carbon stock changes over the 1993 through 1997 time period, the current inventory is based on the activity data coinciding with those years (i.e., 1992 and 1997). However, the 1992 to 1997 carbon stock calculations for some areas were based on the 1982 land uses if a change had occurred between 1982 and 1992, but remained unchanged between 1992 and 1997. This modification allowed for continued accrual or loss of carbon that continues for 20 years following a land use and management change according to the IPCC carbon accounting approach (IPCC/UNEP/OECD/IEA 1997).
- *Landfilled Yard Trimmings*. The Carbon Storage Factors (CSFs), which are used to estimate the amount of yard trimmings carbon stored in landfills, were adjusted to correct for a mass balance problem in the experimental results that are the basis of these data (Barlaz 1998). These adjustments, which are based on the CH_4 yields for each yard trimmings component from Eleazer et al. (1997), resulted in a 5 percent decrease in the weighted average CSF for yard trimmings.

The combination of these changes and the historical data changes described below resulted in an average annual decrease in carbon sequestration from land-use change and forestry of 24.7 Tg CO_2 Eq. (2.3 percent) for the period 1990 through 1992 and 51.6 Tg CO_2 Eq. (5.3 percent) for the period 1993 through 2000.

Landfills

The methodological change for estimating CH_4 emissions from landfills was incorporating municipal solid waste generation data from U.S. territories. The combination of this change and the historical data changes described below resulted in an average annual decrease of less than 0.05 Tg CO_2 Eq. (less than 0.05 percent) in CH_4 emissions for the period 1990 through 2000.

Human Sewage (Domestic Wastewater)

Several changes were made to the methodology for estimating N_2O emissions from human sewage. Previously, the estimate included only N_2O emissions from wastewater treatment plant effluent. This year, the methodology was expanded to include direct emissions from wastewater treatment plants. In addition, the emissions now also reflect nitrogen from the use of garbage disposals, and from bath and laundry water, which represents an increase of approximately 75 percent. Another change was to subtract out the nitrogen in sewage sludge that leaves the treatment plant to be disposed on agricultural land, landfilled, or incinerated. In earlier estimates, this reduction was only accounted for partially. These changes resulted in an average annual increase of 6.3 Tg CO_2 Eq. (80.9 percent) in N_2O emissions for the period 1990 through 2000.

Changes in Historical Data

- In the CO_2 Emissions from Fossil Fuel Combustion section of the Energy chapter, energy consumption data have been updated by the Energy Information Administration (EIA 2002b) for all years. The major changes include: (1) reorganization of the electric power generation sector; (2) revisions to electric power fuel use statistics based on EIA's use of non-utility power plant data in place of fuel supplier data; and (3) revisions to historical data per extensive review and resolution of anomalies by EIA. These revisions specifically impacted natural gas and renewable energy estimates. The combination of these changes, the methodological change described above, and the methodological changes in "Emissions and Storage from Non-Energy Uses of Fossil Fuels" (which affect the emissions from this source) resulted in an average annual increase of 52.0 Tg CO_2 Eq. (1.0 percent) in CO_2 emissions for 1990 through 2000.
- In the Stationary Combustion (excluding CO_2) section of the Energy chapter, changes to emission estimates were entirely due to revised data from EIA (2002b). These revisions are explained in more detail in the section above on CO_2 Emissions from Fossil Fuel Combustion and Carbon Stored in Products from Non-Energy Uses of Fossil Fuels. One specific revision affecting stationary combustion is the inclusion of wood energy consumption by electric utilities and non-utilities in the electric power sector. EIA previously allocated this consumption under the industrial sector. The combination of these changes and the methodological change described above resulted in an average annual increase of 0.2 Tg CO_2 Eq. (2.8 percent) in CH_4 emissions and an average annual decrease of 0.4 Tg CO_2 Eq. (3.0 percent) in N_2O emissions for the period 1990 through 2000.
- In the Mobile Combustion (excluding CO_2) section of the energy chapter, the following historical data changes were made:
    - Vehicle Miles Traveled (VMT) Adjustment for Gasoline and Diesel Highway Vehicles: VMT for alternative fuel vehicles were calculated separately using EIA Data Tables (EIA 2002a). Since the VMT estimates from Federal Highway Administration include total VMT in the United States, it was necessary to subtract VMT from alternative fuel vehicles from this total.
    - Locomotive fuel consumption: The data source for locomotive fuel consumption was changed to AAR (2001), which reports annual diesel consumption for Class I railroad locomotives, and Benson (2002), which provided diesel consumption for Class II and Class III railroad locomotives.

The combination of these changes and the methodological revisions described above resulted in an average annual increase of 0.1 Tg CO_2 Eq. (1.8 percent) in CH_4 emissions and 0.1 Tg CO_2 Eq. (0.2 percent) in N_2O emissions for the period 1990 through 2000.

- In the Coal Mining section of the Energy Chapter, an error was corrected in the spreadsheet for recovery estimates for 1991 and 1992. For the year 2000, the recovery information was updated based on improved information from one underground mine. The combination of these changes and the methodological revision described above resulted in an average annual increase of 0.1 Tg CO_2 Eq. (0.1 percent) in CH_4 emissions for the period 1990 through 2000.
- In the Natural Gas Systems section of the Energy chapter, the following changes were made:
    - Methane emission estimates have been revised to incorporate new activity driver data for natural gas consumption in the transportation sector (EIA 2002e), the number of associated wells (API 2002), and the number of non-associated wells (EIA 2002d).
    - Updated emission reduction data has become available for the 1990 through 2001 time series from the EPA Natural Gas STAR Program. Historical data has been revised to incorporate the updated data.

  The combination of these changes and the methodological revisions described above resulted in an average annual increase of 1.3 Tg CO_2 Eq. (1.1 percent) in CH_4 emissions for the period 1990 through 2000.
- In the Municipal Solid Waste Combustion section of the Energy chapter, scrap tire weight data were updated to reflect information from the RMA/STMC website *Scrap Tires, Facts and Figures* (2002). New data on plastics, synthetic fibers, and synthetic rubber in 2000 from *Municipal Solid Waste in the U.S.: 2000 Facts and Figures* were also incorporated into the municipal solid waste analysis. The combination of these changes and the methodological revision described above resulted in an average annual increase of 0.6 Tg CO_2 Eq. (2.6 percent) in CO_2 emissions for the period 1990 through 2000.
- In the International Bunker Fuels section of the Energy chapter, there was a change in historical military fuel consumption reported by the DoD (DESC 2002). Based on available Service data and expert judgment, a small fraction of the total jet fuel was reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years. This change resulted in reduced military aviation fuel consumption reported between 1997 and 2000. DoD is increasing the use of JP8 (a type of jet fuel) in land-based vehicles and equipment as the Department implements its policy of using a single fuel (JP8) for all tactical equipment. Total aviation emissions increased in the year 2000 due to revised historical data on total jet fuel expenditures by foreign air carriers in U.S. ports (BEA 2002). Military marine fuel consumption data provided by the DoD was revised downward for 2000, though this had little effect on total emissions. These changes resulted in an emissions decrease of 0.97 Tg CO2 Eq. (-1 percent) in a combination of CO_2, CH_4, and N_2O emissions for 2000.
- In the Iron and Steel Production section of the Industrial Processes chapter, 1997 and 2000 coal consumption data for U.S. coke plants were revised using updated estimates from EIA (EIA 2002c). These changes resulted in a decrease of 4.3 Tg CO_2 Eq. (5.6 percent) in CO_2 emissions for 1997 and an increase of less than 0.05 Tg CO_2 Eq. (0.1 percent) in CO_2 emissions for 2000.
- In the Cement Manufacture section of the Industrial Processes chapter, the clinker production data were updated to reflect the information in the *Mineral Industry Surveys, Cement, December 2001* (USGS 2002a). The revisions resulted in an increase of 0.1 Tg CO_2 Eq. (0.3 percent) in CO_2 emissions for 2000.
- In the Ammonia Manufacture and Urea Application section of the Industrial Processes chapter, ammonia production for 2000 was adjusted to reflect revised production information from the U.S. Census Bureau (U.S. Census Bureau 2002). The combination of this change and the methodological changes discussed above resulted in an average annual increase of 1.2 Tg CO_2 Eq. (6.5 percent) in CO_2 emissions for the period 1990 through 2000.

- In the Lime Manufacture section of the Industrial Processes chapter, the activity data was altered to incorporate revised production numbers (USGS 2002b) for dolomitic quicklime and high-calcium hydrated lime. The revision decreased the total lime production for 2000, leading to a decrease of less than 0.05 Tg CO_2 Eq. (less than 0.05 percent) in CO_2 emissions for that year.
- In the Limestone and Dolomite Use section of the Industrial Processes chapter, the limestone and dolomite consumption data used to calculate CO_2 emissions have been revised for the entire 1990 to 2000 time period. The revision included a change in the source of consumption data for flue gas desulphurization from an EIA document to the *Mineral Yearbook: Crushed Stone Annual Report* (Tepordei 2002). The comprehensive activity data revision was responsible for improving the accuracy of end-use consumption estimates for 1990 and 1992, years in which the USGS did not conduct a detailed survey of limestone and dolomite consumption. Additionally, the revision allowed for the more accurate estimation of the consumption data points withheld by the USGS to avoid disclosing proprietary company information. These changes resulted in an average annual increase in CO_2 emissions of 0.3 Tg CO_2 Eq. (5.4 percent) for the period 1990 through 1996 and an average annual decrease in CO_2 emissions of 1.8 Tg CO_2 Eq. (19.9 percent) for the period 1997 through 2000.
- In the Titanium Dioxide Consumption section of the Industrial Processes chapter, the activity data used to calculate CO_2 emissions have been revised to reflect an updated 2000 figure (USGS 2001). This change resulted in a decrease of less than 0.05 Tg CO_2 Eq. (2.3 percent) in CO_2 emissions for 2000.
- In the Carbon Dioxide Consumption section of the Industrial Processes chapter, the activity data used to calculate CO_2 emissions was revised to incorporate the most recent publication by the Freedonia Group, Inc. (2002). The Freedonia Group, Inc. report included data for 1992, 1996, and 2001. Remaining years were extrapolated rather compiling data from previous Freedonia Group, Inc. reports, to ensure data timeseries consistency. This change resulted in an average annual increase of 0.2 Tg CO_2 Eq. (14 percent) in CO_2 emissions from this source from 1990 through 2000.
- In the Petrochemical Production section of the Industrial Processes chapter, the activity data used to calculate CH_4 emissions were revised to reflect modified data from the American Chemistry Council (ACC 2002). The production data was altered for ethylene for the years 1995, 1996, 1999, and 2000. Methanol data was revised for 1995 only and styrene data was revised for 1996 only. These changes resulted in an average annual increase of less than 0.05 Tg CO_2 Eq. (0.2 percent) in CH_4 emissions for the period 1995 through 2000.
- In the Silicon Carbide section of the Industrial Processes chapter, the activity data used to calculate CH_4 emissions have been revised to correct an error in the 1999 calculation. This change resulted in a decrease of less than 0.05 Tg CO_2 Eq. (6.9 percent) in CH_4 emissions for 1999.
- In the Nitric Acid Production section of the Industrial Processes chapter, 2000 production data used last year were revised using updated estimates from Chemical and Engineering News (C&EN 2002). The change resulted in an average annual decrease of 0.1 Tg CO_2 Eq. (0.3 percent) in N_2O emissions for the period 1990 through 2000.
- In the Adipic Acid Production section of the Industrial Processes chapter, the 2000 capacity data for the smallest plant in the 1990-2000 report were based on projections of an expansion in capacity. However, no data exists to confirm the expansion. Consequently, this year's inventory keeps the 2000 capacity data for this plant equal to its 1998 capacity data. In addition, facility-specific emissions data were used directly for another plant. The change resulted in an annual average decrease of 0.7 Tg CO_2 Eq. (8.2 percent) in N_2O emissions for the period 1990 through 2000.
- In the Substitution of Ozone Depleting Substances section of the Industrial Processes chapter, a review of the current chemical substitution trends, together with input from industry representatives, resulted in updated assumptions for the Vintaging Model in the fire-extinguishing sector. These changes resulted in an average annual decrease of 0.3 Tg CO_2 Eq. (0.7 percent) in HFC and PFC emissions for the period 1994 through 2000.

- In the Aluminum Production section of the Industrial Processes chapter, the estimates of PFC emissions for 2000 have been revised due to the receipt of additional smelter-specific information on aluminum production and anode effect frequency and duration. These data were provided by the EPA in cooperation with participants in the Voluntary Aluminum Industrial Partnership program. The changes resulted in a decrease of less than 0.05 Tg CO_2 Eq. (0.3 percent) in PFC emissions for 2000.
- In the Magnesium Production and Processing section of the Industrial Processes chapter, the emissions estimates for this report were revised to reflect new activity data for magnesium produced and processed (particularly the quantities die cast). The revision of the estimates of the quantities of magnesium die cast was the most important of these changes, setting the pattern for the changes in the emission estimates. Both estimated die-casting and estimated emissions increased for the year 1996 and decreased for the years 1997 through 2000. The combination of these changes and the methodological revision described above resulted in an average annual decrease of 0.1 Tg CO_2 Eq. (1.9 percent) in SF_6 emissions for the period 1990 through 2000.
- In the Enteric Fermentation section of the Agriculture chapter, the majority of the change in cattle emissions is due to the diet assumption discussed above, but the animal population data were also updated to include revisions completed by the organizations that produce these estimates. Specifically, the Food and Agriculture Organization updated horse populations from 1990 through 2000 (FAO 2002a). Additionally, some cattle population data were revised to reflect updated USDA estimates. The combination of these changes and the methodological revisions described above resulted in an average annual decrease of 9.3 Tg CO_2 Eq. (7.3 percent) in CH_4 emissions for the period 1990 through 2000.
- In the Manure Management section of the Agriculture chapter, historical data for swine, turkey, sheep, and horse populations were updated. The changes are detailed below:
    - The 2001 inventory includes corrections made to the population data for swine. The 2000 inventory contained errors in the swine population for the following states and years: South Dakota, 1990; Wisconsin, 1992; and Georgia and Kentucky; 1999. These data were corrected. An additional error was identified in the N_2O emissions calculations, in which the total managed swine population reflected an incorrect sum of weight class populations. These formulas were corrected. An error was also identified in the previous inventory in which the swine population data listed for Pennsylvania in 1991 and 1992 were incorrect. This was due to an inaccuracy in the online USDA database from which these data were collected. USDA verified the correct data are published in the USDA publication *Hogs and Pigs - Final Estimates 1988-92* (USDA 1994). The results of all of these corrections are a slight change for the swine CH_4 emission estimates (up to a 4 percent increase) and a 19 percent increase in the N_2O emission estimates for all years of the swine inventory estimates.
    - The 2000 inventory contained incorrect population data for turkeys in 2000. These errors were due to incorrect spreadsheet linking and were corrected. The result is a slight change in poultry CH_4 and N_2O emissions for that year of the inventory.
    - The 2000 inventory contained incorrectly calculated sheep populations for sheep on-feed and not-on-feed for all years of the inventory for the "Other" state populations classification. This calculation was corrected, resulting in an estimated increase of 3 percent to 11 percent N_2O emissions. This calculation did not affect CH_4 emissions estimates.
    - The Food and Agriculture Organization of the United Nations has an online database that is used for horse population estimates. These data, from 1990 through 2000, have been updated from the data used in the previous Inventory. Therefore, all N_2O and CH_4 emission estimates for horses have changed slightly (up to 2 percent) relative to the previous inventory. The effect of the population changes on the predicted CH_4 emissions is less than the effect on the predicted N_2O emissions due to the nonlinear effect of the change on the CH_4 calculations.

The combination of these changes and the methodological change described above resulted in an average annual increase of 1.3 Tg CO_2 Eq. (4.0 percent) in CH_4 emissions and 0.2 Tg CO_2 Eq. (1.2 percent) in N_2O emissions for the period 1990 through 2000.

- In the Rice Cultivation section of the Agriculture chapter, one change has been made to the historical data. Acreage harvested in Missouri in the year 2000 has been revised based on the latest statistics from the USDA (2002d). This change resulted in a less than one percent change in total harvested rice area for that year. As a result, there was a decrease of less than 0.05 Tg CO_2 Eq. (0.1 percent) in CH_4 emissions for 2000.
- In the Agricultural Soil Management section of the Agriculture chapter, there were several changes to historical data that are described below:
  - Crop production figures for 2000 were revised using the most recent estimates provided by USDA (2002d).
  - New manure data were incorporated based on the following updated livestock population estimates: Swine population numbers were corrected for several years from 1990 through 1999. Spreadsheet errors affecting the year 2000 turkey and sheep population data were found and corrected. The horse population data for 1990 through 2000 were revised with the updated data from the FAO online database. (USDA 2002a-c,e-g; FAO 2002b).
  - Estimates of sewage sludge nitrogen applied to land were revised for 1990 through 1994. The percent of total sludge produced that gets land applied was modified to exclude surface disposal.
  - Commercial and organic fertilizer consumption data were updated for 2000 using the most recent AAPFCO estimates (2002).

  These revisions resulted in a decrease of 3.0 Tg CO_2 Eq. (1.0 percent) in N_2O emissions for 2000, and an average annual increase of 0.3 Tg CO_2 Eq. (0.1 percent) in N_2O emissions for the period 1990 through 2000.
- In the Field Burning of Agricultural Residues section of the Agriculture chapter, the year 2000 crop production data have been revised for all crops. The new data reflect the most current statistics from the USDA (2002d). This change resulted in a decrease of less than 0.05 Tg CO_2 Eq. (0.3 percent) in CH_4 emissions and a decrease of less than 0.05 Tg CO_2 Eq. (0.4 percent) in N_2O emission for 2000.
- In the Land-Use Change and Forestry chapter, the following changes were made:
  - In the Agricultural Soils section, probability density functions were constructed for management factors based on a statistical analysis of estimated changes in carbon stocks from published studies addressing land use and management impacts (Ogle et al. in review). The probability density functions were used in place of the management factors provided in the documentation for the default IPCC carbon accounting approach (IPCC/UNEP/OECD/IEA 1997). Similarly, probability density functions were constructed for reference carbon stocks based on a statistical analysis of field measurements recorded in the National Soil Survey Characterization Database (NRCS 1997). The probability density functions were used in place of the reference carbon stocks that are provided in the documentation for the default IPCC carbon accounting approach (IPCC/UNEP/OECD/IEA 1997).
  - In the Agricultural Soils section, the 1998 to 2001 estimates for the CRP enrollment were updated with data provided by the Farm Services Agency (Barbarika 2002).
  - In the Landfilled Yard Trimmings section, the landfilled yard trimmings data for 1998 through 2000 were updated to reflect revised estimates in EPA (2002c).

The combination of these changes and the methodological revisions described above resulted in an average annual decrease in carbon sequestration from land-use change and forestry of 24.7 Tg CO2 Eq. (2.3 percent) for the period 1990 through 1992 and 51.6 Tg CO_2 Eq. (5.3 percent) for the period 1993 through 2000.

- In the Landfills section of the Waste chapter, this report reflects an updated database of flare and landfill-gas-to-energy (LFGTE) projects. The CH_4 mitigated from LFGTE projects increased slightly from 1990 through 1999 and decreased slightly in 2000. The difference is primarily attributed to the availability of additional LFGTE projects included in this year's LFGTE database, as well as revised estimates of megawatt capacity for electricity projects and landfill gas flow for direct use projects. This year's estimate of CH_4 emissions avoided through flaring reflects new data on flares that became operational prior to 1990. In addition, new data in the LFGTE database led to increased matches between the flare data and the LFGTE data, resulting in the exclusion of additional flares from the estimate of emission reductions through flaring (note: emission reductions associated with landfills that have both a flare and a LFGTE project are counted in the LFGTE totals). The combination of these changes and the methodological change described above resulted in an average annual decrease of less than 0.05 Tg CO_2 Eq. (less than 0.05 percent) in CH_4 emissions for the period 1990 through 2000.
- In the Wastewater Treatment section of the Waste chapter, the U.S. population estimates were updated for the 1991 through 2000 period with data from the 2000 Census. The revision resulted in an average annual decrease of 0.2 Tg CO_2 Eq. (0.8 percent) in CH_4 emissions for the period 1990 through 2000.

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 2001. A summary of these estimates is provided in Table 1-8 and Table 1-9 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] This report also discusses the methods and data used to calculate these emission estimates.

In June of 1992, the United States signed, and later ratified in October, 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. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food prdocution is not threatened and to enable economic development to proceed in a sustainable manner." [2, 3]

Parties to the Convention, by ratifying, committed "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…"[4] The United States views this report as an opportunity to fulfill this commitment under the UNFCCC.

In 1988, preceding the creation of the UNFCCC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). 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 collaborated 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 IPCC accepted the *Revised 1996 IPCC Guidelines* at its Twelfth Session (Mexico City, 11-13 September 1996). This report presents information in accordance with these guidelines. In addition, this inventory is in accordance with the recently published IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, which further expanded upon the methodologies in the *Revised 1996 IPCC Guidelines.*

Overall, this inventory of anthropogenic greenhouse gas emissions (1) provides a basis for the ongoing development of methodologies for estimating sources and sinks of greenhouse gases; (2) provides 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) is a prerequisite for accounting for reductions and evaluating possible mitigation strategies.

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

[2] 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).

[3] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <http://unfccc.int>. (UNEP/WMO 2000)

[4] 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://unfccc.int>. (UNEP/WMO 2000)

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 (CO_2), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving 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.[5] 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, 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 contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. The UNFCCC defers to this earlier international treaty. Consequently, Parties are not required to include these gases in national greenhouse gas inventories.[6] Some other fluorine containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several gases that, although they do not have a commonly agreed upon direct radiative forcing effect, do influence the global radiation budget. These tropospheric gases include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in the presence of ultraviolet light (sunlight). Aerosols are extremely small particles or liquid droplets that are often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants. They can affect the absorptive characteristics of the atmosphere. Comparatively, however, the level of scientific understanding of aerosols is still very low. (IPCC 2001)

Carbon dioxide, CH_4, and N_2O 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. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

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[5] For more on the science of climate change, see NRC (2001).

[6] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

Table 1-1: Global atmospheric concentration (ppm unless otherwise specified), rate of concentration change (ppb/year) and atmospheric lifetime (years) of selected greenhouse gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6[a]	CF_4[a]
Pre-industrial atmospheric concentration	280	0.722	0.270	0	40
Atmospheric concentration[b]	370.3	1.842	0.316	4.7	80
Rate of concentration change[c]	1.5[d]	0.007[d]	0.0008	0.24	1.0
Atmospheric Lifetime	50-200[c]	12[f]	114[f]	3,200	>50,000

Source: Current atmospheric concentrations for CO_2, CH_4, N_2O, and SF_6 are from Blasing and Jones (2002). All other data is from IPCC (2001).

[a] Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.

[b] Concentration for CO_2 was measured in 2001. Concentrations for all other gases were measured in 2000.

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

[d] Rate has fluctuated between 0.9 and 2.8 ppm per year for CO_2 and between 0 and 0.013 ppm per year for CH_4 over the period 1990 to 1999.

[e] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.

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

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 affect directly the average global concentration of water vapor, but, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. While a warmer atmosphere has an increased water holding capacity, 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 between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 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 increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 370.3 ppmv in 2001, a 32 percent increase (IPCC 2001 and Blasing and Jones 2002).[7, 8] The IPCC definitively states that "the present atmospheric CO_2 increase is caused by anthropogenic emissions of CO_2" (IPCC 2001). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2.

In its second 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. Atmospheric concentrations of CH_4 have increased by about 150 percent since pre-industrial times, although the rate of increase has been declining. The IPCC has estimated that slightly more

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[7] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2001).

[8] 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 2001).

than half of the current CH_4 flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel use and waste disposal (IPCC 2001).

Methane is removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, a feedback that may increase the atmospheric lifetime of CH_4 (IPCC 2001).

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; 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 N_2O has increased by 16 percent since 1750, from a pre industrial value of about 270 ppb to 316 ppb in 2000, a concentration that has not been exceeded during the last thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere.

Ozone (O_3). Ozone is present in both the upper stratosphere,[9] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[10] 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 stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 1996). The depletion of stratospheric ozone and its radiative forcing was expected to reach a maximum in about 2000 before starting to recover, with detection of such recovery not expected to occur much before 2010 (IPCC 2001).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO_2 and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds mixing with nitrogen oxides (NO_x) in the presence of sunlight. Ozone, carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and particulate matter are included in the category referred to as "criteria pollutants" in the United States under the Clean Air Act[11] and its subsequent amendments. The tropospheric concentrations of ozone and these other pollutants 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 hydrobro-mofluorocarbons (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[12] countries beginning in 1996, and then followed by a complete phase-out by the year 2030. While ozone depleting gases

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[9] 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.

[10] 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.

[11] [42 U.S.C § 7408, CAA § 108]

[12] 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.

covered under the *Montreal Protocol* and its Amendments are not covered by the UNFCCC, they are reported in this inventory under Annex T for informational purposes.

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 are primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process. Currently, they have a small aggregate radiative forcing impact, but it is anticipated that their contribution to overall radiative forcing will increase (IPCC 2001). 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, but they have a significant growth rate, extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2001).

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, OH) 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.[13] Additionally, NO_x emissions from aircraft are also likely to decrease CH_4 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 the photo-degradation of 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 substances 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 and biomass burning. They affect radiative forcing in both direct and indirect ways: directly by scattering and absorbing solar and thermal infrared radiation; and indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

The indirect radiative forcing from aerosols are typically divided into two effects. The first effect involves decreased droplet size and increased droplet concentration resulting from an increase in airborne aerosols. The second effect involves an increase in the water content and lifetime of clouds due to the effect of reduced droplet size on precipitation efficiency (IPCC 2001). Recent research has placed a greater focus on the second indirect radiative forcing effect of aerosols.

Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic aerosols, sulfates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous[14] aerosols (e.g., black carbon, organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning.

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[13] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

[14] Carbonaceous aerosols are aerosols that are comprised mainly of organic substances and forms of black carbon (or soot) (IPCC 2001).

Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) Used in This Report

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-32	5.6	650
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 GWP of CH_4 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.

The net effect of aerosols on radiative forcing is believed to be negative (i.e., net cooling effect on the climate), although because they remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[15] 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).

The IPCC's Third Assessment Report notes that "the indirect radiative effect of aerosols is now understood to also encompass effects on ice and mixed-phase clouds, but the magnitude of any such indirect effect is not known, although it is likely to be positive" (IPCC 2001). Additionally, current research suggests that another constituent of aerosols, elemental carbon, may have a positive radiative forcing (Jacobson 2001). The primary anthropogenic emission sources of elemental carbon include diesel exhaust, coal combustion, and biomass burning.

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 1-2). It is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). Direct radiative effects occur when the gas itself influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP weighted emissions are measured in teragrams of CO_2 equivalents (Tg CO_2 Eq.)[16] The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

$$\text{Tg CO}_2\text{ Eq} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000\,\text{Gg}}\right)$$

where,

Tg CO_2 Eq. = Teragrams of Carbon Dioxide Equivalents
Gg = Gigagrams (equivalent to a thousand metric tons)
GWP = Global Warming Potential
Tg = Teragrams

GWP values allow for a comparison of the impacts of emissions and reductions of different gases. 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.

> *"...consistent with decision 2/CP.3, Annex I Parties should report aggregate emissions and removals of greenhouse gases, expressed in CO_2 equivalent terms at summary inventory level, using GWP values provided by the IPCC in its Second Assessment Report, … based on the effects of greenhouse gases over a 100-year time horizon."*[17]

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[15] 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).

[16] Carbon comprises 12/44ths of carbon dioxide by weight.

[17] Framework Convention on Climate Change; <http://unfccc.int/cop8/latest/5_sbstal5add1.pdf>; 1 November 2002; Report of the Conference of the Parties at its eighth session; held at New Delhi from 23 October to 1 November 2002; Addendum; Part One: Action taken by the Conference of the Parties at its eighth session; Decision -/CP.8; Communications from Parties included in Annex I to the Convention: Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention, Part 1: UNFCCC reporting guidelines on annual inventories; p. 6. Advance unedited version. FCCC (2002)

Box 1-1: The IPCC Third Assessment Report and Global Warming Potentials

The IPCC recently published its Third Assessment Report (TAR), providing the most current and comprehensive scientific assessment of climate change. Within this report, the GWPs of several gases were revised relative to the IPCC's Second Assessment Report (SAR), and new GWPs have been calculated for an expanded set of gases. Since the SAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function (presented in WMO 1999). The GWPs are drawn from WMO (1999) and the SAR, with updates for those cases where significantly different new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of CO_2 is about 12 percent lower than that in the SAR, the GWPs of the other gases relative to CO_2 tend to be larger, taking into account revisions in lifetimes. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons, which were not presented in the SAR. Table 1-3 presents the new GWPs, relative to those presented in the SAR.

Table 1-3: Comparison of 100 Year GWPs

Gas	SAR	TAR	Change	
Carbon dioxide (CO_2)	1	1	NC	NC
Methane (CH_4)*	21	23	2	10%
Nitrous oxide (N_2O)	310	296	(14)	(5%)
HFC-23	11,700	12,000	300	3%
HFC-32	650	550	(100)	(15%)
HFC-125	2,800	3,400	600	21%
HFC-134a	1,300	1,300	NC	NC
HFC-143a	3,800	4,300	500	13%
HFC-152a	140	120	(20)	(14%)
HFC-227ea	2,900	3,500	600	21%
HFC-236fa	6,300	9,400	3,100	49%
HFC-4310mee	1,300	1,500	200	15%
CF_4	6,500	5,700	(800)	(12%)
C_2F_6	9,200	11,900	2,700	29%
C_4F_{10}	7,000	8,600	1,600	23%
C_6F_{14}	7,400	9,000	1,600	22%
SF_6	23,900	22,200	(1,700)	(7%)

Source: (IPCC 2001)
NC (No Change)
* The GWP of CH_4 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.

Although the GWPs have been updated by the IPCC, this report uses GWPs from the Second Assessment Report. The UNFCCC reporting guidelines for national inventories[18] were updated in 2002 but continue to require the use of GWPs from the SAR so that current estimates of aggregate greenhouse gas emissions for 1990 through 2001 are consistent and comparable with estimates developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. For informational purposes, emission estimates that use the updated GWPs are presented below and in even more detail in Annex S. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, as shown in Table 1-4. All estimates provided throughout this report are also presented in unweighted units.

Table 1-4: Effects on U.S. Greenhouse Gas Emission Trends Using IPCC SAR and TAR GWP Values (Tg CO_2 Eq.)

	Change from 1990 to 2001		Revisions to Annual Estimates	
Gas	**SAR**	**TAR**	**1990**	**2001**
CO_2	791.1	791.1	0	0
CH_4	(38.12)	(41.75)	61.3	57.7
N_2O	27.0	25.8	(18.0)	(19.2)
HFCs, PFCs, and SF_6	16.6	10.0	(2.6)	(9.2)
Total	**796.6**	**785.1**	**40.8**	**29.3**
Percent Change	**13.0%**	**12.7%**	**0.7%**	**0.4%**

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[18] See <http://unfccc.int/cop8/latest/5_sbstal5add1.pdf>.

Table 1-5 below shows a comparison of total emissions estimates by sector using both the IPCC SAR and TAR GWP values. For most sectors, the change in emissions was minimal. The effect on emissions from waste was by far the greatest (8.7 percent), due the predominance of CH_4 emissions in this sector. Emissions from all other sectors were comprised of mainly CO_2 or a mix of gases, which moderated the effect of the changes.

Table 1-5: Comparison of Emissions by Sector using IPCC SAR and TAR GWP Values (Tg CO_2 Eq.)

Sector	1990	1995	1996	1997	1998	1999	2000	2001
Energy								
SAR GWP (Used In Inventory)	5,147.5	5,481.6	5,661.4	5,733.0	5,749.4	5,809.5	6,010.4	5,927.1
TAR GWP	5,168.4	5,500.9	5,680.3	5,751.5	5,767.6	5,826.9	6,027.7	5,944.1
Difference (%)	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Industrial Processes								
SAR GWP (Used In Inventory)	302.2	308.3	318.8	321.4	325.9	313.7	312.6	287.6
TAR GWP	298.1	302.3	310.0	312.8	317.5	304.5	302.9	277.3
Difference (%)	(1.4%)	(1.9%)	(2.8%)	(2.7%)	(2.6%)	(2.9%)	(3.1%)	(3.6%)
Agriculture								
SAR GWP (Used In Inventory)	441.0	468.4	473.7	479.0	481.3	479.3	475.1	474.9
TAR GWP	443.1	470.8	475.2	480.3	482.7	480.8	476.4	476.2
Difference (%)	0.5%	0.5%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Land-Use Change and Forestry								
SAR GWP (Used In Inventory)	(1,072.8)	(1,064.2)	(1,061.0)	(840.6)	(830.5)	(841.1)	(834.6)	(838.1)
TAR GWP	(1,072.8)	(1,064.2)	(1,061.0)	(840.6)	(830.5)	(841.1)	(834.6)	(838.1)
Difference (%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Waste								
SAR GWP (Used In Inventory)	248.9	256.6	253.1	249.2	244.7	247.0	249.2	246.6
TAR GWP	270.8	279.1	275.2	270.9	266.0	268.4	270.8	267.9
Difference (%)	8.8%	8.8%	8.7%	8.7%	8.7%	8.7%	8.7%	8.7%
Net Emissions (Sources and Sinks)								
SAR GWP (Used In Inventory)	**5,066.8**	**5,450.7**	**5,646.0**	**5,942.0**	**5,970.9**	**6,008.5**	**6,212.7**	**6,098.1**
TAR GWP	**5,107.6**	**5,488.9**	**5,679.6**	**5,974.9**	**6,003.3**	**6,039.6**	**6,243.2**	**6,127.4**
Difference (%)	**0.8%**	**0.7%**	**0.6%**	**0.6%**	**0.5%**	**0.5%**	**0.5%**	**0.5%**

NC (No change)
Note: Totals may not sum due to independent rounding.

Greenhouse gases with relatively 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, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), 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.

Recent Trends in U.S. Greenhouse Gas Emissions

In 2001, total U.S. greenhouse gas emissions were 6,936.2 teragrams of CO_2 equivalents (Tg CO_2 Eq.)[19] (13.0 percent above 1990 emissions). Emissions declined for the second time since 1990, decreasing by 1.6 percent (111.2 Tg CO_2 Eq.) from 2000 to 2001, primarily because of a decrease in CO_2 emissions from fossil fuel combustion. The reduction in fossil fuel combustion emissions is linked to the following factors: 1) slowing of economic growth in 2001, 2) a considerable

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[19] Estimates are presented in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.), which weight each gas by its Global Warming Potential, or GWP, value. (See section on Global Warming Potentials, Chapter 1.)

Figure 1-1

U.S. GHG Emissions by Gas

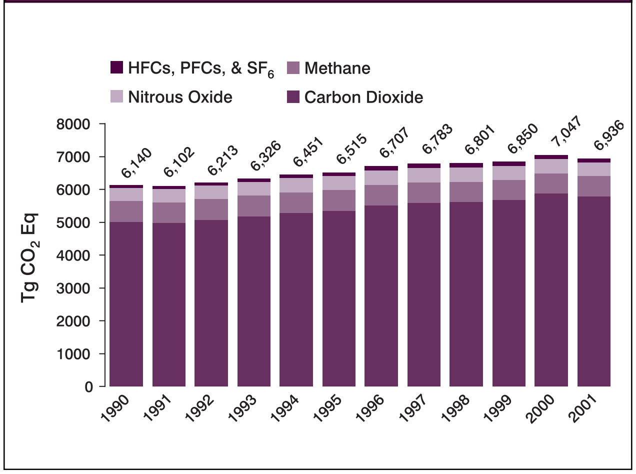


Figure 1-2

Annual Percent Change in U.S. GHG Emissions

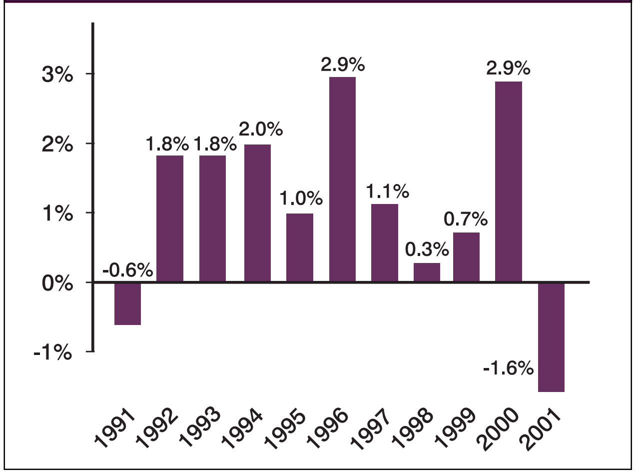
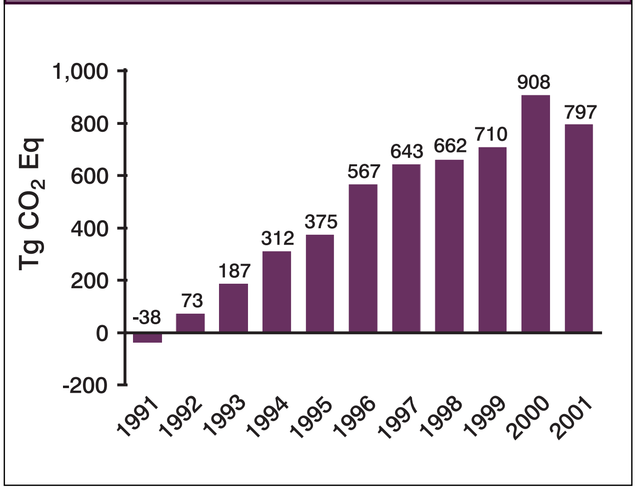


Figure 1-3

Absolute Change in U.S. GHG Emissions Since 1990



reduction in industrial output, leading to decreased demand for electricity and fuel, 3) warmer winter conditions compared to 2000, and 4) an increased share of output from nuclear facilities. (See the following section for an analysis of emission trends by general economic sectors). 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 a nearly constant 80 percent of global warming potential (GWP) weighted emissions in the 1990s. Emissions from this source category grew by 17 percent (800.1 Tg CO_2 Eq.) from 1990 to 2001 and were responsible for most of the increase in national emissions during this period. The recent annual change in CO_2 emissions from fossil fuel combustion was a reduction of 77.3 Tg CO_2 Eq. (1.4 percent), which is the second decrease in emissions since the Inventory base year 1990, the first being in 1991. The source's average annual growth rate was 1.3 percent from 1990 through 2001. Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. On an annual basis, the overall consumption of fossil fuels in the United States generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

In the longer-term, energy consumption patterns respond to changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs) and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Table 1-6: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg CO_2 Eq. and Percent)

Sector	Fuel Type	1996 to 1997		1997 to 1998		1998 to 1999		1999 to 2000		2000 to 2001	
Electricity Generation	Coal	44.1	3%	30.6	2%	8.7	0%	89.4	5%	(50.1)	(3%)
Electricity Generation	Natural Gas	13.9	7%	29.1	13%	12.0	5%	20.6	8%	4.3	2%
Electricity Generation	Petroleum	9.0	14%	29.7	40%	(7.6)	(7%)	(5.7)	(6%)	10.7	12%
Transportation[a]	Petroleum	7.3	0%	33.0	2%	58.7	4%	49.8	3%	19.7	1%
Residential	Natural Gas	(14.0)	(3%)	(23.7)	(9%)	10.0	9%	13.9	3%	(9.6)	(1%)
Commercial	Natural Gas	3.1	2%	(10.8)	(6%)	1.7	1%	9.1	5%	1.6	1%
Industrial	Coal	1.2	1%	(8.7)	(6%)	(6.1)	(4%)	2.3	2%	(7.7)	(6%)
Industrial	Natural Gas	1.1	0%	(11.7)	(2%)	(17.6)	(4%)	12.5	3%	(33.5)	(7%)
All Sectors[b]	**All Fuels[b]**	**74.2**	**1%**	**20.5**	**0%**	**68.3**	**1%**	**202.8**	**4%**	**(77.9)**	**(1%)**

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

Energy-related CO_2 emissions also depend on the type of fuel or energy consumed and its carbon intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 because of the lower carbon content of natural gas. Table 1-6 shows annual changes in emissions during the last six years for coal, petroleum, and natural gas in selected sectors.

Milder weather conditions in summer and winter of 1997 (compared to 1996) moderated the growth of CO_2 emissions from fossil fuel combustion. The shut-down of several nuclear power plants, however, led electric utilities to increase their consumption of coal and other fuels to offset the lost nuclear capacity.

In 1998, warm winter temperatures contributed to a significant drop in residential and commercial 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.

In 1999, the increase in emissions from fossil fuel combustion was driven largely by growth in petroleum consumption for transportation. In addition, residential and commercial heating fuel demand partially recovered as winter temperatures dropped relative to 1998, although temperatures were still warmer than normal.[20] These increases were offset, in part, by a decline in emissions from electric power producers due primarily to: 1) an increase in net generation of electricity by nuclear plants that reduced demand from fossil fuel plants; and 2) moderated summer temperatures compared to the previous year, thereby reducing electricity demand for air conditioning.

Emissions from fuel combustion increased considerably in 2000, due to several factors. The primary reason for the increase was the robust U.S. economy, which produced a high demand for fuels—especially for petroleum in the transportation sector—despite increases in the price of both natural gas and petroleum. Colder winter conditions relative to the previous year triggered a rise in residential and commercial demand for heating. Structural and other economic changes taking place within U.S. industry—especially manufacturing—lead to lower coal consumption. Additionally, electricity generation became more carbon intensive as coal and natural gas consumption offset reduced hydropower output.

In 2001, the U.S. economy slowed for the second time since 1990, resulting in decreased emissions from CO_2 emissions from fossil fuel combustion also for the second time since 1990. A significant reduction in industrial output accompanied this slowdown, primarily in manufacturing, leading to lower emissions from the industrial sector. Several other factors also played a role in this decrease in emissions. Warmer winter conditions compared to 2000, along with higher natural gas prices, reduced demand for heating fuels. Additionally, nuclear facilities operated at their highest capacity on record, replacing electricity produced from fossil fuels. Since there are no greenhouse gas emissions associated with electricity production from nuclear plants, this substitution reduces the carbon intensity of electricity generation.

Other significant trends in emissions from additional source categories over the twelve year period from 1990 through 2001 included the following:

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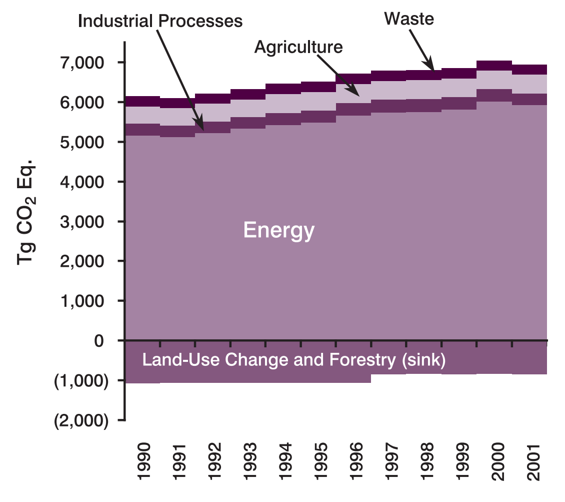
[20] Normals are based on data from 1961 through 1990. Source: NOAA (2002)

- Net CO_2 flux from land use change and forestry decreased by 234.7 Tg CO_2 Eq. (22 percent), primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks.
- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 62.7 Tg CO_2 Eq. This increase was significantly offset, however, by reductions in PFC emissions from aluminum production (14.0 Tg CO_2 Eq. or 77 percent), reductions in emissions of HFC-23 from the production of HCFC-22 (15.2 Tg CO_2 Eq. or 43 percent), and reductions of SF_6 from electric power transmission and distribution systems (16.8 Tg CO_2 Eq. or 52 percent). Reductions in PFC emissions from aluminum production were the result of both industry emission reduction efforts and lower domestic aluminum production. HFC-23 emissions from the production of HCFC-22 decreased because a reduction in the intensity of emissions from that source offset increased HCFC-22 production. Reduced emissions of SF_6 from electric power transmission and distribution systems are primarily the result of higher purchase prices for SF_6 and efforts by industry to reduce emissions.
- Methane emissions from coal mining dropped by 26.4 Tg CO_2 Eq. (30 percent) as a result of the mining of less gassy coal from underground mines and the increased use of CH_4 collected from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 26.8 Tg CO_2 Eq. (10 percent) as fertilizer consumption and cultivation of nitrogen-fixing and other crops rose.
- Carbon dioxide emissions from waste combustion increased 12.8 Tg CO_2 Eq. (91 percent), as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.
- By 1998, all of the three major adipic acid producing plants had voluntarily implemented N_2O abatement technology, and as a result, emissions fell by 10.3 Tg CO_2 Eq. (68 percent). The majority of this decline occurred from 1996 collected and combusted by landfill operators has increased.
- Methane emissions from U.S. landfills decreased by 9.1 Tg CO_2 Eq. (4 percent), as the amount of landfill gas collected and combusted by landfill operators has increased.

Figure 1-4

U.S. GHG Emissions by Chapter/IPCC Sector



Overall, from 1990 to 2001, total emissions of CO_2 and N_2O increased by 791.1 (16 percent) and 27.0 Tg CO_2 Eq. (7 percent), respectively, while CH_4 emissions decreased by 38.1 Tg CO_2 Eq. (6 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 16.6 Tg CO_2 Eq. (18 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because many of them have 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, trees in urban areas, agricultural soils, and landfilled yard trimmings, which was estimated to be 12 percent of total emissions in 2001.

As an alternative, emissions of all gases can be totaled for each of the IPCC sectors. Over the twelve year period of 1990 to 2001, total emissions in the Energy and Agriculture sectors climbed by 779.6 (15 percent) and 33.8 Tg CO_2 Eq. (8 percent), respectively, while emissions from the Industrial Processes and Waste sectors decreased 14.6 Tg CO_2 Eq. (5 percent) and 2.3 Tg CO_2 Eq. (1 percent), respectively. Over the same period, estimates of net carbon sequestration in the Land-Use Change and Forestry sector declined by 234.7 Tg CO_2 Eq. (22 percent).

Table 1-8 summarizes emissions and sinks from all U.S. anthropogenic sources in weighted units of Tg CO_2 Eq., while unweighted gas emissions and sinks in gigagrams (Gg) are provided in Table 1-9. Alternatively, emissions and sinks are aggregated by chapter in Table 1-10 and Figure 1-4.

Table 1-8: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**5,003.7**	**5,334.4**	**5,514.8**	**5,595.4**	**5,614.2**	**5,680.7**	**5,883.1**	**5,794.8**
Fossil Fuel Combustion	4,814.8	5,141.5	5,325.8	5,400.0	5,420.5	5,488.8	5,692.2	5,614.9
Iron and Steel Production	85.4	74.4	68.3	71.9	67.4	64.4	65.8	59.1
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.2	41.4
Waste Combustion	14.1	18.5	19.4	21.2	22.5	23.9	25.4	26.9
Ammonia Manufacture & Urea Application	19.3	20.5	20.3	20.7	21.9	20.6	19.6	16.6
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3	12.9
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	5.5	5.2
Limestone and Dolomite Use	5.5	7.0	7.6	7.1	7.3	7.7	5.8	5.3
Aluminum Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4	4.1
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2	4.1
Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	1.9	1.9
Carbon Dioxide Consumption	0.9	1.1	1.1	1.2	1.2	1.2	1.2	1.3
Ferroalloys	2.0	1.9	2.0	2.0	2.0	2.0	1.7	1.3
Land-Use Change and Forestry (Sink)[a]	(1,072.8)	(1,064.2)	(1,061.0)	(840.6)	(830.5)	(841.1)	(834.6)	(838.1)
International Bunker Fuels[b]	*113.9*	*101.0*	*102.3*	*109.9*	*112.9*	*105.3*	*99.3*	*97.3*
CH_4	**644.0**	**650.0**	**636.8**	**629.5**	**622.7**	**615.5**	**613.4**	**605.9**
Landfills	212.1	216.1	212.1	207.5	202.4	203.7	205.8	202.9
Natural Gas Systems	122.0	127.2	127.4	126.0	124.0	120.3	121.2	117.3
Enteric Fermentation	117.9	123.0	120.5	118.3	116.7	116.6	115.7	114.8
Coal Mining	87.1	73.5	68.4	68.1	67.9	63.7	60.9	60.7
Manure Management	31.3	36.2	34.9	36.6	39.0	38.9	38.2	38.9
Wastewater Treatment	24.1	26.6	26.8	27.3	27.7	28.2	28.3	28.3
Petroleum Systems	27.5	24.2	23.9	23.6	22.9	21.6	21.2	21.2
Rice Cultivation	7.1	7.6	7.0	7.5	7.9	8.3	7.5	7.6
Stationary Sources	8.1	8.5	8.7	7.5	7.2	7.4	7.6	7.4
Mobile Sources	5.0	4.9	4.8	4.7	4.6	4.5	4.4	4.3
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7	1.7	1.5
Field Burning of Agricultural Residues	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8
Silicon Carbide Production	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**397.6**	**430.9**	**441.7**	**440.9**	**436.8**	**433.0**	**429.9**	**424.6**
Agricultural Soil Management	267.5	284.1	293.2	298.2	299.2	297.0	294.6	294.3
Mobile Sources	50.6	60.9	60.7	60.3	59.7	58.8	57.5	54.8
Manure Management	16.2	16.6	17.0	17.3	17.3	17.4	17.9	18.0
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.1	19.1	17.6
Human Sewage	12.7	13.9	14.1	14.4	14.6	15.1	15.1	15.3
Stationary Combustion	12.5	13.2	13.8	13.7	13.7	13.7	14.3	14.2
Adipic Acid	15.2	17.2	17.0	10.3	6.0	5.5	6.0	4.9
N_2O Product Usage	4.3	4.5	4.5	4.8	4.8	4.8	4.8	4.8
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.5
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
International Bunker Fuels[b]	*1.0*	*0.9*	*0.9*	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*
HFCs, PFCs, and SF_6	**94.4**	**99.5**	**113.6**	**116.8**	**127.6**	**120.3**	**121.0**	**111.0**
Substitution of Ozone Depleting Substances	0.9	21.7	30.4	37.7	44.5	50.9	57.3	63.7
HCFC-22 Production	35.0	27.0	31.1	30.0	40.2	30.4	29.8	19.8
Electrical Transmission and Distribution	32.1	27.5	27.7	25.2	20.9	16.4	15.4	15.3
Semiconductor Manufacture	2.9	5.9	5.4	6.5	7.3	7.7	7.4	5.5
Aluminum Production	18.1	11.8	12.5	11.0	9.0	8.9	7.9	4.1
Magnesium Production and Processing	5.4	5.6	6.5	6.3	5.8	6.0	3.2	2.5
Total	**6,139.6**	**6,514.9**	**6,707.0**	**6,782.6**	**6,801.3**	**6,849.5**	**7,047.4**	**6,936.2**
Net Emissions (Sources and Sinks)	**5,066.8**	**5,450.7**	**5,646.0**	**5,942.0**	**5,970.9**	**6,008.5**	**6,212.7**	**6,098.1**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data. Parentheses indicate negative values (or sequestration).

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

Note: Totals may not sum due to independent rounding.

Table 1-9: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**5,003,685**	**5,334,446**	**5,514,811**	**5,595,361**	**5,614,198**	**5,680,677**	**5,883,118**	**5,794,804**
Fossil Fuel Combustion	4,814,758	5,141,548	5,325,798	5,400,034	5,420,519	5,488,804	5,692,170	5,614,853
Iron and Steel Production	85,414	74,357	68,324	71,864	67,429	64,376	65,755	59,074
Cement Manufacture	33,278	36,847	37,079	38,323	39,218	39,991	41,190	41,357
Waste Combustion	14,068	18,472	19,418	21,173	22,454	23,903	25,351	26,907
Ammonia Manufacture & Urea Application	19,306	20,453	20,282	20,650	21,934	20,615	19,587	16,588
Lime Manufacture	11,238	12,804	13,495	13,685	13,914	13,466	13,315	12,859
Natural Gas Flaring	5,514	8,729	8,233	7,565	6,250	6,679	5,525	5,179
Limestone and Dolomite Use	5,470	7,042	7,614	7,055	7,331	7,671	5,763	5,281
Aluminum Production	6,315	5,265	5,580	5,621	5,792	5,895	5,410	4,114
Soda Ash Manufacture and Consumption	4,141	4,304	4,239	4,354	4,325	4,217	4,181	4,147
Titanium Dioxide Production	1,308	1,670	1,657	1,836	1,819	1,853	1,918	1,857
Carbon Dioxide Consumption	895	1,088	1,138	1,162	1,186	1,210	1,233	1,257
Ferroalloys	1,980	1,866	1,954	2,038	2,027	1,996	1,719	1,329
Land-Use Change & Forestry (Sink)[a]	(1,072,807)	(1,064,173)	(1,061,016)	(840,622)	(830,477)	(841,054)	(834,637)	(838,137)
International Bunker Fuels[b]	*113,863*	*101,037*	*102,272*	*109,858*	*112,859*	*105,262*	*99,268*	*97,346*
CH_4	**30,667**	**30,954**	**30,324**	**29,977**	**29,652**	**29,311**	**29,207**	**28,851**
Landfills	10,099	10,290	10,100	9,880	9,639	9,701	9,798	9,663
Natural Gas Systems	5,810	6,059	6,069	6,001	5,903	5,728	5,772	5,588
Enteric Fermentation	5,612	5,855	5,737	5,635	5,557	5,551	5,509	5,468
Coal Mining	4,149	3,502	3,255	3,244	3,235	3,033	2,902	2,893
Manure Management	1,490	1,723	1,661	1,741	1,858	1,852	1,820	1,850
Wastewater Treatment	1,147	1,267	1,278	1,301	1,318	1,341	1,348	1,350
Petroleum Systems	1,309	1,153	1,138	1,123	1,090	1,029	1,010	1,011
Rice Cultivation	339	363	332	356	376	395	357	364
Stationary Sources	388	406	415	358	342	351	363	353
Mobile Sources	236	232	227	223	217	214	211	204
Petrochemical Production	56	72	75	77	78	80	79	71
Field Burning of Agricultural Residues	33	31	36	36	37	36	37	36
Silicon Carbide Production	1	1	1	1	1	1	1	+
International Bunker Fuels[b]	*8*	*6*	*6*	*7*	*7*	*6*	*6*	*5*
N_2O	**1,282**	**1,389**	**1,424**	**1,421**	**1,408**	**1,396**	**1,386**	**1,369**
Agricultural Soil Management	863	916	946	962	965	958	950	949
Mobile Sources	163	197	196	195	192	190	185	177
Manure Management	52	53	55	56	56	56	58	58
Nitric Acid	58	64	67	68	67	65	62	57
Human Sewage	41	45	46	46	47	49	49	49
Stationary Combustion	40	43	45	44	44	44	46	46
Adipic Acid	49	56	55	33	19	18	19	16
N_2O Product Usage	14	14	14	15	15	15	15	15
Field Burning of Agricultural Residues	1	1	1	1	1	1	1	1
Waste Combustion	1	1	1	1	1	1	1	1
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M
HCFC-22 Production[c]	3	2	3	3	3	3	3	2
Electrical Transmission &Distribution[d]	1	1	1	1	1	1	1	1
Semiconductor Manufacture	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M
Magnesium Production & Processing[d]	+	+	+	+	+	+	+	+
NO_x	**22,860**	**22,434**	**22,149**	**22,284**	**21,963**	**21,199**	**20,555**	**20,048**
CO	**130,575**	**109,149**	**104,063**	**101,132**	**98,976**	**95,464**	**93,965**	**100,653**
NMVOCs	**20,937**	**19,520**	**17,184**	**16,994**	**16,403**	**16,245**	**15,418**	**15,148**

+ Does not exceed 0.5 Gg.

M Mixture of multiple gases

[a] Sinks are not included in CO_2 emissions total, and are based partially on projected activity data.

[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.

Note: Parentheses indicate negative values (or sequestration).

Box 1-2: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total emissions can be compared with other economic and social indices to highlight changes over time. These comparisons include: 1) emissions per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; 2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; 3) emissions per unit of electricity consumption, because the electric power industry—utilities and nonutilities combined—was the largest source of U.S. greenhouse gas emissions in 2001; 4) emissions per unit of total gross domestic product as a measure of national economic activity; and 5) emissions per capita.

Table 1-7 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 1.1 percent since 1990. This rate is slower than that for total energy or fossil fuel and much slower than that for either electricity consumption or overall gross domestic product. At the same time, total U.S. greenhouse gas emissions have grown at about the same rate as national population during the last decade (see Figure 1-5). Overall, atmospheric CO_2 concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

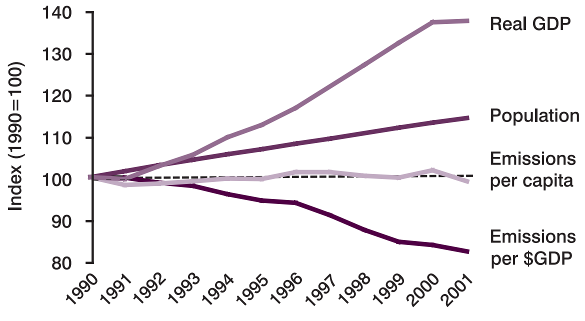
Table 1-7: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Growth Rate[f]
GHG Emissions[a]	99	101	103	105	106	109	110	111	112	115	113	**1.1%**
Energy Consumption[b]	100	102	104	106	108	112	112	113	115	118	115	**1.3%**
Fossil Fuel Consumption[b]	100	102	104	106	107	111	112	113	114	118	115	**1.3%**
Electricity Consumption[b]	102	102	106	109	112	115	117	121	124	128	127	**2.2%**
GDP[c]	100	103	105	110	112	116	122	127	132	137	137	**2.9%**
Population[d]	101	103	104	105	107	108	109	111	112	113	114	**1.2%**
Atmospheric CO_2 Concentration[e]	100	101	101	101	102	102	103	104	104	104	105	**0.4%**

[a] GWP weighted values
[b] Energy content weighted values (EIA 2002a)
[c] Gross Domestic Product in chained 1996 dollars (BEA 2002)
[d] (U.S. Census Bureau 2002)
[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 2002)
[f] Average annual growth rate

Figure 1-5

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



Source: BEA (2002), U.S. Census Bureau (2002), and emission estimates in this report

Table 1-10: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg CO_2 Eq.)

Chapter/IPCC Sector	1990	1995	1996	1997	1998	1999	2000	2001
Energy	5,147.5	5,481.6	5,661.4	5,733.0	5,749.4	5,809.5	6,010.4	5,927.1
Industrial Processes	302.2	308.2	318.8	321.4	325.9	313.7	312.6	287.6
Agriculture	441.0	468.4	473.7	479.0	481.3	479.3	475.1	474.9
Land-Use Change and Forestry (Sink)*	(1072.8)	(1064.2)	(1061.0)	(840.6)	(830.5)	(841.1)	(834.6)	(838.1)
Waste	248.8	256.6	253.1	249.2	244.7	247.0	249.2	246.6
Total	**6,139.6**	**6,514.9**	**6,707.0**	**6,782.6**	**6,801.3**	**6,849.5**	**7,047.4**	**6,936.2**
Net Emissions (Sources and Sinks)	**5,066.8**	**5,450.7**	**5,646.0**	**5,942.0**	**5,970.9**	**6,008.5**	**6,212.7**	**6,098.1**

* Sinks are only included in net emissions total, and are based partially on projected activity data.
Note: Totals may not sum due to independent rounding.
Note: Parentheses indicate negative values (or sequestration).

Emissions by Economic Sector

Throughout this report, emission estimates are grouped into six sectors (i.e., chapters) defined by the IPCC: Energy, Industrial Processes, Solvent Use, Agriculture, Land-Use Change and Forestry, and Waste. While it is important to use this characterization for consistency with UNFCCC reporting guidelines, it is also useful to allocate emissions into more commonly used sectoral categories. This section reports emissions by the following "economic sectors": Residential, Commercial, Industry, Transportation, Electricity Generation, and Agriculture, and U.S. Territories. Using this categorization, emissions from electricity generation accounted for the largest portion (33 percent) of U.S. greenhouse gas emissions. Transportation activities, in aggregate, accounted for the second largest portion (27 percent). Additional discussion and data on these two economic sectors is provided below.

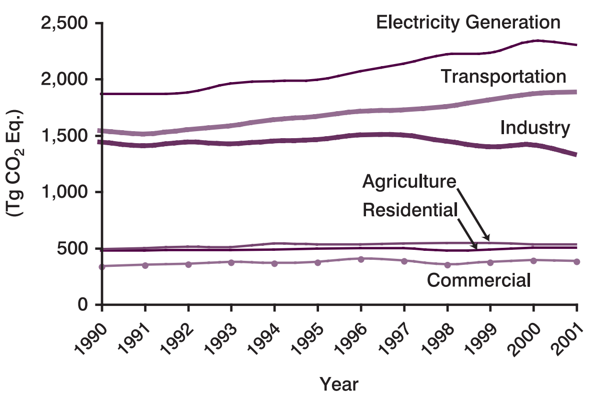
Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2001. In contrast to electricity generation and transportation, emissions from industry have declined over the past decade, as structural changes have occurred in the U.S. economy (i.e., shifts from a manufacturing base to a service-based economy), fuel switching has occurred, and efficiency improvements have been made. The residential, agriculture, commercial economic sectors, and U.S. territories contributed the remaining 21 percent of emissions. Residences accounted for approximately 5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 8 percent of U.S. emissions, but unlike all other economic sectors these emissions were dominated by non-CO_2 emissions. The commercial sector accounted for about 7 percent of emissions, while U.S. territories accounted for 1 percent of total emissions.

Carbon dioxide was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, and landfilling of yard trimmings.

Table 1-11 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 1-6 shows the trend in emissions by sector from 1990 to 2001.

Figure 1-6

Emissions Allocated to Economic Sectors



Note: Does not include U.S. Territories

Table 1-11: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2001)

Sector/Source	1990	1995	1996	1997	1998	1999	2000	2001	Percent[a]
Electricity Generation	**1,862.3**	**1,990.1**	**2,064.1**	**2,130.4**	**2,217.2**	**2,227.5**	**2,331.8**	**2,297.7**	**33.1%**
CO_2 from Fossil Fuel Combustion	1,805.0	1,931.8	2,003.9	2,070.8	2,160.3	2,173.5	2,277.8	2,242.8	32.3%
Waste Combustion[b]	14.4	18.7	19.7	21.4	22.7	24.1	25.6	27.1	0.4%
Transmission & Distribution[c]	32.1	27.5	27.7	25.2	20.9	16.4	15.4	15.3	0.2%
Stationary Combustion[d]	8.1	8.6	9.1	9.3	9.6	9.6	10.0	9.8	0.1%
Limestone and Dolomite Use	2.7	3.5	3.8	3.5	3.7	3.8	2.9	2.6	+
Transportation	**1,525.6**	**1,651.0**	**1,694.1**	**1,706.8**	**1,736.5**	**1,797.7**	**1,849.0**	**1,866.8**	**26.9%**
CO_2 from Fossil Fuel Combustion	1,470.5	1,577.8	1,617.4	1,626.9	1,653.9	1,713.0	1,762.7	1,780.9	25.7%
Mobile Combustion[d]	55.2	65.3	65.0	64.5	63.7	62.7	61.5	58.6	0.8%
Substitution of ODS[e]	+	7.8	11.7	15.4	18.8	21.9	24.8	27.3	0.4%
Industry	**1,423.3**	**1,444.7**	**1,484.9**	**1,485.4**	**1,433.5**	**1,381.4**	**1,400.6**	**1,315.7**	**19.0%**
CO_2 from Fossil Fuel Combustion	909.0	945.7	987.5	992.5	942.5	913.2	940.7	887.2	12.8%
Natural Gas Systems	122.0	127.2	127.4	126.0	124.0	120.3	121.2	117.3	1.7%
Coal Mining	87.1	73.5	68.4	68.1	67.9	63.7	60.9	60.7	0.9%
Iron and Steel Production	85.4	74.4	68.3	71.9	67.4	64.4	65.8	59.1	0.9%
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.2	41.4	0.6%
Petroleum Systems	27.5	24.2	23.9	23.6	22.9	21.6	21.2	21.2	0.3%
HCFC-22 Production[f]	35.0	27.0	31.1	30.0	40.2	30.4	29.8	19.8	0.3%
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.1	19.1	17.6	0.3%
Ammonia Manufacture	19.3	20.5	20.3	20.7	21.9	20.6	19.6	16.6	0.2%
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3	12.9	0.2%
Substitution of ODS[e]	+	3.6	6.3	6.6	7.0	7.5	8.0	11.7	0.2%
Aluminum Production[g]	24.4	17.1	18.0	16.6	14.8	14.8	13.3	8.2	0.1%
Stationary Combustion[d]	5.7	6.1	6.3	6.1	6.0	5.8	6.0	6.2	0.1%
Semiconductor Manufacture[e]	2.9	5.9	5.4	6.5	7.3	7.7	7.4	5.5	0.1%
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	5.5	5.2	0.1%
Adipic Acid	15.2	17.2	17.0	10.3	6.0	5.5	6.0	4.9	0.1%
N_2O Product Usage	4.3	4.5	4.5	4.8	4.8	4.8	4.8	4.8	0.1%
Soda Ash Manufacture & Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2	4.1	0.1%
Limestone and Dolomite Use	2.7	3.5	3.8	3.5	3.7	3.8	2.9	2.6	+
Magnesium Production & Processing[c]	5.4	5.6	6.5	6.3	5.8	6.0	3.2	2.5	+
Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	1.9	1.9	+
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7	1.7	1.5	+
Ferroalloys	2.0	1.9	2.0	2.0	2.0	2.0	1.7	1.3	+
Carbon Dioxide Consumption	0.9	1.1	1.1	1.2	1.2	1.2	1.2	1.3	+
Silicon Carbide Production	+	+	+	+	+	+	+	+	+
Agriculture	**487.8**	**525.8**	**526.1**	**537.9**	**539.4**	**539.8**	**526.0**	**525.7**	**7.6%**
Agricultural Soil Management	267.5	284.1	293.2	298.2	299.2	297.0	294.6	294.3	4.2%
Enteric Fermentation	117.9	123.0	120.5	118.3	116.7	116.6	115.7	114.8	1.7%
Manure Management[d]	47.5	52.7	51.9	53.8	56.4	56.2	56.1	56.9	0.8%
CO_2 from Fossil Fuel Combustion	46.3	56.9	52.0	58.3	57.6	59.9	50.4	50.4	0.7%
Rice Cultivation	7.1	7.6	7.0	7.5	7.9	8.3	7.5	7.6	0.1%
Field Burning of Agricultural Residues[d]	1.1	1.0	1.2	1.2	1.2	1.2	1.2	1.2	+
Mobile Combustion[d]	0.4	0.5	0.4	0.5	0.5	0.5	0.4	0.4	+
Stationary Combustion[d]	+	+	+	+	+	+	+	+	+
Residential	**334.5**	**371.3**	**402.1**	**385.4**	**352.8**	**372.4**	**390.1**	**379.4**	**5.5%**
CO_2 from Fossil Fuel Combustion	328.9	358.5	388.6	371.7	338.8	357.3	373.9	363.3	5.2%
Substitution of ODS[e]	+	6.9	7.6	9.2	9.8	10.7	11.6	11.6	0.2%
Stationary Combustion[d]	5.7	5.8	5.9	4.5	4.2	4.5	4.6	4.4	0.1%

Continued on next page.

Table 1-11: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2001) continued from page 1-16

Sector/Source	1990	1995	1996	1997	1998	1999	2000	2001	Percent[a]
Commercial	**472.4**	**488.0**	**495.5**	**494.0**	**474.2**	**480.6**	**497.6**	**496.5**	**7.2%**
CO_2 from Fossil Fuel Combustion	221.4	226.9	236.4	237.1	219.5	221.7	234.3	235.9	3.4%
Landfills	212.1	216.1	212.1	207.5	202.4	203.7	205.8	202.9	2.9%
Wastewater Treatment	24.1	26.6	26.8	27.3	27.7	28.2	28.3	28.3	0.4%
Human Sewage	12.7	13.9	14.1	14.4	14.6	15.1	15.1	15.3	0.2%
Substitution of ODS[e]	0.9	3.4	4.8	6.5	8.9	10.7	12.8	12.9	0.2%
Stationary Combustion[d]	1.1	1.1	1.2	1.2	1.1	1.1	1.2	1.1	+
U.S. Territories	**33.7**	**44.0**	**40.1**	**42.8**	**47.9**	**50.2**	**52.3**	**54.4**	**0.8%**
CO_2 from Fossil Fuel Combustion	33.7	44.0	40.1	42.8	47.9	50.2	52.3	54.4	0.8%
Total	**6,139.6**	**6,514.9**	**6,707.0**	**6,782.6**	**6,801.3**	**6,849.5**	**7,047.4**	**6,936.2**	**100.0%**
Sinks	**(1,072.8)**	**(1,064.2)**	**(1,061.0)**	**(840.6)**	**(830.5)**	**(841.1)**	**(834.6)**	**(838.1)**	**(12.1%)**
Forests	(982.7)	(979.0)	(979.0)	(759.0)	(751.7)	(762.7)	(755.3)	(759.0)	(10.9%)
Urban Trees	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(0.8%)
Agricultural Soils	(13.3)	(14.9)	(13.6)	(13.9)	(11.5)	(11.9)	(13.8)	(15.2)	(0.2%)
Landfilled Yard Trimmings	(18.2)	(11.6)	(9.7)	(9.0)	(8.7)	(7.8)	(6.9)	(5.3)	(0.1%)
Net Emissions (Sources and Sinks)	**5,066.8**	**5,450.7**	**5,646.0**	**5,942.0**	**5,970.9**	**6,008.5**	**6,212.7**	**6,098.1**	

Note: Includes all emissions of CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. Parentheses indicate negative values (or sequestration).
Totals may not sum due to independent rounding.
ODS (Ozone Depleting Substances)
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.05%.
- Not applicable.
[a] Percent of total emissions for year 2001.
[b] Includes both CO_2 and N_2O.
[c] SF_6 emitted.
[d] Includes both CH_4 and N_2O.
[e] May includes a mixture of HFCs, PFCs, and SF_6.
[f] HFC-23 emitted.
[g] Includes both CO_2 and PFCs.

Emissions with Electricity Distributed to Economic Sectors

It can also be useful to view greenhouse gas emissions from economic sectors with emissions related to electricity generation distributed into end-use categories (i.e., emissions from electricity generation are allocated to the economic sectors in which the electricity is consumed). The generation, transmission, and distribution of electricity, which is the largest economic sector in the United States, accounted for 33 percent of total U.S. greenhouse gas emissions in 2001. Emissions increased by 23 percent since 1990, as electricity demand grew and fossil fuels remained the dominant energy source for generation. The electricity generation sector in the United States is composed of traditional electric utilities as well as other entities, such as power marketers and nonutility power producers. The majority of electricity generated by these entities was through the combustion of coal in boilers to produce high-pressure steam that is passed through a turbine. Table 1-12 provides a detailed summary of emissions from electricity generation-related activities.

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electricity generation sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity (EIA 2002b and Duffield 2002). These three source categories include CO_2 from fossil fuel combustion, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution.[21]

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[21] Emissions were not distributed to U.S. territories, since the electricity generation sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

Table 1-12: Electricity Generation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Fuel Type or Source	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**1,821.8**	**1,953.8**	**2,027.1**	**2,095.5**	**2,186.5**	**2,201.2**	**2,306.1**	**2,272.3**
CO_2 from Fossil Fuel Combustion	1,805.0	1,931.8	2,003.9	2,070.8	2,160.3	2,173.5	2,277.8	2,242.8
Coal	1,530.3	1,643.4	1,734.0	1,778.1	1,808.7	1,817.5	1,906.9	1,856.8
Natural Gas	175.3	228.3	205.0	218.9	248.0	260.1	280.6	284.9
Petroleum	99.0	59.7	64.5	73.5	103.2	95.6	89.9	100.7
Geothermal	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Waste Combustion	14.4	18.7	19.7	21.4	22.7	24.1	25.6	27.1
Limestone and Dolomite Use	2.7	3.5	3.8	3.5	3.7	3.8	2.9	2.6
CH_4	**0.6**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**
Stationary Combustion*	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7
N_2O	**7.8**	**8.3**	**8.7**	**9.0**	**9.2**	**9.2**	**9.6**	**9.4**
Stationary Combustion*	7.6	8.0	8.5	8.7	8.9	8.9	9.3	9.1
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
SF_6	**32.1**	**27.5**	**27.7**	**25.2**	**20.9**	**16.4**	**15.4**	**15.3**
Electrical Transmission and Distribution	32.1	27.5	27.7	25.2	20.9	16.4	15.4	15.3
Total	**1,862.3**	**1,990.1**	**2,064.1**	**2,130.4**	**2,217.2**	**2,227.5**	**2,331.8**	**2,297.7**

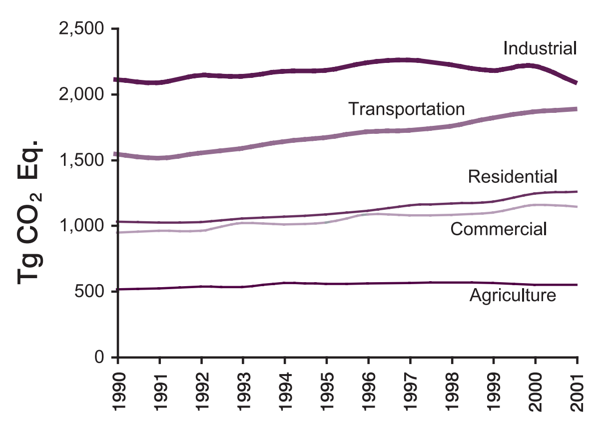
Note: Totals may not sum due to independent rounding.
* Includes only stationary combustion emissions related to the generation of electricity.

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (30 percent). Emissions from the residential and commercial sectors also increase substantially due to their relatively large share of electricity consumption. Transportation activities remain the second largest contributor to emissions. In all sectors except agriculture, CO_2 accounts for more than 75 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels.

Table 1-13 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electricity generation distributed to them. Figure 1-7 shows the trend in these emissions by sector from 1990 to 2001.

Figure 1-7

Emissions with Electricity Distributed to Economic Sectors



Note: Does not include U.S. Territories

Transportation

Transportation activities accounted for 27 percent of U.S. greenhouse gas emissions in 2001. Table 1-14 provides a detailed summary of greenhouse gas emissions from transportation-related activities. Total emissions in Table 1-14 differ slightly from those shown in Table 1-13 primarily because the table below includes all transportation activities, including those that had been counted under the Agriculture economic sector.

From 1990 to 2001, transportation emissions rose by 22 percent due, in part, to increased demand for travel and the stagnation of fuel efficiency across the U.S. vehicle fleet. 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 30 percent from 1990 to 2001) and the gallons of

Table 1-13: U.S Greenhouse Gas Emissions by "Economic Sector" and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq.) and Percent of Total in 2001

Sector/Gas	1990	1995	1996	1997	1998	1999	2000	2001	Percent[a]
Industry	**2,097.3**	**2,164.0**	**2,224.1**	**2,244.7**	**2,209.4**	**2,165.0**	**2,200.6**	**2,074.0**	**29.9%**
Direct Emissions	1,423.3	1,444.7	1,484.9	1,485.4	1,433.5	1,381.4	1,400.6	1,315.7	19.0%
CO_2	1,081.1	1,116.6	1,153.3	1,163.1	1,110.1	1,077.4	1,103.5	1,037.6	15.0%
CH_4	240.0	229.0	223.8	221.8	218.9	209.6	207.4	203.2	2.9%
N_2O	40.8	45.3	46.0	40.0	35.2	33.9	33.5	31.1	0.4%
HFCs, PFCs, and SF_6	61.3	53.9	61.8	60.5	69.3	60.6	56.3	43.7	0.6%
Electricity-Related	674.0	719.3	739.2	759.3	775.9	783.6	799.9	758.4	10.9%
CO_2	659.3	706.2	725.9	746.9	765.2	774.3	791.1	750.0	10.8%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.8	3.0	3.1	3.2	3.2	3.2	3.3	3.1	+
SF_6	11.6	9.9	9.9	9.0	7.3	5.8	5.3	5.1	0.1%
Transportation	**1,528.8**	**1,654.1**	**1,697.2**	**1,710.0**	**1,739.6**	**1,800.9**	**1,852.4**	**1,870.5**	**27.0%**
Direct Emissions	1,525.6	1,651.0	1,694.1	1,706.8	1,736.5	1,797.7	1,849.0	1,866.8	26.9%
CO_2	1,470.5	1,577.8	1,617.4	1,626.9	1,653.9	1,713.0	1,762.7	1,780.9	25.7%
CH_4	4.5	4.4	4.3	4.2	4.1	4.0	4.0	3.9	0.1%
N_2O	50.6	60.9	60.7	60.3	59.7	58.8	57.46	54.75	0.8%
HFCs[b]	+	7.8	11.7	15.4	18.8	21.9	24.78	27.35	0.4%
Electricity-Related	3.1	3.1	3.1	3.1	3.2	3.2	3.45	3.62	0.1%
CO_2	3.1	3.0	3.0	3.1	3.1	3.2	3.4	3.6	0.1%
CH_4	+	+	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+	+	+
SF_6	0.1	+	+	+	+	+	+	+	+
Residential	**943.2**	**1,019.5**	**1,080.5**	**1,073.8**	**1,076.2**	**1,095.5**	**1,154.7**	**1,138.7**	**16.4%**
Direct Emissions	334.5	371.3	402.1	385.4	352.8	372.4	390.1	379.4	5.5%
CO_2	328.9	358.5	388.6	371.7	338.8	357.3	373.9	363.3	5.2%
CH_4	4.6	4.7	4.7	3.6	3.3	3.5	3.7	3.5	0.1%
N_2O	1.1	1.2	1.2	1.0	0.9	0.9	1.0	0.9	+
HFCs	+	6.9	7.6	9.2	9.8	10.7	11.6	11.6	0.2%
Electricity-Related	608.7	648.3	678.4	688.4	723.4	723.1	764.5	759.3	10.9%
CO_2	595.4	636.4	666.3	677.2	713.4	714.5	756.1	750.9	10.8%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.6	2.7	2.9	2.9	3.0	3.0	3.1	3.1	+
SF_6	10.5	9.0	9.1	8.2	6.8	5.3	5.1	5.1	0.1%
Commercial	**1,024.5**	**1,080.7**	**1,109.7**	**1,150.9**	**1,164.2**	**1,177.7**	**1,240.9**	**1,252.6**	**18.1%**
Direct Emissions	472.4	488.0	495.5	494.0	474.2	480.6	497.6	496.5	7.2%
CO_2	221.4	226.9	236.4	237.1	219.5	221.7	234.3	235.9	3.4%
CH_4	236.9	243.5	239.8	235.7	230.9	232.7	234.9	232.1	3.3%
N_2O	13.1	14.3	14.5	14.8	15.0	15.4	15.5	15.6	0.2%
HFCs	0.9	3.4	4.8	6.5	8.9	10.7	12.8	12.9	0.2%
Electricity-Related	552.2	592.7	614.2	656.9	690.0	697.1	743.3	756.1	10.9%
CO_2	540.2	581.8	603.2	646.2	680.5	688.9	735.1	747.8	10.8%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.3	2.5	2.6	2.8	2.8	2.9	3.1	3.1	+
SF_6	9.5	8.2	8.2	7.8	6.5	5.1	4.9	5.0	0.1%
Agriculture	**512.1**	**552.6**	**555.3**	**560.4**	**564.0**	**560.3**	**546.5**	**546.0**	**7.9%**
Direct Emissions	487.8	525.8	526.1	537.9	539.4	539.8	526.0	525.7	7.6%
CO_2	46.3	56.9	52.0	58.3	57.6	59.9	50.4	50.4	0.7%
CH_4	157.1	167.6	163.2	163.3	164.6	164.7	162.3	162.2	2.3%
N_2O	284.4	301.4	310.9	316.3	317.3	315.2	313.3	313.1	4.5%
Electricity-Related	24.3	26.8	29.2	22.5	24.6	20.5	20.5	20.3	0.3%
CO_2	23.8	26.3	28.7	22.2	24.2	20.3	20.3	20.0	0.3%
CH_4	+	+	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+
SF_6	0.4	0.4	0.4	0.3	0.2	0.2	0.1	0.1	+
U.S. Territories	**33.7**	**44.0**	**40.1**	**42.8**	**47.9**	**50.2**	**52.3**	**54.4**	**0.8%**
CO_2	33.7	44.0	40.1	42.8	47.9	50.2	52.3	54.4	0.3%
Total	**6,139.6**	**6,514.9**	**6,707.0**	**6,782.6**	**6,801.3**	**6,849.5**	**7,047.4**	**6,936.2**	**-**

Note: Emissions from electricity generation are allocated based on aggregate electricity consumption in each end-use sector. Totals may not sum due to independent rounding.

\+ Does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.

[a] Percents for year 2001.

[b] Includes primarily HFC-134a.

Table 1-14: Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**1,473.5**	**1,580.9**	**1,620.4**	**1,630.0**	**1,657.0**	**1,716.2**	**1,766.1**	**1,784.4**
Passenger Cars	600.3	587.2	594.3	592.8	607.9	618.6	621.7	632.7
Light-Duty Trucks	306.2	392.9	406.5	419.1	427.6	446.1	450.2	460.0
Other Trucks	203.9	237.0	246.5	257.6	269.3	284.2	294.7	298.3
Buses	7.5	7.9	8.2	8.3	8.6	9.6	9.3	8.6
Alternative Fuel Vehicles	1.3	1.2	1.1	1.1	1.3	1.1	1.3	1.2
Aircraft[a]	176.9	171.4	180.2	179.0	183.0	186.8	195.3	183.9
Boats and Vessels	48.6	51.7	48.1	33.6	27.4	38.6	59.7	58.3
Locomotives	28.1	30.8	31.8	31.6	32.4	34.1	33.8	34.3
Other[b]	100.7	100.7	103.8	107.0	99.5	97.1	100.2	107.2
International Bunker Fuels[c]	*113.9*	*101.0*	*102.3*	*109.9*	*112.9*	*105.3*	*99.3*	*97.3*
CH_4	**5.0**	**4.9**	**4.8**	**4.7**	**4.6**	**4.5**	**4.4**	**4.3**
Passenger Cars	2.4	2.0	2.0	2.0	2.0	1.9	1.9	1.8
Light-Duty Trucks	1.6	1.9	1.8	1.7	1.7	1.6	1.5	1.5
Other Trucks and Buses	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Alternative Fuel Vehicles	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.1
Boats	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
Other[d]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
International Bunker Fuels[c]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**50.6**	**60.9**	**60.7**	**60.3**	**59.7**	**58.8**	**57.5**	**54.8**
Passenger Cars	31.0	33.4	33.1	32.6	32.2	31.2	30.2	28.7
Light-Duty Trucks	14.1	21.1	21.1	21.1	20.6	20.4	19.9	18.9
Other Trucks and Buses	2.5	3.2	3.4	3.6	3.7	3.8	3.8	3.8
Alternative Fuel Vehicles	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
Aircraft	1.7	1.7	1.8	1.7	1.8	1.8	1.9	1.8
Boats	0.4	0.5	0.4	0.3	0.3	0.4	0.5	0.3
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Other[d]	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7
International Bunker Fuels[c]	*1.0*	*0.9*	*0.9*	*1.0*	*1.0*	*0.9*	*0.9*	*0.9*
HFCs	+	**7.8**	**11.7**	**15.4**	**18.8**	**21.9**	**24.8**	**27.3**
Mobile Air Conditioners[e]	+	6.7	9.8	12.9	15.7	18.2	20.4	22.5
Refrigerated Transport	+	1.2	1.9	2.5	3.2	3.8	4.4	4.9
Total	**1,529.1**	**1,654.5**	**1,697.6**	**1,710.4**	**1,740.1**	**1,801.4**	**1,852.8**	**1,870.8**

+ Does not exceed 0.05 Tg CO_2 Eq.

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, industrial equipment, and snowmobiles.

[e] Includes primarily HFC-134a.

gasoline consumed each year in the United States have increased 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, urban sprawl, low fuel prices, and increasing popularity of sport utility vehicles and other light-duty trucks that tend to have lower fuel efficiency. A similar set of social and economic trends has led to a significant increase in air travel and freight transportation by both air and road modes during the 1990s.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with nearly two-thirds being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 21 percent from 1990 to 2001. This rise in CO_2 emissions, combined with increases of 27.3 Tg CO_2 Eq. and 4.2 Tg CO_2 Eq. in HFC and N_2O emissions over the same period, led to an increase in overall emissions from transportation activities of 22 percent.

Methodology and Data Sources

Emissions of greenhouse gases from various source and sink categories 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 report 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 methodologies were expanded and more comprehensive methods were applied.

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 and augmented with additional data where available. Emission estimates for NO_x, CO, and NMVOCs were taken directly, except where noted, from EPA data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2003), which provides the latest estimates of regional and national emissions of local air 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 local air pollutants are conceptually similar to the IPCC recommended methodologies, the large number of sources EPA used in developing its local air pollutant estimates makes it difficult to reproduce the methodologies from EPA (2003) 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 local air 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 civilian and military ships and aircraft engaged in the international transport of passengers and cargo are not included in U.S. totals, but are 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.

Box 1-3: IPCC Good Practice Guidance

In response to a request by Parties to the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC) prepared and published a report on inventory good practice. The report, entitled *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (Good Practice),* was developed with extensive participation of experts from the United States and many other countries.[22] It focuses on providing direction to countries to produce emission estimates that are as accurate and transparent as possible, with the least possible uncertainty. In addition, G*ood Practice* was designed as a tool to complement the methodologies suggested in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)*.

In order to obtain these goals, *Good Practice* gives specific guidance in the following areas:

- Selection of the most appropriate estimation method, within the context of the *IPCC Guidelines*
- Implementation of quality control and quality assurance measures
- Proper assessment and documentation of data and information
- Quantification of uncertainties for each source category

By providing such direction, the IPCC hopes to help countries provide inventories that are transparent, documented, and comparable.

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[22] See <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>

In order to aggregate emissions by economic sector, source category emission estimates were generated according to the methodologies outlined in the appropriate sections of this report. Those emissions, then, were simply reallocated into economic sectors. In most cases, the IPCC subcategories distinctly fit into an apparent economic sector category. Several exceptions exist, and the methodologies used to disaggregate these subcategories are described below:

- *Agricultural CO_2 Emissions from Fossil Fuel Combustion, and non-CO_2 emissions from Stationary and Mobile Combustion.* Emissions from on-farm energy use were accounted for in the Energy chapter as part of the industrial and transportation end-use sectors. To calculate agricultural emissions related to fossil fuel combustion, energy consumption estimates were obtained from economic survey data from the U.S. Department of Agriculture (Duffield 2002) and fuel sales data (EIA 1991 through 2002). To avoid double counting, emission estimates of CO_2 from fossil fuel combustion and non-CO_2 from stationary and mobile sources were subtracted from the industrial economic sector, although some of these fuels may have been originally accounted for under the transportation end-use sector.
- *Landfills, Wastewater Treatment and Human Sewage.* CH_4 emissions from landfills and wastewater treatment, as well as N_2O emissions from human sewage, were allocated to the commercial sector.
- *Waste Combustion.* CO_2 and N_2O emissions from waste combustion were allocated completely to the electricity generation sector since nearly all-waste combustion occurs in waste-to-energy facilities.
- *Limestone and Dolomite Use.* CO_2 emissions from limestone and dolomite use are allocated to the electricity generation (50 percent) and industrial (50 percent) sectors, because 50 percent of the total emissions for this source are used in flue gas desulfurization.
- *Substitution of Ozone Depleting Substances.* All greenhouse gas emissions resulting from the substitution of ozone depleting substances were placed in the industrial economic sector, with the exception of emissions from domestic, commercial, mobile and transport refrigeration/air-conditioning systems were placed in the residential, commercial, and transportation sectors, respectively. Emissions from non-MDI aerosols were attributed to the residential economic sector.

The UNFCCC reporting guidelines requires countries to complete a "top-down" Reference Approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology. This estimation sources than those contained in that section of the Energy chapter. This reference method estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys (see Annex W). The reference approach assumes that once carbon-based fuels are brought into a national economy they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

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 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 highly accurate. For some 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 UNFCCC reporting guidelines follow the recommendation in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and 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.

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. This report 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 X 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 CH_4 and N_2O 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 SF_6 from electrical transmission and distribution is limited due to a lack of activity data regarding national SF_6 consumption or average equipment leak rates.

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 Inventory of U.S. Greenhouse Gas Emissions and Sinks is segregated into six sector-specific chapters, listed below in Table 1-15.

Table 1-15: 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 of CO_2 from forest management, other land-use activities, and land-use change.
Waste	Emissions from waste management activities.

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

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 Category:
Description of source pathway and emission trends.

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 CO_2 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 electricity generation sector, are treated individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-16.

Table 1-16: List of Annexes

ANNEX A	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
ANNEX B	Methodology for Estimating the Carbon Content of Fossil Fuels
ANNEX C	Methodology for Estimating Carbon Stored in Products from Non-Energy Uses of Fossil Fuels
ANNEX D	Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Stationary Combustion
ANNEX E	Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related GHG Emissions
ANNEX F	Methodology for Estimating CH_4 Emissions from Coal Mining
ANNEX G	Methodology for Estimating CH_4 Emissions from Natural Gas Systems
ANNEX H	Methodology for Estimating CH_4 Emissions from Petroleum Systems
ANNEX I	Methodology for Estimating CO_2 Emissions from Municipal Solid Waste Combustion
ANNEX J	Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
ANNEX K	Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
ANNEX L	Methodology for Estimating CH_4 Emissions from Enteric Fermentation
ANNEX M	Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
ANNEX N	Methodology for Estimating N_2O Emissions from Agricultural Soil Management
ANNEX O	Methodology for Estimating Net Changes in Forest Carbon Stocks
ANNEX P	Methodology for Estimating Net Changes in Carbon Stocks in Mineral and Organic Soils
ANNEX Q	Methodology for Estimating CH_4 Emissions from Landfills
ANNEX R	Key Source Analysis
ANNEX S	Global Warming Potential Values
ANNEX T	Ozone Depleting Substance Emissions
ANNEX U	Sulfur Dioxide Emissions
ANNEX V	Complete List of Source Categories
ANNEX W	IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion
ANNEX X	Sources of Greenhouse Gas Emissions Excluded
ANNEX Y	Constants, Units, and Conversions
ANNEX Z	Abbreviations
ANNEX AA	Chemical Formulas
ANNEX AB	Glossary

2. Energy

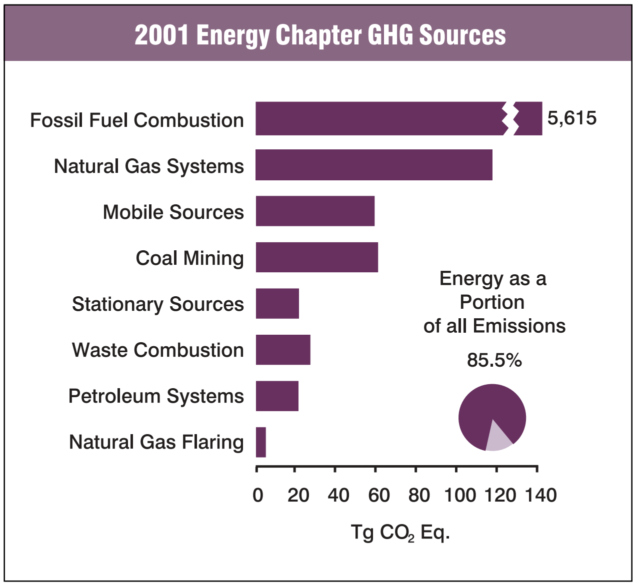
Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 85 percent of total emissions on a carbon equivalent basis in 2001. This included 97, 35, and 16 percent of the nation's carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 81 percent of national emissions from all sources on a carbon equivalent basis, while the non-CO_2 emissions from energy-related activities 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). Globally, approximately 23,300 Tg CO_2 were added to the atmosphere through the combustion of fossil fuels at the end of the 1990s, of which the United States accounted for about 24 percent (see Figure 2-2).[1] Due to the relative importance of fossil fuel combustion-related CO_2 emissions, they are considered separately, and in more detail than other energy-related emissions. Fossil fuel combustion also emits CH_4 and N_2O, as well as ambient air 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 these ambient air pollutant emissions.

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 fugitive 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 because biomass fuels are of biogenic origin. It is assumed that the carbon released during the consumption of biomass 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.

Figure 2-1



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[1] Global CO_2 emissions from fossil fuel combustion were taken from Marland et al. (2002) <http://cdiac.esd.ornl.gov/trends/emis/meth_reg.htm>.

Table 2-1 summarizes emissions for the Energy chapter in units of teragrams of CO_2 equivalents (Tg CO_2 Eq.), while unweighted gas emissions in gigagrams (Gg) are provided in Table 2-2. Overall, emissions due to energy-related activities were 5,927.1 Tg CO_2 Eq. in 2001, an increase of 15 percent since 1990.

Table 2-1: Emissions from Energy (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**4,834.3**	**5,168.7**	**5,353.4**	**5,428.8**	**5,449.2**	**5,519.4**	**5,723.0**	**5,646.9**
Fossil Fuel Combustion	4,814.8	5,141.5	5,325.8	5,400.0	5,420.5	5,488.8	5,692.2	5,614.9
Waste Combustion	14.1	18.5	19.4	21.2	22.5	23.9	25.4	26.9
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	5.5	5.2
Biomass-Wood*	175.0	193.3	197.1	176.6	173.8	176.6	180.3	173.4
International Bunker Fuels*	113.9	101.0	102.3	109.9	112.9	105.3	99.3	97.3
Biomass-Ethanol*	4.4	8.1	5.8	7.4	8.1	8.5	9.7	10.2
Carbon Stored in Products*	214.5	238.1	240.9	249.7	258.5	271.9	263.6	252.8
CH_4	**249.7**	**238.4**	**233.2**	**229.9**	**226.6**	**217.4**	**215.4**	**211.0**
Natural Gas Systems	122.0	127.2	127.4	126.0	124.0	120.3	121.2	117.3
Coal Mining	87.1	73.5	68.4	68.1	67.9	63.7	60.9	60.7
Petroleum Systems	27.5	24.2	23.9	23.6	22.9	21.6	21.2	21.2
Stationary Combustion	8.1	8.5	8.7	7.5	7.2	7.4	7.6	7.4
Mobile Combustion	5.0	4.9	4.8	4.7	4.6	4.5	4.4	4.3
International Bunker Fuels*	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**63.4**	**74.4**	**74.8**	**74.3**	**73.6**	**72.7**	**72.0**	**69.2**
Mobile Combustion	50.6	60.9	60.7	60.3	59.7	58.8	57.5	54.8
Stationary Combustion	12.5	13.2	13.8	13.7	13.7	13.7	14.3	14.2
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
International Bunker Fuels*	1.0	0.9	0.9	1.0	1.0	0.9	0.9	0.9
Total	**5,147.5**	**5,481.6**	**5,661.4**	**5,733.0**	**5,749.4**	**5,809.5**	**6,010.4**	**5,927.1**

* 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.

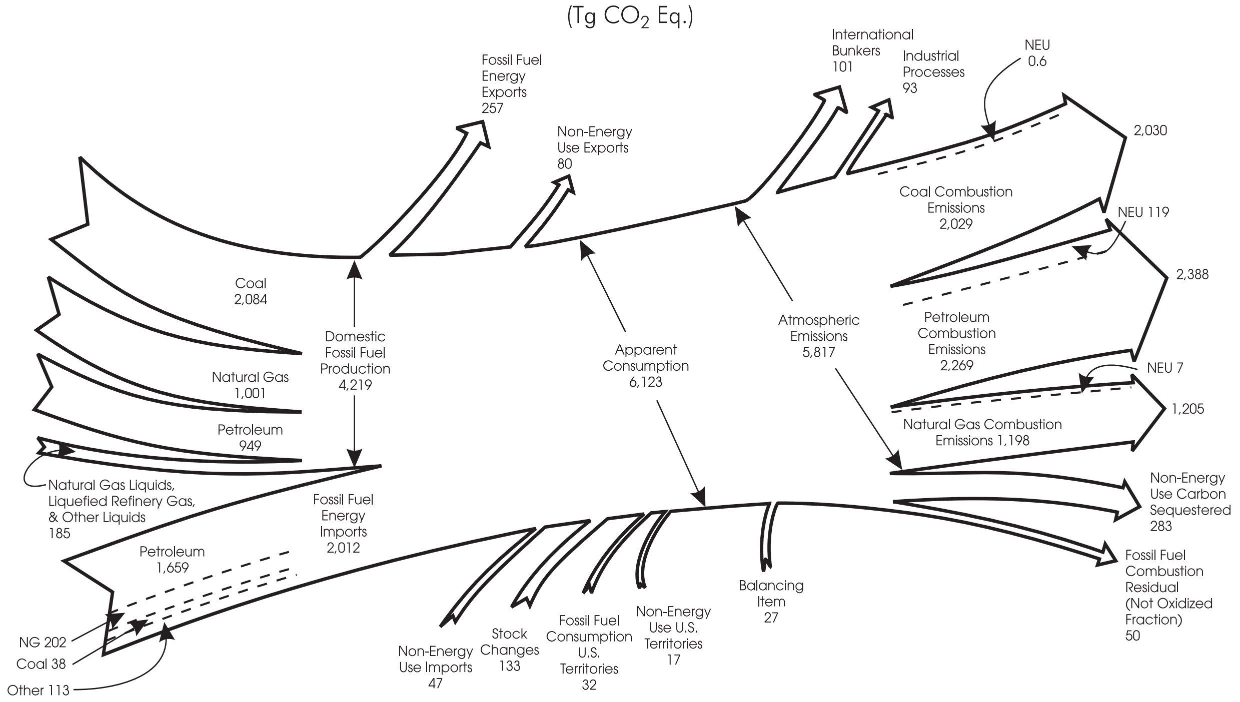
Table 2-2: Emissions from Energy (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**4,834,340**	**5,168,749**	**5,353,449**	**5,428,772**	**5,449,223**	**5,519,386**	**5,723,047**	**5,646,940**
Fossil Fuel Combustion	4,814,758	5,141,548	5,325,798	5,400,034	5,420,519	5,488,804	5,692,170	5,614,853
Waste Combustion	14,068	18,472	19,418	21,173	22,454	23,903	25,351	26,907
Natural Gas Flaring	5,514	8,729	8,233	7,565	6,250	6,679	5,525	5,179
Biomass-Wood*	174,991	193,333	197,104	176,589	173,822	176,589	180,321	173,426
International Bunker Fuels*	113,863	101,037	102,272	109,858	112,859	105,262	99,268	97,346
Biomass-Ethanol*	4,380	8,099	5,809	7,356	8,128	8,451	9,667	10,226
Carbon Stored in Products*	214,454	238,061	240,891	249,693	258,475	271,894	263,646	252,772
CH_4	**11,891**	**11,352**	**11,105**	**10,949**	**10,788**	**10,354**	**10,258**	**10,049**
Natural Gas Systems	5,810	6,059	6,069	6,001	5,903	5,728	5,772	5,588
Coal Mining	4,149	3,502	3,255	3,244	3,235	3,033	2,902	2,893
Petroleum Systems	1,309	1,153	1,138	1,123	1,090	1,029	1,010	1,011
Stationary Combustion	388	406	415	358	342	351	363	353
Mobile Combustion	236	232	227	223	217	214	211	204
International Bunker Fuels*	8	6	6	7	7	6	6	5
N_2O	**205**	**240**	**241**	**240**	**237**	**234**	**232**	**223**
Mobile Combustion	163	197	196	195	192	190	185	177
Stationary Combustion	40	43	45	44	44	44	46	46
Waste Combustion	1	1	1	1	1	1	1	1
International Bunker Fuels*	3	3	3	3	3	3	3	3

* 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.

Figure 2-2

2001 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)



Note: Totals may not sum due to independent rounding.

The "Balancing Item" above accounts for the statistical imbalances and unknowns in the reported data sets combined here.

NEU = Non-Energy Use
NG = Natural Gas

Carbon Dioxide Emissions from Fossil Fuel Combustion

Carbon dioxide emissions from fossil fuel combustion have declined for the first time since 1991, decreasing by 1.4 percent from 2000 to 2001. The primary reason for this reduction is due to slow growth of the U.S. economy and a decline in manufacturing output, which reduced overall demand for fuels. In 2001, CO_2 emissions from fossil fuel combustion were 5,614.9 Tg CO_2 Eq., or 16.6 percent above emissions in 1990 (see Table 2-3).[2]

Trends in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

Longer-term changes in energy consumption patterns, however, tend to be more a function of aggregate societal trends that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Carbon dioxide emissions also depend on the source of energy and its carbon intensity. The amount of carbon in fuels varies significantly by fuel type. For example, coal

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[2] An additional discussion of fossil fuel emission trends is presented in the Recent Trends in U.S. Greenhouse Gas Emissions section of the Introduction chapter.

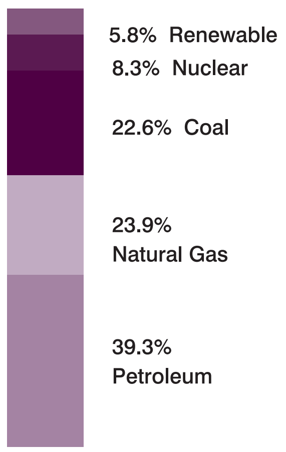
Table 2-3: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (Tg CO_2 Eq.)

Fuel/Sector	1990	1995	1996	1997	1998	1999	2000	2001
Coal	**1,697.3**	**1,805.8**	**1,893.4**	**1,939.1**	**1,957.3**	**1,961.1**	**2,051.5**	**1,993.8**
Residential	2.5	1.6	1.6	1.5	1.2	1.3	1.1	1.1
Commercial	12.3	11.1	11.5	12.1	8.7	9.7	8.6	8.6
Industrial	151.6	148.8	145.3	146.4	137.8	131.7	134.0	126.3
Transportation	NE	NE	NE	NE	NE	NE	NE	N
Electricity Generation	1,530.3	1,643.4	1,734.0	1,778.1	1,808.7	1,817.5	1,906.9	1,856.8
U.S. Territories	0.6	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Natural Gas	**1,012.5**	**1,172.6**	**1,193.9**	**1,200.3**	**1,177.2**	**1,183.8**	**1,240.3**	**1,202.1**
Residential	238.8	263.0	284.2	270.2	246.5	256.5	270.3	260.8
Commercial	142.6	164.3	171.3	174.3	163.5	165.2	174.3	175.8
Industrial	419.9	478.8	494.6	495.8	484.1	466.4	478.9	445.5
Transportation	35.9	38.2	38.9	41.1	35.1	35.6	35.5	33.9
Electricity Generation	175.3	228.3	205.0	218.9	248.0	260.1	280.6	284.9
U.S. Territories	NO	NO	NO	NO	NO	NO	0.6	1.2
Petroleum	**2,104.5**	**2,162.7**	**2,238.2**	**2,260.3**	**2,285.6**	**2,343.6**	**2,400.0**	**2,418.6**
Residential	87.6	94.0	102.8	100.0	91.1	99.5	102.4	101.4
Commercial	66.6	51.4	53.6	50.6	47.2	46.7	51.4	51.4
Industrial	383.7	374.9	399.6	408.6	378.2	375.0	378.2	365.8
Transportation	1,434.6	1,539.6	1,578.5	1,585.8	1,618.8	1,677.5	1,727.3	1,747.0
Electricity Generation	99.0	59.7	64.5	73.5	103.2	95.6	89.9	100.7
U.S. Territories	33.1	43.1	39.1	41.8	47.0	49.3	50.8	52.3
Geothermal*	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**4,814.8**	**5,141.5**	**5,325.8**	**5,400.0**	**5,420.5**	**5,488.8**	**5,692.2**	**5,614.9**

NE (Not estimated)
NO (Not occurring)
* 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 2-3

2001 U.S. Energy Consumption by Energy Source



Source: Annual Energy Review 2001, EIA (2002a), Table 1.3

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.[3] Producing a unit of heat or electricity using natural gas instead of coal can reduce the CO_2 emissions associated with energy consumption, and using nuclear or renewable energy sources (e.g., wind) can essentially eliminate emissions (see Box 2-2).

In the United States, 86 percent of the energy consumed in 2001 was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure 2-3 and Figure 2-7). The remaining portion was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (6 percent), primarily hydroelectric power (EIA 2002a). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for an average

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

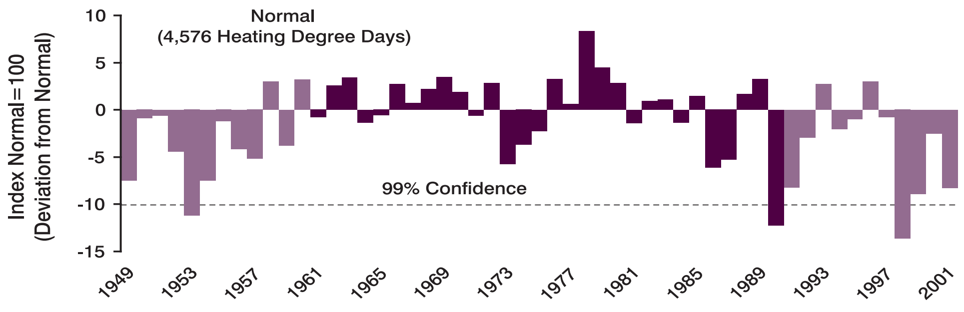
Box 2-1: Weather and Non-Fossil Energy Effects on CO_2 from Fossil Fuel Combustion Trends

After a fairly typical year in 2000, weather conditions became warmer in 2001. The warmer winter conditions led to decreased demand for heating fuels, while a warmer summer increased electricity demand for air conditioning in the residential and commercial sectors. Heating degree days in the United States in 2001 were 8 percent below normal (see Figure 2-4) while cooling degree days in 2001 were 7 percent above normal (see Figure 2-5).[4]

Although no new U.S. nuclear power plants have been constructed in recent years, the utilization (i.e., capacity factors[5]) of existing plants reached record levels in 2001, approaching 90 percent. This increase in utilization translated into an increase in electricity output by nuclear plants of approximately 2 percent in 2001. This output by nuclear plants, however, was more than offset by reduced electricity output by hydroelectric power plants, which declined by almost 23 percent. Electricity generated by nuclear plants in 2001 provided approximately 3.5 times as much of the energy consumed in the United States as hydroelectric plants. Nuclear and hydroelectric power plant capacity factors since 1973 are shown in Figure 2-6.

Figure 2-4

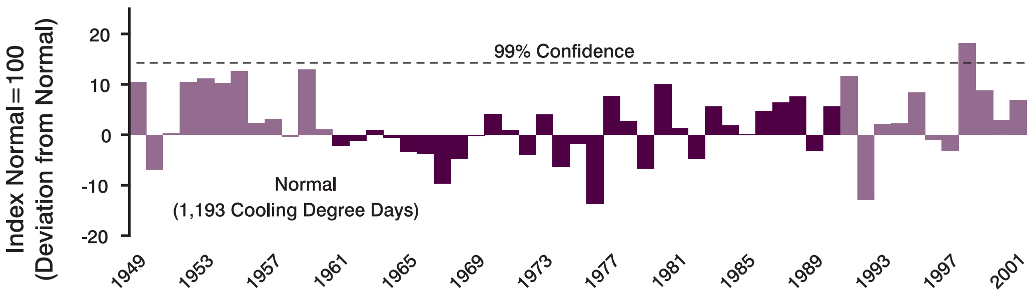
Annual Deviations from Normal Heating Degree Days for the United States (1949-2001)



Annual Deviations from Normal Cooling Degree Days for the United States (1949–2001)
Note: Climatological normal data are highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.
Source: NOAA (2002)

Figure 2-5

Annual Deviations from Normal Cooling Degree Days for the United States (1949-2001)



Annual Deviations from Normal Cooling Degree Days for the United States (1949–2001)
Note: Climatological normal data are highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.
Source: NOAA (2002)

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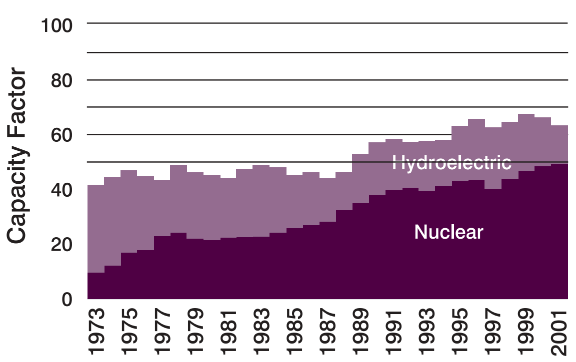
[4] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F, while cooling degree days are deviations of the mean daily temperature above 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990. The variation in these normals during this time period was ±10 percent and ±14 percent for heating and cooling degree days, respectively (99 percent confidence interval).

[5] The capacity factor is defined as the ratio of the electrical energy produced by a generating unit for a given period of time to the electrical energy that could have been produced at continuous full-power operation during the same period (EIA 2001b).

Box 2-1: Weather and Non-Fossil Energy Effects on CO_2 from Fossil Fuel Combustion Trends (Continued)

Figure 2-6



Aggregate Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1973-2001)

Source: Annual Energy Review, EIA (2002a), Table 9.2

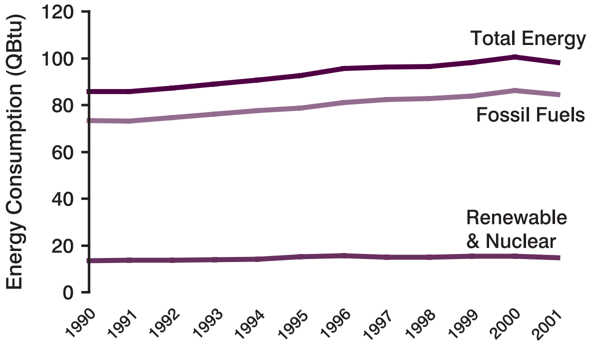
For the purpose of international reporting, the IPCC (IPCC/UNEP/OECD/IEA 1997) recommends that particular adjustments be made to national fuel consumption statistics. Certain fossil fuels can be manufactured into plastics, asphalt, lubricants, or other products. A portion of the carbon consumed for these non-energy products can be stored (i.e., sequestered) indefinitely. 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. (See the Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter.) The fraction of this carbon stored in products that is eventually combusted in waste incinerators or combustion plants is accounted for in the Waste Combustion section of this chapter.

of 39 percent of total energy consumption from 1990 through 2001. Natural gas and coal followed in order of importance, accounting for 24 and 23 percent of total consumption, respectively. Most petroleum was consumed in the transportation end-use sector, while the vast majority of coal was used in electricity generation. Natural gas broadly consumed in all end-use sectors except transportation (see Figure 2-8) (EIA 2002a).

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process the carbon stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, CO, and NMVOCs.[6] These other carbon containing non-CO_2 gases are emitted as a by-product of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, except for the soot and ash left behind during the combustion process, all the carbon in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

Figure 2-7

U.S. Energy Consumption (Quadrillion Btu)



Note: Expressed as gross calorific values.
Source: Annual Energy Review 2001, EIA (2002a), Table 1.3

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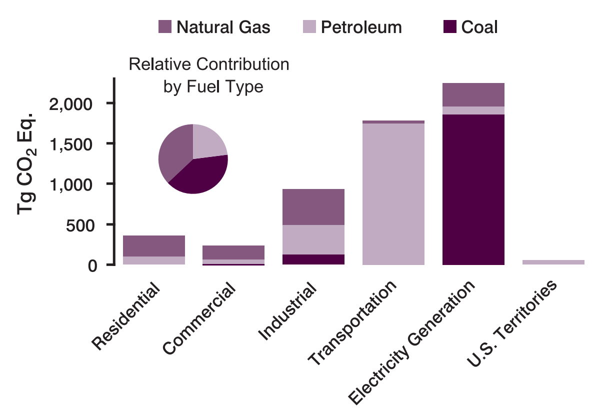
[6] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

Figure 2-8

2001 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Note: The electricity generation sector also includes emissions of less than 0.01 Tg CO_2 Eq. from geothermal-based generation

According to the UNFCCC reporting guidelines, CO_2 emissions from the consumption of fossil fuels for aviation and marine international transport activities (i.e., international bunker fuels) should be reported separately, and not included in national emission totals. Estimates of carbon in products and international bunker fuel emissions for the United States are provided in Table 2-4 and Table 2-5.

End-Use Sector Consumption

An alternative method of presenting CO_2 emissions is to allocate emissions associated with electricity generation to the sectors in which it is used. Four end-use sectors were defined: industrial, transportation, residential, and commercial.[7] For the discussion below, electricity generation emissions have been distributed to each end-use sector based upon the sector's share of national electricity consumption. This method of distributing emissions assumes that each sector consumes electricity generated from an equally carbon-intensive mix of fuels and other energy sources. In reality, sources of electricity vary widely in carbon intensity (e.g., coal versus wind power). By giving equal carbon-intensity weight to each sector's electricity consumption, emissions attributed to one end-use sector may be somewhat overestimated, while emissions attributed to another end-use sector may be slightly underestimated. After the end-use sectors are discussed, emissions from electricity generation are addressed separately. Emissions from U.S. territories are also calculated separately due to a lack of end-use-specific consumption data. Table 2-6 and Figure 2-9 summarize CO_2 emissions from direct fossil fuel combustion and pro-rated electricity generation emissions from electricity consumption by end-use sector.

Table 2-4: Fossil Fuel Carbon in Products (Tg CO_2 Eq.)*

Sector	1990	1995	1996	1997	1998	1999	2000	2001
Industrial	212.6	235.9	238.3	247.0	255.7	268.9	260.6	249.7
Transportation	1.2	1.2	1.1	1.2	1.2	1.2	1.2	1.1
Territories	0.6	1.0	1.5	1.6	1.5	1.8	1.8	1.9
Total	**214.5**	**238.1**	**240.9**	**249.7**	**258.5**	**271.9**	**263.6**	**252.8**

* See Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section for additional detail.
Note: Totals may not sum due to independent rounding.

Table 2-5: CO_2 Emissions from International Bunker Fuels (Tg CO_2 Eq.)*

Vehicle Mode	1990	1995	1996	1997	1998	1999	2000	2001
Aviation	46.6	51.1	52.2	55.9	55.0	58.8	58.4	58.9
Marine	67.3	49.9	50.1	54.0	57.9	46.4	40.9	38.5
Total	**113.9**	**101.0**	**102.3**	**109.9**	**112.9**	**105.3**	**99.3**	**97.3**

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

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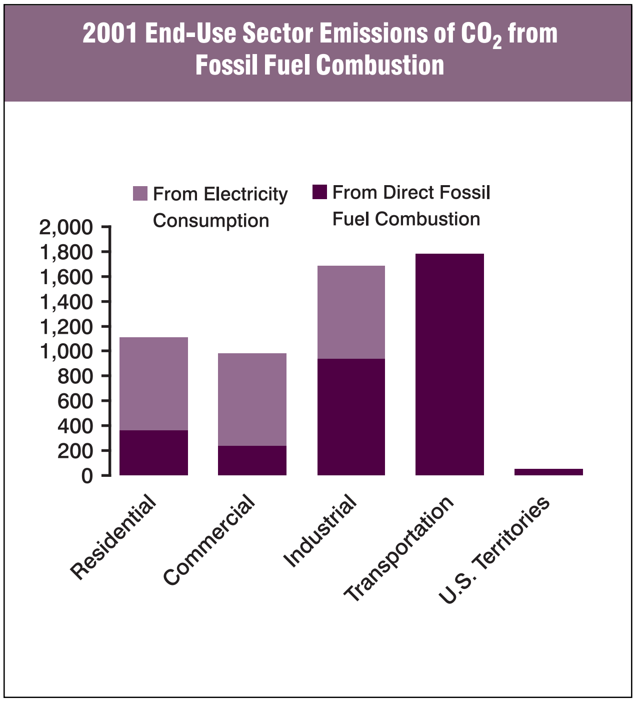
[7] See Glossary (Annex AB) for more detailed definitions of the industrial, residential, commercial, and transportation end-use sector, as well as electricity generation.

Table 2-6: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1995	1996	1997	1998	1999	2000	2001
Industrial	**1,632.1**	**1,710.3**	**1,767.4**	**1,796.8**	**1,764.6**	**1,744.8**	**1,779.5**	**1,684.5**
Combustion	955.3	1,002.6	1,039.5	1,050.8	1,000.1	973.2	991.1	937.7
Electricity	676.8	707.7	727.9	746.0	764.5	771.7	788.4	746.8
Transportation	**1,473.5**	**1,580.9**	**1,620.4**	**1,630.0**	**1,657.0**	**1,716.2**	**1,766.1**	**1,784.4**
Combustion	1,470.5	1,577.8	1,617.4	1,626.9	1,653.9	1,713.0	1,762.7	1,780.9
Electricity	3.0	3.0	3.0	3.1	3.1	3.2	3.4	3.6
Residential	**918.8**	**996.4**	**1,056.6**	**1,048.0**	**1,051.6**	**1,069.4**	**1,127.3**	**1,111.1**
Combustion	328.9	358.5	388.6	371.7	338.8	357.3	373.9	363.3
Electricity	589.9	637.8	668.1	676.4	712.8	712.1	753.5	747.8
Commercial	**756.6**	**810.0**	**841.2**	**882.5**	**899.4**	**908.2**	**966.9**	**980.5**
Combustion	221.4	226.9	236.4	237.1	219.5	221.7	234.3	235.9
Electricity	535.2	583.1	604.8	645.4	679.9	686.5	732.6	744.6
U.S. Territories	**33.7**	**44.0**	**40.1**	**42.8**	**47.9**	**50.2**	**52.3**	**54.4**
Total	**4,814.8**	**5,141.5**	**5,325.8**	**5,400.0**	**5,420.5**	**5,488.8**	**5,692.2**	**5,614.9**
Electricity Generation	**1,805.0**	**1,931.8**	**2,003.9**	**2,070.8**	**2,160.3**	**2,173.5**	**2,277.8**	**2,242.8**

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

Figure 2-9



2001 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

Transportation End-Use Sector

The transportation end-use sector accounted for the largest share (approximately 32 percent) of CO_2 emissions from fossil fuel combustion.[8] Almost all of the energy consumed in the transportation sector was petroleum-based, with nearly two-thirds being gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder.[9]

Carbon dioxide emissions from fossil fuel combustion for transportation increased by 21 percent from 1990 to 2001, to 1,784.4 Tg CO_2 Eq. The growth in transportation end-use sector emissions has been relatively steady, including a 1.0 percent single year increase in 2001. Like overall energy demand, transportation fuel demand is a function of many short and long-term factors. In the short term only minor adjustments can generally be made through consumer behavior (e.g., not driving as far for summer vacation). However, long-term adjustments such as vehicle purchase choices, transport mode choice and access (i.e., trains versus planes), and urban planning can have a significant impact on fuel demand.

Motor gasoline and other petroleum product prices rose in 2000 to levels not seen since 1990, though they decreased slightly in 2001 (see Figure 2-10). Despite unfavorable economic conditions, demand for transportation fuel in 2001 increased from 2000 levels. Since 1990, travel activity in the United States has grown more rapidly than population, with a 14 percent increase in vehicle miles traveled per capita. In the meantime, improvements in the average fuel efficiency of the U.S. vehicle fleet stagnated after increasing steadily since

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[8] Note that electricity generation is actually the largest emitter of CO_2 when electricity is not distributed among end-use sectors.

[9] See Glossary (Annex AB) for a more detailed definition of the transportation end-use sector.

1977 (FHWA 1996 through 2002). The average miles per gallon achieved by the U.S. vehicle fleet has remained fairly constant since 1991. This trend is due, in part, to the increasing dominance of new motor vehicle sales by less fuel-efficient light-duty trucks and sport-utility vehicles (see Figure 2-11).

Table 2-7 provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. Fifty-seven percent of the emissions from this end-use sector in 2001 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, accounting for 16 and 13 percent of CO_2 emissions from the transportation end-use sector, respectively.[10]

Industrial End-Use Sector

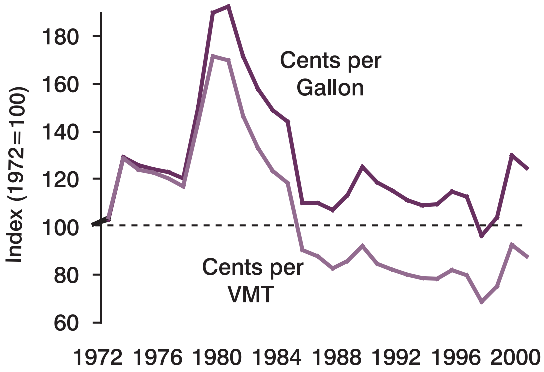
The industrial end-use sector accounted for 30 percent of CO_2 emissions from fossil fuel combustion. On average, 56 percent of these emissions resulted from the direct consumption of fossil fuels for steam and process heat production. The remaining 44 percent was associated with their consumption of 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.[11] The largest of these activities in terms of energy consumption is manufacturing, which was estimated in 1998 to have accounted for about 84 percent of industrial energy consumption (EIA 1997). Just six industries—Petroleum, Chemicals, Primary Metals, Pulp and Paper, Food, and Stone, Clay, and Glass products—represent 83 percent of total manufacturing energy use.

In theory, emissions from the industrial end-use sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption are also affected by weather conditions.[12] In addition, structural changes within the U.S. economy that lead to shifts in industrial output away from energy intensive manufacturing products to less energy intensive products (e.g., from steel to computer equipment) also have a significant affect on industrial emissions.

Figure 2-10

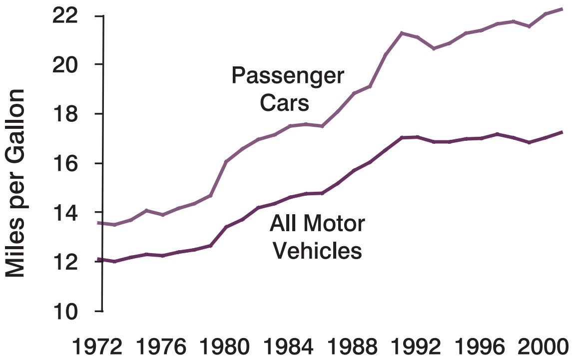
Motor Gasoline Retail Prices (Real)



Source for gasoline prices: Annual Energy Review 2001, EIA (2002a), Table 5.22
Source for motor vehicle fuel efficiency: FHWA (1996 through 2002)

Figure 2-11

Motor Vehicle Fuel Efficiency



Source: FHWA (1996 through 2002)

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[10] These percentages include emissions from bunker fuels.

[11] See Glossary (AnnexAB) for a more detailed definition of the industrial end-use sector.

[12] Some commercial customers are large enough to obtain an industrial price for natural gas and/or electricity and are consequently grouped with the industrial end-use sector in U.S. energy statistics. These misclassifications of large commercial customers likely cause the industrial end-use sector to appear to be more sensitive to weather conditions.

Table 2-7: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (Tg CO_2 Eq.)

Fuel/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001
Gasoline	**955.3**	**1,023.0**	**1,041.4**	**1,050.6**	**1,072.5**	**1,098.7**	**1,105.7**	**1,129.3**
Automobiles	594.0	582.4	589.6	588.2	603.5	614.2	617.5	628.8
Light Trucks	297.3	381.3	394.3	406.0	414.2	431.7	435.7	445.2
Other Trucks	39.8	37.1	36.1	34.7	34.6	33.7	33.4	32.4
Buses	1.6	1.0	0.9	0.7	0.7	0.7	0.6	0.5
Motor Cycles	1.7	1.7	1.7	1.7	1.7	1.8	1.8	1.6
Boats (Recreational)	11.2	9.2	8.5	8.4	8.1	9.3	9.6	9.5
Agricultural Equipment	7.0	8.0	7.9	8.4	7.7	5.9	5.6	6.9
Construction Equipment	2.7	2.4	2.4	2.5	2.0	1.5	1.6	4.4
Distillate Fuel Oil (Diesel)	**277.3**	**311.9**	**328.9**	**342.4**	**355.6**	**373.5**	**385.1**	**394.1**
Automobiles	6.3	4.9	4.7	4.6	4.4	4.4	4.1	3.9
Light-Duty Trucks	8.9	11.6	12.2	13.1	13.4	14.4	14.6	14.8
Other Trucks	164.2	199.9	210.4	222.9	234.7	250.5	261.3	265.9
Buses	5.8	6.9	7.3	7.6	7.9	9.0	8.7	8.1
Locomotives	27.5	30.2	31.2	30.9	31.7	33.4	33.1	33.5
Ships & Boats	14.0	12.3	15.0	14.6	13.1	15.6	15.5	16.8
Agricultural Equipment	26.1	25.0	26.3	26.0	24.4	23.5	25.7	28.3
Construction Equipment	13.1	11.9	13.4	13.6	14.4	14.4	15.9	17.6
Ships (Bunkers)	11.4	9.1	8.3	9.1	11.5	8.2	6.2	5.2
Jet Fuel	**220.4**	**219.9**	**229.8**	**232.1**	**235.6**	**242.9**	**251.2**	**240.4**
Commercial Aircraft	118.2	121.4	124.9	129.4	131.4	137.3	141.0	131.6
Military Aircraft	34.8	24.1	23.1	21.0	21.5	20.6	21.0	22.8
General Aviation Aircraft	6.3	5.3	5.8	6.1	7.7	9.2	9.5	9.3
Other Aircraft[a]	14.6	17.9	23.9	19.7	19.9	17.0	21.4	17.8
Aircraft (Bunkers)	46.6	51.1	52.2	55.9	55.0	58.8	58.4	58.9
Aviation Gasoline	**3.1**	**2.7**	**2.6**	**2.7**	**2.4**	**2.7**	**2.5**	**2.4**
General Aviation Aircraft	3.1	2.7	2.6	2.7	2.4	2.7	2.5	2.4
Residual Fuel Oil	**79.2**	**71.0**	**66.4**	**55.5**	**52.6**	**51.9**	**69.2**	**65.2**
Locomotives	+	+	+	+	+	+	+	+
Ships & Boats[b]	23.4	30.2	24.6	10.6	6.2	13.7	34.6	32.0
Ships (Bunkers)[b]	55.8	40.8	41.8	44.9	46.4	38.2	34.6	33.2
Natural Gas	**35.9**	**38.2**	**38.9**	**41.1**	**35.1**	**35.6**	**35.5**	**33.9**
Automobiles	+	0.1	+	+	+	+	+	+
Light Trucks	+	+	+	+	+	+	+	+
Buses	+	0.1	0.1	0.2	0.2	0.3	0.4	0.4
Pipeline	35.9	38.0	38.7	40.9	34.9	35.3	35.0	33.5
LPG	**1.3**	**1.0**	**0.9**	**0.8**	**1.0**	**0.8**	**0.8**	**0.8**
Light Trucks	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3
Other Trucks	0.8	0.5	0.5	0.4	0.6	0.5	0.5	0.5
Buses	+	+	+	+	+	+	+	+
Electricity	**3.0**	**3.0**	**3.0**	**3.1**	**3.1**	**3.2**	**3.4**	**3.6**
Buses	+	+	+	+	+	+	+	+
Locomotives & Transit Cars	0.6	0.6	0.6	0.7	0.6	0.7	0.7	0.8
Pipeline	2.4	2.4	2.4	2.4	2.5	2.5	2.7	2.8
Lubricants	**11.7**	**11.2**	**10.9**	**11.5**	**12.0**	**12.1**	**12.0**	**12.1**
Total (Including Bunkers)[c]	**1,587.3**	**1,681.9**	**1,722.7**	**1,739.9**	**1,769.9**	**1,821.5**	**1,865.4**	**1,881.8**
Total (Excluding Bunkers)[c]	**1,473.5**	**1,580.9**	**1,620.4**	**1,630.0**	**1,657.0**	**1,716.2**	**1,766.1**	**1,784.4**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

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

[b] Fluctuations in emission estimates from the combustion of residual fuel oil are currently unexplained, but may be related to data collection problems.

[c] Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates including international bunker fuel-related emissions are presented for informational purposes.

From 2000 to 2001, total industrial production and manufacturing output were reported to have decreased by 3.9 and 4.4 percent, respectively (FRB 2002). Output declined in all six of the aforementioned industries that account for the majority of energy use in manufacturing. The largest declines were in the Primary Metals (-11.4 percent) and Pulp and Paper industries (-5.1 percent) (see Figure 2-12).

Despite the growth in industrial output (42 percent) and the overall U.S. economy (37 percent) from 1990 to 2001, emissions from the industrial end-use sector increased only slightly (by 3 percent). The reasons for the disparity between rapid growth in industrial output and stagnant growth in industrial emissions are not entirely clear. It is likely, though, that several factors have influenced industrial emission trends, including: 1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, 2) improvements in energy efficiency; and 3) a lowering of the carbon intensity of fossil fuel consumption as industry shifts from its historical reliance on coal and coke to heavier usage of natural gas. Carbon dioxide emissions from fossil fuel combustion and electricity use within the industrial end-use sectors were 1,684.5 Tg CO_2 Eq. in 2001.

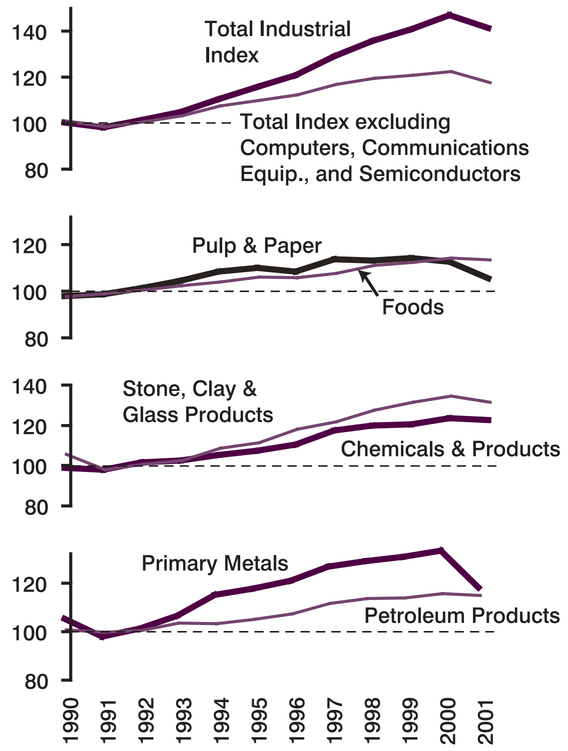
Industry was the largest user of fossil fuels for non-energy applications. Fossil fuels can be used for producing products such as fertilizers, plastics, asphalt, or lubricants that can sequester or store carbon for long periods of time. Asphalt used in road construction, for example, stores carbon essentially 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 17 percent between 1990 and 2001, to 249.7 Tg CO_2 Eq.[13]

Residential and Commercial End-Use Sectors

The residential and commercial end-use sectors accounted for an average 20 and 17 percent, respectively, of CO_2 emissions from fossil fuel combustion. Both end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances contributing to about 67 and 76 percent of emissions from the residential and commercial end-use sectors, respectively. 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 these end-use sectors. In 2001, CO_2 emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,111.1 Tg CO_2 Eq. and 980.5 Tg CO_2 Eq., respectively.

Figure 2-12

Industrial Production Indexes (Index 1992=100)



Source: FRB (2002)

Since 1990, emissions from residences and commercial buildings have increased steadily, unlike those from the industrial sector, which experienced sizeable reductions during the economic downturns of 1991 and 2001 (see Table 2-6). This difference exists because short-term fluctuations in energy consumption in these sectors are correlated more with the weather than by prevailing economic conditions. In the long-term, both end-use sectors are also affected by population growth, regional migration trends, and changes in housing and building attributes (e.g., size and insulation).

A number of contrasting trends influenced emissions in 2001. Emissions from residential natural gas consumption actually decreased by 4 percent, due, in part, to warmer winter weather.

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[13] See the Carbon Stored in Products in Non-Energy Uses of Fossil Fuels for a more detailed discussion. Also, see Waste Combustion in the Waste chapter for a discussion of emissions from the incineration or combustion of fossil fuel-based products.

Winter conditions in the United States were warmer than normal in 2001 (heating degree days were 8 percent below normal), and slightly warmer than conditions in 2000 (see Figure 2-13).

Electricity sales to the residential and commercial end-use sectors in 2001 increased by 1 and 3 percent, respectively. Hotter summer conditions in 2001 are partially responsible for this trend, due to increased air-conditioning related electricity consumption (see Figure 2-14). However, other factors such as growth in personal income and population are also important drivers of emissions from these sectors.

Although the residential and commercial sector usually exhibit similar emission trends, total emissions from the commercial end-use sector increased by 1.4 percent, while emissions from the residential sector decreased by 1.4 percent in 2001. This occurred despite an increase in electricity consumption from both sectors. The reason for the opposing trends in these two sectors is mainly due to 1) strong commercial development in 2001 (EIA 2002d), and 2) the nature of energy use in each sector. The reduction in emissions from the residential sector results from a combination of lower natural gas consumption and a modest increase in electricity use. The residential sector consumes a much higher proportion of natural gas for its energy needs, and due to higher natural gas prices and a warmer winter, consumed a lesser amount of natural gas. Consumption of electricity in the residential sector is much more price-sensitive due to the individual choices by consumers. For the first time since the early 1980's, the retail price of residential electricity increased, causing consumers to moderate their electricity usage to a relatively modest 1 percent growth. The commercial sector is much more reliant on electricity to meet energy needs, and had to consume a higher amount of electricity for air conditioning during the hotter summer of 2001.

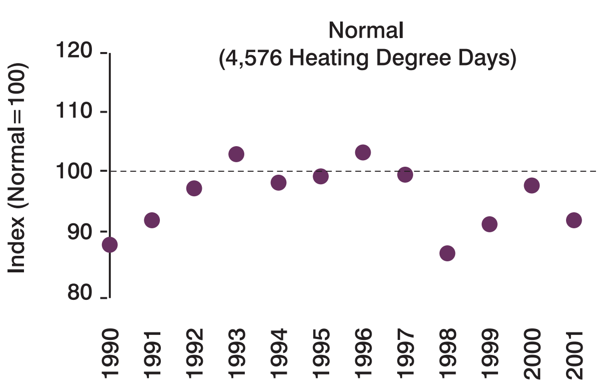
Electricity Generation

The process of generating electricity is the single largest source of CO_2 emissions in the United States (39 percent). Electricity was consumed primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 2-15). Electricity generation also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 40 percent in 2001.

The electric power industry includes all power producers, consisting of both regulated utilities and nonutilities (e.g., independent power producers, qualifying cogenerators, and other small power producers). While utilities primarily generate power for the U.S. electric grid for sale to retail customers, nonutilities produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g., to utilities for distribution and resale to

Figure 2-13

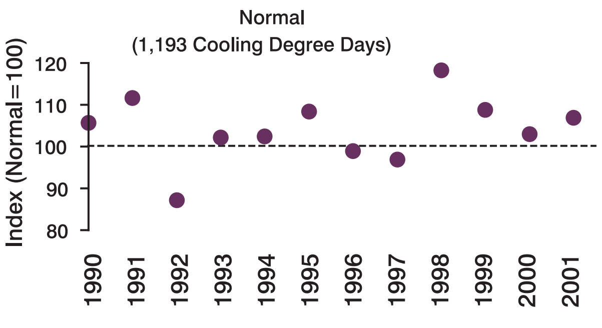
Heating Degree Days [14]



Note: Excludes Alaska and Hawaii
Source: Annual Energy Review, EIA (2002a), Table 1.7

Figure 2-14

Cooling Degree Days [15]



Note: Excludes Alaska and Hawaii
Source: Annual Energy Review, EIA (2002a), Table 1.8

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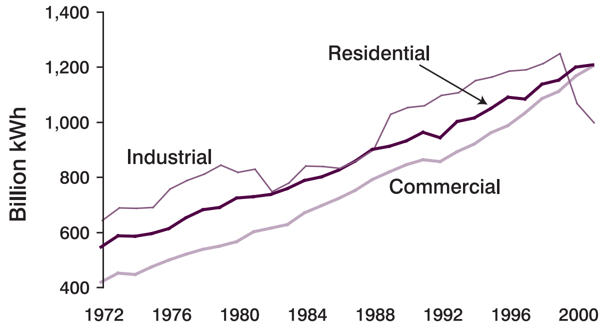
[14] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990.

[15] Degree days are relative measurements of outdoor air temperature. 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.

Figure 2-15

Electricity Generation Retail Sales by End-Use Sector



Note: The transportation end-use sector consumes minor quantities of electricity.
Source: Annual Energy Review, EIA (2002a), Table 8.5

customers). However, the electric power industry in the United States has been undergoing significant changes as both Federal and State government agencies have modified regulations to create a more competitive market for electricity generation. These changes have led to the growth of nonutility power producers, including the sale of generating capacity by electric utilities to nonutilities. Due to this restructuring, the distinction between utilities and non-utilities has become much less meaningful. As a result, the Department of Energy no longer categorizes electric power generation into these ownership groups, and is instead using two new functional categories: electricity-only and combined-heat-and-power. Electricity-only plants are those that solely produce electricity, whereas combined-heat-and-power plants produce both electricity and heat.[16]

In 2001, CO_2 emissions from electricity generation decreased by 1.5 percent relative to the previous year, coinciding with decreased electricity consumption and a slowly growing U.S. economy. An additional factor contributing to the decrease in emissions was the power crisis in California. Emissions decreased despite a reduction in the volume and share of generation of electricity from renewable resources, including a 24 percent reduction in output from hydroelectric dams, which was replaced by additional fossil fuel consumption to produce electricity. The overall carbon intensity from energy consumption for electricity generation increased (see Table 2-9) as a result.

Coal is consumed primarily by the electric power sector in the United States, which accounted for 90 percent of total coal consumption for energy purposes in 2001. Consequently, changes in electricity demand have a significant impact on coal consumption and associated U.S. CO_2 emissions. Coal consumption for electricity generation decreased by 2.6 percent in 2001, due to a reduction in electricity demand and fuel-switching from coal to natural gas and petroleum, which increased consumption of both fuels.

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.* Total fossil fuel consumption for each year is estimated by aggregating consumption data by end-use 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.). The United States does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately.[17] Portions of the fuel consumption data for three fuel categories—coking coal, petroleum coke, and natural gas—were reallocated to the industrial processes chapter, as they were actually consumed during non-energy related industrial activity.[18]
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

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[16] Refer to Appendix H in EIA's Annual Energy Review 2001 for a more detailed explanation of recent changes in the U.S. electric power sector and the new classification system.

[17] 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 of 53 Tg CO_2 Eq. in 2000.

[18] See sections on Iron and Steel Production, Ammonia Manufacture, Titanium Dioxide Production, Ferroalloy Production, and Aluminum Production in the Industrial Processes chapter.

Box 2-2: Carbon Intensity of U.S. Energy Consumption

Fossil fuels are the dominant source of energy in the United States, and CO_2 is emitted as a product from their combustion. Useful energy, however, can be generated from many other sources that do not emit CO_2 in the energy conversion process. In the United States, useful energy is also produced from renewable (i.e., hydropower, biofuels, geothermal, solar, and wind) and nuclear sources.[19]

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 from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that carbon that is oxidized.[20] Fossil fuels vary in their average carbon content, ranging from about 53 Tg CO_2 Eq./QBtu for natural gas to upwards of 95 Tg CO_2 Eq./QBtu for coal and petroleum coke.[21] In general, the carbon content per unit of energy 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 Tg CO_2 Eq./Btu). 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 their combustion is assumed to be offset by the carbon sequestered in the growth of new biomass.[22] 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 2-8 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 is related to the large percentage of its energy derived from natural gas for heating. The carbon intensity of the commercial sector has declined since 1990 to a comparable level in 2001, as commercial businesses shift 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, both around 70 Tg CO_2 Eq./EJ), which were the primary sources of energy. Lastly, the electricity generation sector had the highest carbon intensity due to its heavy reliance on coal for generating electricity.

In contrast to Table 2-8, Table 2-9 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 electricity generation and the end-use sectors in which that electricity was eventually consumed.[23] This table, therefore, provides a more complete picture of the actual carbon intensity of each end-use sector per unit of energy consumed. The transportation end-use sector in Table 2-9 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

Table 2-8: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (Tg CO_2 Eq./QBtu)

Sector	1990	1995	1996	1997	1998	1999	2000	2001
Residential[a]	56.6	56.4	56.4	56.5	56.4	56.5	56.4	56.5
Commercial[a]	59.2	57.6	57.5	57.3	57.0	57.0	57.0	57.0
Industrial[a]	64.1	63.3	63.2	63.5	62.9	62.7	62.9	62.7
Transportation[a]	70.6	70.4	70.4	70.3	70.3	70.4	70.5	70.5
Electricity Generation[b]	86.6	85.7	86.6	86.4	85.7	85.5	85.4	85.1
U.S. Territories[c]	73.3	73.0	72.6	72.5	72.7	73.0	72.5	72.1
All Sectors[c]	**72.4**	**71.9**	**72.0**	**72.2**	**72.3**	**72.3**	**72.3**	**72.3**

[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.

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[19] Small quantities of CO_2, however, are released from some geologic formations tapped for geothermal energy. These emissions are included with fossil fuel combustion emissions from the electricity generation. Carbon dioxide emissions may also be generated from upstream activities (e.g., manufacture of the equipment) associated with fossil fuel and renewable energy activities, but are not accounted for here.

[20] Generally, more than 97 percent of the carbon in fossil fuel is oxidized to CO_2 with most carbon combustion technologies used in the United States.

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

[22] 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.

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

Table 2-9: Carbon Intensity from all Energy Consumption by Sector (Tg CO_2 Eq./QBtu)

Sector	1990	1995	1996	1997	1998	1999	2000	2001
Transportation[a]	70.4	70.1	70.1	70.0	70.0	70.0	70.1	70.1
Other End-Use Sectors[a, b]	62.8	61.6	61.7	63.1	63.5	63.2	63.5	63.4
Electricity Generation[c]	58.8	57.1	57.5	58.8	59.1	58.3	59.3	59.7
All Sectors[d]	**61.1**	**60.1**	**60.1**	**60.8**	**61.0**	**60.7**	**61.1**	**61.4**

[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.

amount of biomass based fuels such as ethanol. The "other end-use sectors" (i.e., residential, commercial, and industrial) use significant quantities of biofuels such as wood, thereby lowering the overall carbon intensity. The carbon intensity of the electricity generation sector differs greatly from the scenario in Table 2-8, 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 CO_2.

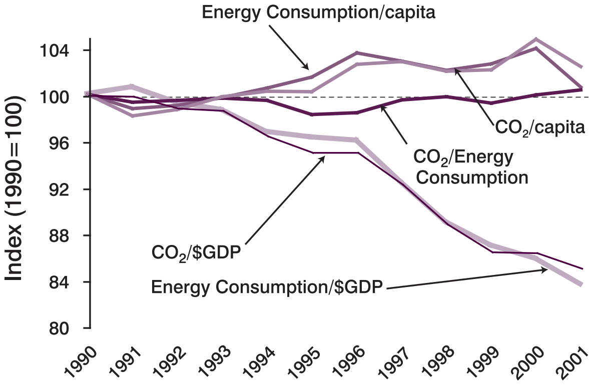
By comparing the values in Table 2-8 and Table 2-9, a few observations can be made. The use of renewable and nuclear energy sources has resulted in a significantly lower carbon intensity of the U.S. economy. Over the eleven-year period of 1990 through 2001, however, the carbon intensity of U.S. energy consumption has been fairly constant, as the proportion of renewable and nuclear energy technologies has not changed significantly.

Although the carbon intensity of total energy consumption has remained fairly constant, per capita energy consumption has increased, leading to greater energy-related CO_2 emissions per capita in the United States since 1990 (see Figure 2-16). Due to structural changes and the strong growth in the U.S. economy, though, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have declined since 1990.

Figure 2-17 and Table 2-10 present the detailed CO_2 emission trends underlying the carbon intensity differences and changes described in Table 2-8. In Figure 2-17, changes over time in both overall end-use sector-related emissions and electricity-related emissions for each year since 1990 are highlighted. In Table 2-10 changes in emissions since 1990 are presented by sector and fuel type to provide a more detailed accounting.

Figure 2-16

U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



Source: BEA (2002), U.S. Census (2002), and emission and energy consumption estimates in this report.

Figure 2-17

Change in CO_2 Emissions from Fossil Fuel Combustion Since 1990 by End-Use Sector

Dark shaded columns relate to changes in emissions from electricity consumption. Lightly shaded columns relate to changes in emissions from both electricity and direct fossil fuel combustion.

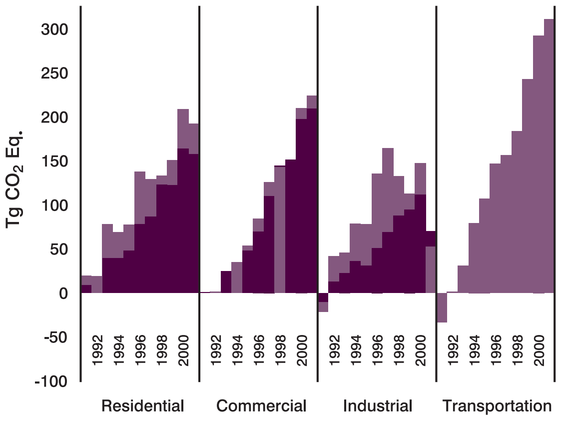


Table 2-10: Change in CO_2 Emissions from Direct Fossil Fuel Combustion Since 1990 (Tg CO_2 Eq.)

Sector/Fuel Type	1991	1995	1996	1997	1998	1999	2000	2001
Residential	**10.8**	**29.7**	**59.7**	**42.8**	**10.0**	**28.4**	**45.0**	**34.4**
Coal	(0.3)	(0.9)	(0.9)	(1.0)	(1.2)	(1.2)	(1.3)	(1.3)
Natural Gas	9.2	24.2	45.4	31.4	7.7	17.7	31.6	22.0
Petroleum	1.9	6.3	15.2	12.4	3.5	11.9	14.8	13.8
Commercial	**0.8**	**5.4**	**14.9**	**15.6**	**(2.0)**	**0.2**	**12.9**	**14.4**
Coal	(1.0)	(1.2)	(0.7)	(0.1)	(3.6)	(2.6)	(3.7)	(3.7)
Natural Gas	5.9	21.8	28.7	31.7	21.0	22.6	31.7	33.3
Petroleum	(4.1)	(15.1)	(13.0)	(16.0)	(19.4)	(19.9)	(15.1)	(15.1)
Industrial	**(11.8)**	**47.2**	**84.2**	**95.5**	**44.8**	**17.9**	**35.8**	**(17.7)**
Coal	(0.5)	(2.8)	(6.4)	(5.2)	(13.9)	(19.9)	(17.6)	(25.3)
Natural Gas	6.4	58.9	74.7	75.8	64.1	46.5	59.0	25.5
Petroleum	(17.7)	(8.8)	15.9	24.8	(5.5)	(8.7)	(5.6)	(17.9)
Transportation	**(33.4)**	**107.4**	**146.9**	**156.5**	**183.5**	**242.6**	**292.3**	**310.4**
Coal	-	-	-	-	-	-	-	-
Natural Gas	(3.2)	2.3	3.0	5.2	(0.8)	(0.3)	(0.4)	(2.0)
Petroleum	(30.2)	105.1	144.0	151.3	184.2	242.9	292.7	312.4
Electricity Generation	**(0.3)**	**126.8**	**198.9**	**265.9**	**355.4**	**368.5**	**472.8**	**437.8**
Coal	1.7	113.1	203.7	247.8	278.5	287.2	376.6	326.6
Natural Gas	4.1	53.0	29.7	43.6	72.7	84.7	105.3	109.6
Petroleum	(6.1)	(39.3)	(34.5)	(25.5)	4.2	(3.4)	(9.1)	1.7
Geothermal	0.0	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
U.S. Territories	**5.6**	**10.3**	**6.4**	**9.1**	**14.2**	**16.4**	**18.6**	**20.7**
Coal	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Natural Gas	-	-	-	-	-	-	-	-
Petroleum	5.5	10.0	6.1	8.7	13.9	16.2	17.7	19.2
All Sectors	**(28.4)**	**326.8**	**511.0**	**585.3**	**605.8**	**674.0**	**877.4**	**800.1**

+ Does not exceed 0.05 Tg CO_2 Eq.
NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

of carbon that could potentially be released to the atmosphere if all of the carbon in each fuel was converted to CO_2. The carbon content coefficients used by the United States are presented in Annexes A and B.

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. Because U.S. aggregate energy statistics include consumption of fossil fuels for non-energy uses, the portion of carbon that remains in products after they are manufactured was subtracted from potential carbon emission estimates.[24] 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 end-use sectors and U.S. territories. Emissions of CO_2 associated with the disposal of these fossil fuel-based products are not accounted for here, but are instead accounted for under the Waste Combustion section in this chapter.

4. *Subtract the amount of carbon from international bunker fuels*. According to the UNFCCC reporting guidelines emissions from international transport activities, or bunker fuels, should not be included in national totals. U.S. energy consumption statistics include these bunker fuels (e.g., distillate fuel oil, residual fuel oil, and jet fuel) as part of consumption by

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[24] See Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter for a more detailed discussion.

the transportation end-use sector, however, so emissions from international transport activities were calculated separately and the carbon content of these fuels was subtracted from the transportation end-use 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).[25]

5. *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). Unoxidized or partially oxidized organic (i.e., carbon containing) combustion products were assumed to have eventually oxidized to CO_2 in the atmosphere.[26]
6. *Allocate transportation emissions by vehicle type.* This report provides a more detailed accounting of emissions from transportation because it was such a large consumer of fossil fuels in the United States.[27] 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. The difference between total U.S. jet fuel consumption (as reported by EIA) and civilian air carrier consumption for both domestic and international flights (as reported by DOT and BEA) plus military jet fuel consumption is reported as "other" under the jet fuel category in Table 2-7, and includes such fuel uses as blending with heating oils and fuel used for chartered aircraft flights.

Data Sources

Fuel consumption data for the United States and its territories, and carbon content of fuels were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE), primarily from the *Annual Energy Review* and other EIA databases (EIA 2002a). 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) (DESC 2002) supplied data on military jet fuel use. Estimates of international bunker fuel emissions are discussed in the section entitled International Bunker Fuels. Estimates of carbon stored in products are discussed in the section entitled Carbon Stored in Products from Non-fuel Uses of Fossil Fuels.

IPCC provided fraction oxidized values for petroleum and natural gas (IPCC/UNEP/OECD/IEA 1997). Bechtel (1993) provided the fraction oxidation value for coal.

Fuel consumption data for the allocation of transportation end-use sector emissions were taken from AAR (2001), Benson (2002), BEA (1991 through 2002), DESC (2002), DOE (1993 through 2002), EIA (2002a), EIA (2002b), EIA (2002c), EIA (1991 through 2002), FAA (1995 through 2002), and FHWA (1996 through 2002), and USAF (1998). For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex E, and Annex J.

Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2002a) and fossil fuel consumption data as discussed above and presented in Annex A.

For consistency of reporting, the IPCC has recommended that countries report energy data 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.[28]

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[25] See International Bunker Fuels section in this chapter for a more detailed discussion.

[26] See Indirect CO_2 from CH_4 Oxidation section in this chapter for a more detailed discussion.

[27] Electricity generation is not considered a final end-use sector, because energy is consumed primarily to provide electricity to the other sectors.

[28] See IPCC Reference Approach for estimating CO_2 emissions from fossil fuel combustion in Annex W for a comparison of U.S. estimates using top-down and bottom-up approaches.

It is also important to note that U.S. fossil fuel energy statistics are generally presented using gross calorific values (GCV) (i.e., higher heating values). 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).[29]

Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted 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 production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the amount of carbon contained in the fuel per unit of useful energy can vary.

Although statistics of total fossil fuel and other energy consumption are relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is less certain. For example, for some fuels the sectoral allocations are based on price rates (i.e., tariffs), but a commercial establishment may be able to negotiate an industrial rate or a small industrial establishment may end up paying an industrial rate, leading to a misallocation of emissions. Also, the deregulation of the natural gas industry and the more recent deregulation of the electric power industry have likely led to some minor problems in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

Non-energy uses of fuel can add complexity because the carbon might not be emitted to the atmosphere (e.g., plastics, asphalt, etc.) or might be emitted at a delayed rate. This report makes assumptions about the proportions of fuels used in these non-energy production processes that result in the sequestration of carbon. 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. More detailed discussions on the uncertainties associated with carbon stored in products from non-energy uses of fossil fuels are provided in that section in this chapter.

Various uncertainties surround the estimation of emissions from international bunker fuels, which are subtracted from U.S. totals. These uncertainties are primarily due to the difficulty in collecting accurate fuel consumption data for international transport activities. Small aircraft and many marine vessels often carry enough fuel to complete multiple voyages without refueling, which, if used for both domestic and international trips, may be classified as solely international. The data collected for aviation does not include some smaller planes making international voyages, and also designates some flights departing to Canada and Mexico as domestic. More detailed discussions on these uncertainties are provided in the International Bunker Fuels section of this chapter.

Another source of uncertainty is fuel consumption by U.S. territories. The United States does not collect energy statistics for its territories at the same level of detail 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 2-7, 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 aggregate fuel-type estimates from EIA. Further research is planned to improve the allocation into detailed transportation end-use sector emissions. In particular, residual fuel consumption data for marine vessels are highly uncertain, as shown by the large fluctuations in emissions.

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

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[29] A crude convention to convert between gross and net calorific values is to multiply the heat content of solid and liquid fossil fuels by 0.95 and gaseous fuels by 0.9 to account for the water content of the fuels. Biomass-based fuels in U.S. energy statistics, however, are generally presented using net calorific values.

Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

Besides being combusted for energy, fossil fuels are also consumed for non-energy purposes. The types of fuels used for non-energy uses are listed in Table 2-11. These fuels are used in the industrial and transportation end-use sectors and are quite diverse, including natural gas, LPG, asphalt (a viscous liquid mixture of heavy crude oil distillates), petroleum coke (manufactured from heavy oil), and coal coke (manufactured from coking coal.) The non-energy fuel uses are equally diverse, and include application as solvents, lubricants, and waxes, or as raw materials in the manufacture of plastics, rubber, synthetic fibers, and fertilizers.

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, more than 64 percent of the total carbon consumed for non-energy purposes is stored in products, and not released to the atmosphere. However, some of the products release CO_2 at the end of their commercial life when they are disposed. These emissions are covered separately in this chapter in the Waste Combustion section.

There is some overlap between fossil fuels consumed for non-energy uses and the fossil-derived CO_2 emissions accounted for in the Industrial Processes chapter. To avoid double-counting, the "raw" non-energy fuel consumption data reported by EIA are adjusted to account for these overlaps, as shown in Table 2-11. In 2001, fossil fuel consumption for non-energy uses constituted 7 percent (5,752.5 TBtu) of overall fossil fuel consumption, approximately the same proportion as in 1990. There are also net exports of petrochemicals that are not completely accounted for in the EIA data, and these affect the total carbon content of non-energy fuels; the effects of these adjustments are also shown in the table. In 2001, the adjusted

Table 2-11: 2001 Non-Energy Fossil Fuel Consumption, Storage, and Emissions (Tg CO_2 Eq. unless otherwise noted)

	Consumption (TBtu)		Carbon Content		Storage	Carbon	
Sector/Fuel Type	Total	Adjusted[a]	Total	Adjusted[b]	Factor	Stored	Emissions
Industry	**6,060.6**	**5,328.6**	**366.5**	**360.1**		**249.7**	**110.4**
Industrial Coking Coal	689.1	24.9	2.3	2.3	0.75	1.8	0.6
Natural Gas to Chemical Plants	333.9	333.9	17.7	17.1	0.61	10.4	6.7
Asphalt & Road Oil	1,257.6	1,257.6	95.1	95.1	1.00	95.1	+
LPG	1,690.4	1,690.4	104.6	101.4	0.61	61.7	39.7
Lubricants	174.3	174.3	12.9	12.9	0.09	1.2	11.7
Pentanes Plus	239.2	239.2	16.0	15.5	0.61	9.5	6.1
Petrochemical Feedstocks							+
Naphtha (<401 deg. F)	493.7	493.7	32.8	31.9	0.61	19.4	12.5
Other Oil (>401 deg. F)	662.5	662.5	48.5	47.2	0.61	28.7	18.5
Still Gas	31.0	31.0	2.0	2.0	0.80	1.6	0.4
Petroleum Coke	181.1	113.2	11.6	11.6	0.50	5.8	5.8
Special Naphtha	78.5	78.5	5.7	5.7	0.00	-	5.7
Distillate Fuel Oil	11.7	11.7	0.9	0.9	0.50	0.4	0.4
Residual Fuel	56.6	56.6	4.5	4.5	0.50	2.2	2.2
Waxes	36.3	36.3	2.6	2.6	1.00	2.6	+
Miscellaneous Products	124.9	124.9	9.3	9.3	1.00	9.3	+
Transportation	**164.6**	**164.6**	**12.2**	**12.2**		**1.1**	**11.1**
Lubricants	164.6	164.6	12.2	12.2	0.09	1.1	11.1
U.S. Territories	**259.3**	**259.3**	**19.0**	**19.0**		**1.9**	**17.1**
Lubricants	1.5	1.5	0.1	0.1	0.09	+	0.1
Other Petroleum (Misc. Prod.)	257.8	257.8	18.9	18.9	0.10	1.9	17.0
Total	**6,484.5**	**5,752.5**	**397.7**	**391.3**	**0.65**	**252.8**	**138.6**

[a] To avoid double-counting, coal coke, petroleum coke, and natural gas consumption are adjusted for industrial process consumption addressed in the Industrial Process chapter.

[b] Natural gas, LPG, Pentanes Plus, Naphthas, and Other Oils are adjusted to account for exports of chemical intermediates derived from these fuels.

\- Not applicable.

Note: Totals may not sum due to independent rounding.

Table 2-12: Storage and Emissions from Non-Energy Fossil Fuel Consumption (Tg CO_2 Eq.)

Variable	1990	1995	1996	1997	1998	1999	2000	2001
Potential Emissions	324.8	362.9	372.4	385.5	402.3	427.9	410.8	391.3
Carbon Stored	214.5	238.1	240.9	249.7	258.5	271.9	263.6	252.8
Emissions	110.4	124.8	131.6	135.8	143.8	156.0	147.2	138.6

carbon content of fuels consumed for non-energy uses was approximately 391.3 Tg CO_2 Eq., an increase of 20 percent since 1990. About 252.8 Tg CO_2 Eq. of this carbon was stored, while the remaining 138.6 Tg CO_2 Eq. was emitted. The proportion of carbon emitted has remained about the same, at about 34 to 36 percent of total non-energy consumption, since 1990. Table 2-12 shows the fate of the non-energy fossil fuel carbon for 1990 and 1995 through 2001.

Methodology

The first step in estimating carbon stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The carbon content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific carbon content values (see Annex A). Consumption of natural gas, LPG, pentanes plus, naphthas, and other oils were adjusted to account for net exports of these products. Consumption values for industrial coking coal, petroleum coke, and natural gas in Table 2-11 are adjusted to subtract non-energy uses that are addressed in the Industrial Process chapter.[30]

For the remaining non-energy uses, the amount of carbon stored was estimated by multiplying the potential emissions by a storage factor. For several fuel types, such as petrochemical feedstocks, liquid petroleum gases (LPG), pentanes plus, natural gas for non-fertilizer uses, asphalt and road oil, and lubricants, U.S. data on carbon stocks and flows were used to develop carbon storage factors, calculated as the ratio of (a) the carbon stored by the fuel's non-energy products to (b) the total carbon content of the fuel consumed. A lifecycle approach was used in the development of these factors in order to account for losses in the production process and during use. Annex C provides more details of these calculations. Because losses associated with municipal solid waste management are handled separately in this chapter under Waste Combustion, the storage factors do not account for losses at the disposal end of the life cycle. For the other fuel types, the storage factors were taken directly from Marland and Rotty (1984).

Lastly, emissions were estimated by subtracting the carbon stored from the potential emissions.

Data Sources

Non-energy fuel consumption and carbon content data were supplied by the EIA (2001a).

Where storage factors were calculated specifically for the United States, data was obtained on fuel products such as asphalt, plastics, synthetic rubber, synthetic fibers, pesticides, and solvents. Data was taken from a variety of industry sources, government reports, and expert communications. Sources include EPA compilations of air emission factors (EPA 1995, EPA 2001), the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 2001b), the National Petrochemical & Refiners Association (NPRA 2001), the National Asphalt Pavement Association (Connolly 2000), the Emissions Inventory Improvement Program (EIIP 1999), the U.S. Census Bureau (1999), the American Plastics Council (APC 2000), the International Institute of Synthetic Rubber Products (IISRP 2000), the Fiber Economics Bureau (FEB 2000), and the Chemical Manufacturer's Handbook (CMA 1999). For the other fuel types, storage factors were taken from Marland and Rotty (1984). Specific data sources are listed in full detail in Annex C.

Uncertainty

The fuel consumption data for non-energy uses and the carbon content values employed here were taken from the same references as the data used for estimating overall CO_2 emissions from fossil fuel combustion. In addition, data used to make adjustments to the fuel consumption estimates were taken from several sources. Given that the uncertainty in these data is expected to be small, the uncertainty of the

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[30] These source categories include Iron and Steel Production, Ammonia Manufacture, Titanium Dioxide Production, Ferroalloy Production, and Aluminum Production.

estimate for the potential carbon emissions is also expected to be small. However, there is a large degree of uncertainty in the storage factors employed, depending upon the fuel type. For each of the calculated storage factors, the uncertainty is discussed in detail in Annex C. Generally, uncertainty arises from assumptions made to link fuel types with their derivative products and in determining the fuel products' carbon contents and emission or storage fates. The storage factors from Marland and Rotty (1984) are also highly uncertain.

Stationary Combustion (excluding CO_2)

Stationary combustion encompasses all fuel combustion activities except those related to transportation (i.e., mobile combustion). Other than CO_2, which was addressed in the previous section, gases from stationary combustion include the greenhouse gases CH_4 and N_2O and the ambient air pollutants NO_x, CO, and NMVOCs.[31] Emissions of these gases from stationary combustion sources depend upon fuel characteristics, size and vintage, along with combustion technology, pollution control equipment, and ambient environmental conditions. Emissions also vary with operation and maintenance 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; 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, shutdown 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 and NMVOC content of the fuel and combustion efficiency.

Emissions of CH_4 decreased 9 percent overall from 8.1 Tg CO_2 Eq. (388 Gg) in 1990 to 7.4 Tg CO_2 Eq. (353 Gg) in 2001. This decrease in CH_4 emissions was primarily due to lower wood consumption in the residential sector. Conversely, N_2O emissions rose 13 percent since 1990 to 14.2 Tg CO_2 Eq. (46 Gg) in 2001. The largest source of N_2O emissions was coal combustion by electricity generators, which alone accounted for 60 percent of total N_2O emissions from stationary combustion in 2001. Overall, however, 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 2001, emissions of NO_x from stationary combustion represented 39 percent of national NO_x emissions, while CO and NMVOC emissions from stationary combustion contributed approximately 4 and 7 percent, respectively, to the national totals. From 1990 to 2001, emissions of NO_x and CO from stationary combustion decreased by 21 and 17 percent, respectively, and emissions of NMVOCs increased by 19 percent.

The decrease in NO_x emissions from 1990 to 2001 are mainly due to decreased emissions from electricity generation. The decrease in CO and increase in NMVOC emissions over this time period can largely be attributed to apparent changes in residential wood use, which is the most significant source of these pollutants from stationary combustion. Table 2-13 through Table 2-16 provide CH_4 and N_2O emission estimates from stationary combustion by sector and fuel type. Estimates of NO_x, CO, and NMVOC emissions in 2001 are given in Table 2-17.[32]

Methodology

Methane and N_2O 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, residential, and electricity generation.

For NO_x, CO, and NMVOCs, the major categories included in this section are those used in EPA (2003): 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.

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

[32] See Annex D for a complete time series of ambient air pollutant emission estimates for 1990 through 2001.

Table 2-13: CH_4 Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001
Electricity Generation	**0.6**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**
Coal	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Fuel Oil	0.1	0.0	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
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Industrial	**2.2**	**2.5**	**2.5**	**2.5**	**2.4**	**2.4**	**2.4**	**2.4**
Coal	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Natural gas	0.8	0.9	1.0	1.0	0.9	0.9	0.9	0.9
Wood	0.9	1.0	1.1	1.0	1.0	1.0	1.0	1.0
Commercial	**0.7**	**0.8**	**0.8**	**0.9**	**0.8**	**0.8**	**0.9**	**0.8**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.2
Natural gas	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Wood	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Residential	**4.6**	**4.7**	**4.7**	**3.6**	**3.3**	**3.5**	**3.7**	**3.5**
Coal	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Wood	3.7	3.8	3.8	2.6	2.4	2.6	2.7	2.6
Total	**8.1**	**8.5**	**8.7**	**7.5**	**7.2**	**7.4**	**7.6**	**7.4**

\+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 2-14: N_2O Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001
Electricity Generation	**7.6**	**8.0**	**8.5**	**8.7**	**8.9**	**8.9**	**9.3**	**9.1**
Coal	7.1	7.6	8.0	8.2	8.4	8.4	8.8	8.6
Fuel Oil	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
Wood	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Industrial	**3.5**	**3.7**	**3.8**	**3.7**	**3.6**	**3.5**	**3.6**	**3.8**
Coal	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.9
Fuel Oil	0.8	0.7	0.7	0.7	0.7	0.6	0.7	0.7
Natural Gas	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Wood	1.8	2.1	2.1	2.0	2.0	2.0	2.0	2.0
Commercial	**0.4**	**0.3**	**0.4**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0
Fuel Oil	0.2	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
Wood	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residential	**1.1**	**1.2**	**1.2**	**1.0**	**0.9**	**0.9**	**1.0**	**0.9**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	0.2	0.3	0.3	0.3	0.2	0.3	0.3	0.3
Natural Gas	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2
Wood	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5
Total	**12.5**	**13.2**	**13.8**	**13.7**	**13.7**	**13.7**	**14.3**	**14.2**

\+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 2-15: CH_4 Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001
Electricity Generation	**27**	**28**	**29**	**30**	**32**	**32**	**33**	**33**
Coal	16	18	18	19	19	19	20	20
Fuel Oil	4	2	2	3	4	4	3	4
Natural Gas	3	4	4	4	5	5	5	5
Wood	4	4	4	4	4	4	4	4
Industrial	**107**	**118**	**120**	**118**	**115**	**113**	**115**	**116**
Coal	16	16	15	16	15	14	14	20
Fuel Oil	8	7	8	8	7	7	7	7
Natural Gas	39	45	46	46	45	43	45	42
Wood	43	50	51	48	48	48	49	48
Commercial	**36**	**38**	**40**	**41**	**38**	**39**	**41**	**38**
Coal	1	1	1	1	1	1	1	1
Fuel Oil	9	7	7	7	7	7	7	7
Natural Gas	14	16	16	17	16	16	17	17
Wood	12	14	15	16	14	16	16	13
Residential	**218**	**223**	**226**	**169**	**157**	**168**	**175**	**166**
Coal	8	5	5	5	4	4	4	4
Fuel Oil	13	14	15	15	13	15	15	15
Natural Gas	23	25	27	26	23	24	26	25
Wood	175	179	179	124	116	124	130	122
Total	**388**	**406**	**415**	**358**	**342**	**351**	**363**	**353**

\+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding

Table 2-16: N_2O Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001
Electricity Generation	**24**	**26**	**27**	**28**	**29**	**29**	**30**	**30**
Coal	23	25	26	27	27	27	28	28
Fuel Oil	1	+	+	1	1	1	1	1
Natural Gas	+	+	+	+	+	+	1	1
Wood	+	1	1	1	1	1	1	1
Industrial	**11**	**12**	**12**	**12**	**12**	**11**	**12**	**12**
Coal	2	2	2	2	2	2	2	3
Fuel Oil	2	2	2	2	2	2	2	2
Natural Gas	1	1	1	1	1	1	1	1
Wood	6	7	7	6	6	6	7	6
Commercial	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	1	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Residential	**4**	**4**	**4**	**3**	**3**	**3**	**3**	**3**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	1	1	1	1	1	1	1	1
Natural Gas	+	+	1	1	+	+	1	+
Wood	2	2	2	2	2	2	2	2
Total	**40**	**43**	**45**	**44**	**44**	**44**	**46**	**46**

\+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.

Table 2-17: NO_x, CO, and NMVOC Emissions from Stationary Combustion in 2001 (Gg)

Sector/Fuel Type	NO_x	CO	NMVOC
Electric Generation	**4,437**	**445**	**57**
Coal	3,782	223	27
Fuel Oil	148	28	5
Natural gas	330	93	13
Other Fuels[a]	NA	NA	NA
Wood	37	33	2
Internal Combustion	140	68	11
Industrial	**2,393**	**1,071**	**152**
Coal	496	118	10
Fuel Oil	147	43	8
Natural gas	875	345	52
Wood	NA	NA	NA
Other Fuels[a]	111	303	28
Internal Combustion	764	263	54
Commercial/Institutional	**384**	**149**	**38**
Coal	28	13	1
Fuel Oil	72	16	4
Natural gas	227	80	15
Wood	NA	NA	NA
Other Fuels[a]	57	40	19
Residential	**611**	**2,503**	**839**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	30	2,292	812
Other Fuels	582	211	27
Total	**7,826**	**4,169**	**1,087**

NA (Not Available)

[a] Includes LPG, waste oil, coke oven gas, and coke (EPA 2003).

[b] Coal, fuel oil, and natural gas emissions are included in "Other Fuels" (EPA 2003).

Note: Totals may not sum due to independent rounding.

See Annex D for emissions in 1990 through 2001.

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 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 combustion, including emission factors and activity data, is provided in Annex D.

Data Sources

Emissions estimates for NO_x, CO, and NMVOCs in this section were taken directly from EPA data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2003). Fuel consumption data for CH_4 and N_2O estimates were provided by the U.S. Energy Information Administration's *Annual Energy Review* (EIA 2002). Estimates for wood biomass consumption for fuel combustion do not include wood wastes, liquors, municipal solid waste, tires, etc. that are reported as biomass by EIA. 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 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 ambient air 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 CH_4, N_2O, and the ambient air pollutants NO_x, CO, and NMVOCs. While air conditioners and refrigerated units in vehicles also emit hydrofluorocarbons (HFCs), these are covered in Chapter 3, Industrial Processes, under the section entitled Substitution of Ozone Depleting Substances. 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, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur 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.

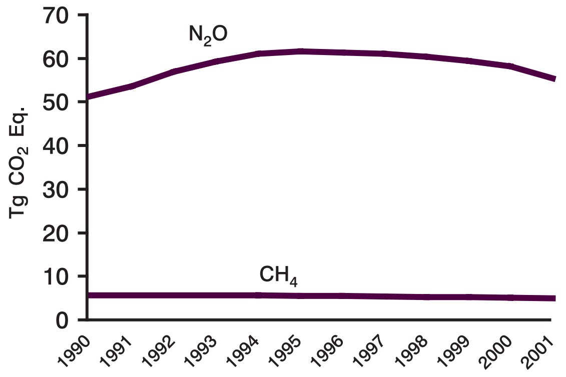
Emissions from mobile combustion were estimated by transport mode (e.g., highway, air, rail), fuel type (e.g., motor gasoline, diesel fuel, jet fuel), and vehicle type (e.g., passenger cars, light-duty trucks). Road transport accounted for the majority of mobile source fuel consumption, and hence, the majority of mobile combustion emissions. Table 2-18 through Table 2-21 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 2001 are given in Table 2-22.[33]

Mobile combustion was responsible for a small portion (0.7 percent) of national CH_4 emissions but was the second largest source of N_2O (13 percent) in the United States. From 1990 to 2001, CH_4 emissions declined by 13 percent, to 4.3 Tg CO_2 Eq. (204 Gg). During the same time period, N_2O emissions rose by 8 percent to 54.8 Tg CO_2 Eq. (177 Gg) (see Figure 2-18). The reason for this conflicting trend was that the control technologies employed on highway vehicles in the United States reduced CO, NO_x, NMVOC, and CH_4 emissions, but resulted in higher average N_2O emission rates. However, 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 predominantly from gasoline-fueled passenger cars and light-duty gasoline trucks.

Fossil-fueled motor vehicles comprise the single largest source of CO, NO_x, and NMVOC emissions in the United States. In 2001, mobile combustion contributed 90 percent of CO emissions, 56 percent of NO_x emissions, and 45 percent of NMVOC emissions.

Figure 2-18

Mobile Source CH_4 and N_2O Emissions



Since 1990, emissions of NMVOCs from mobile combustion decreased by 38 percent, CO emissions decreased 24 percent, and emissions of NO_x decreased by 7 percent.

Methodology

Estimates of 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 for gasoline and diesel highway vehicles were based on VMT and emission factors by vehicle type, fuel type, model year, and control technology. Emissions from alternative fuel vehicles (AFVs)[34] were based on VMT by vehicle and fuel type. Fuel consumption data were employed as a measure of activity for non-highway vehicles and then fuel-specific emission factors were applied.[35] A complete discussion of the methodology used to estimate emissions from mobile combustion is provided in Annex E.

EPA (2003) provided emissions estimates of NO_x, CO, and NMVOCs for eight categories of highway vehicles,[36] aircraft, and seven categories of off-highway vehicles.[37]

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[33] See Annex E for a complete time series of emission estimates for 1990 through 2001.

[34] Alternative fuel and advanced technology vehicles are those that can operate using a motor fuel other than gasoline or diesel. This includes electric or other bifuel or dual fuel vehicles that may be partially powered by gasoline or diesel.

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

[36] 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.

[37] 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.

Data Sources

Emission factors used in the calculations of CH_4 and N_2O emissions are presented in Annex E. The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provided most of the emission factors for CH_4, and were developed using MOBILE5a, a model used by the Environmental Protection Agency (EPA) to estimate exhaust and running loss emissions from highway vehicles. The MOBILE5a model uses information on ambient

Table 2-18: CH_4 Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	1995	1996	1997	1998	1999	2000	2001
Gasoline Highway	**4.3**	**4.1**	**4.0**	**3.9**	**3.8**	**3.7**	**3.6**	**3.4**
Passenger Cars	2.4	2.0	2.0	2.0	2.0	1.9	1.9	1.8
Light-Duty Trucks	1.6	1.8	1.8	1.7	1.6	1.6	1.5	1.5
Heavy-Duty Vehicles	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+
Diesel Highway	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Alternative Fuel Highway	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Highway	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.5**	**0.5**	**0.5**
Ships and Boats	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
Farm Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Construction Equipment	+	+	+	+	+	+	+	+
Aircraft	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.1
Other[b]	+	+	+	+	+	+	+	+
Total	**5.0**	**4.9**	**4.8**	**4.7**	**4.6**	**4.5**	**4.4**	**4.3**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.
[a] See Annex E for definitions of highway vehicle types.
[b] "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-19: N_2O Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001
Gasoline Highway	**45.6**	**55.2**	**54.9**	**54.4**	**53.7**	**52.5**	**51.0**	**48.4**
Passenger Cars	30.9	33.4	33.0	32.5	32.2	31.2	30.2	28.6
Light-Duty Trucks	13.9	20.9	20.8	20.9	20.4	20.2	19.6	18.6
Heavy-Duty Vehicles	0.7	1.0	1.0	1.1	1.1	1.1	1.1	1.1
Motorcycles	+	+	+	+	+	+	+	+
Diesel Highway	**2.0**	**2.6**	**2.6**	**2.8**	**2.9**	**3.0**	**3.0**	**3.1**
Passenger Cars	0.1	0.1	0.1	0.1	0.1	+	+	+
Light-Duty Trucks	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Heavy-Duty Vehicles	1.8	2.3	2.4	2.5	2.6	2.7	2.7	2.8
Alternative Fuel Highway	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**
Non-Highway	**2.9**	**3.0**	**3.1**	**2.9**	**2.9**	**3.1**	**3.3**	**3.1**
Ships and Boats	0.4	0.5	0.4	0.3	0.3	0.4	0.5	0.3
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Farm Equipment	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Construction Equipment	0.1	0.1	0.1	0.2	0.2	0.1	0.2	0.2
Aircraft	1.7	1.7	1.8	1.7	1.8	1.8	1.9	1.8
Other*	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Total	**50.6**	**60.9**	**60.7**	**60.3**	**59.7**	**58.8**	**57.5**	**54.8**

+ Does not exceed 0.05 Tg CO_2 Eq.
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.

temperature, vehicle speeds, national vehicle registration distributions, gasoline volatility, and other variables in order to produce these factors (EPA 1997). Emission factors for CH_4 for Tier 1 and LEV[38] heavy-duty gasoline vehicles were determined using emission factors from the California Air Resources Board mobile source emissions factor model for 2002 (CARB 2000).

Table 2-20: CH_4 Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001
Gasoline Highway	**203**	**195**	**189**	**185**	**180**	**174**	**169**	**163**
Passenger Cars	116	97	95	93	93	91	89	87
Light-Duty Trucks	75	88	85	82	78	76	73	69
Heavy-Duty Vehicles	9	7	6	6	5	5	5	4
Motorcycles	4	4	4	3	3	3	3	2
Diesel Highway	**11**	**13**	**13**	**14**	**14**	**14**	**14**	**14**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	10	13	13	13	13	13	13	13
Alternative Fuel Highway	**1**	**2**	**3**	**3**	**4**	**5**	**5**	**6**
Non-Highway	**21**	**22**	**22**	**21**	**20**	**21**	**23**	**22**
Ships and Boats	3	4	4	3	2	4	5	3
Locomotives	3	3	3	3	3	3	3	3
Farm Equipment	6	6	6	6	5	5	5	6
Construction Equipment	1	1	1	1	1	1	1	1
Aircraft	7	7	7	7	7	7	7	7
Other*	1	1	1	1	1	1	1	1
Total	**236**	**232**	**227**	**223**	**217**	**214**	**211**	**204**

\+ 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: N_2O Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999	2000	2001
Gasoline Highway	**147**	**178**	**177**	**176**	**173**	**169**	**164**	**156**
Passenger Cars	100	108	106	105	104	101	97	92
Light-Duty Trucks	45	67	67	67	66	65	63	60
Heavy-Duty Vehicles	2	3	3	3	4	4	4	3
Motorcycles	+	+	+	+	+	+	+	+
Diesel Highway	**7**	**8**	**9**	**9**	**9**	**10**	**10**	**10**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	1	1	1	1	1	1	1
Heavy-Duty Vehicles	6	7	8	8	8	9	9	9
Alternative Fuel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**1**	**1**
Non-Highway	**9**	**10**	**10**	**9**	**9**	**10**	**11**	**10**
Ships and Boats	1	1	1	1	1	1	2	1
Locomotives	1	1	1	1	1	1	1	1
Farm Equipment	1	1	1	1	1	1	1	1
Construction Equipment	+	+	+	+	+	+	1	1
Aircraft	6	5	6	6	6	6	6	6
Other*	+	+	+	+	+	+	+	1
Total	**163**	**197**	**196**	**195**	**192**	**190**	**185**	**177**

\+ 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.

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[38] See Annex E for definitions of control technology levels.

Table 2-22: NO_x, CO, and NMVOC Emissions from Mobile Combustion in 2001 (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**3,942**	**66,857**	**4,217**
Passenger Cars	2,150	37,250	2,355
Light-Duty Trucks	1,363	26,611	1,638
Heavy-Duty Vehicles	414	2,842	203
Motorcycles	12	181	38
Diesel Highway	**3,542**	**1,025**	**204**
Passenger Cars	6	7	3
Light-Duty Trucks	6	6	4
Heavy-Duty Vehicles	3,530	1,011	198
Non-Highway	**3,770**	**22,387**	**2,379**
Ships and Boats	971	1,952	730
Locomotives	907	90	35
Farm Equipment	480	621	72
Construction Equipment	690	1,041	125
Aircraft[a]	73	233	19
Other[b]	650	18,449	1,397
Total	**11,254**	**90,268**	**6,800**

NE = Not Estimated.

[a] Aircraft estimates include only emissions related to landing and take-off (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 E for emissions from 1990 through 2001.

Emission factors for N_2O from gasoline passenger cars are 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).

Nitrous oxide emission factors for most gasoline vehicles other than passenger cars (i.e., light-duty gasoline trucks, heavy-duty gasoline vehicles, and motorcycles) were scaled from N_2O factors from passenger cars with the same control technology, based on their relative fuel economy. Fuel economy for each vehicle category was derived from data in DOE (1993 through 2001), FHWA (1996 through 2002), EPA/DOE (2001), and Census (2000). 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, and will be replaced as additional testing data become available. Emission factors for N_2O for Tier 1 and LEV heavy-duty gasoline vehicles were estimated from the ratio of NO_x emissions to N_2O emissions for Tier 0 heavy-duty gasoline trucks.[39]

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). Little data exists 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.

Emission factors for AFVs were developed after consulting a number of sources, including Argonne National Laboratory's GREET 1.5 – Transportation Fuel Cycle Model (Wang 1999), Lipman and Delucchi (2002), the Auto/Oil Air Quality Improvement Research Program (1997), the California Air Resources Board (Brasil and McMahon 1999), and the University of California Riverside (Norbeck, et al., 1998). The primary approach taken was to calculate CH_4 emissions from actual test data and determine N_2O emissions from NO_x emissions from the same tests. A complete discussion of the data source and methodology used to determine emission factors from AFVs is provided in Annex E.

Activity data were gathered from several U.S. government sources including BEA (1991 through 2001), Census (2000), DESC (2001), DOC (1991 through 2001), DOT (1991 through 2001), EIA (2002a), EIA (2002b), EIA (2002c), EIA (2002d), EIA (1991 through 2002), EPA/DOE (2001), FAA (1995 through 2002), and FHWA (1996 through 2002). Control technology and standards data for highway vehicles were

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[39] See Annex E for definitions of control technology levels.

obtained from the EPA's Office of Transportation and Air Quality (EPA 2002a, 2002b, 2000, 1998, and 1997). These technologies and standards are defined in Annex E, and were compiled from EPA (1993), EPA (1994a), EPA (1994b), EPA (1998), EPA (1999), and IPCC/UNEP/OECD/IEA (1997). Annual VMT data for 1990 through 2001 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in *Highway Statistics* (FHWA 1996 through 2002).

Emissions estimates for NO_x, CO, NMVOCs were taken directly from EPA data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2003).

Uncertainty

Mobile combustion emissions from each vehicle mile traveled can vary significantly due to assumptions concerning fuel type and composition, technology type, operating speeds and conditions, 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 temporally variable profiles of both vehicle usage by age and vehicle usage by model year in the United States. Data for these profiles were provided by EPA (2000).

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 (i.e., CO, NO_x, and hydrocarbons) have been extensively researched, and thus involve lower uncertainty than emissions of unregulated gases. Although CH_4 has not been singled out for regulation in the United States, overall hydrocarbon emissions from mobile combustion—a component of which is CH_4—are regulated.

Compared to CH_4, CO, NO_x, and NMVOCs, there is relatively little data available to estimate emission factors for N_2O. Nitrous oxide is not a regulated air 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 vehicles with aged catalysts emit more than new vehicles. The emission factors used were, therefore, derived from aged cars (EPA 1998). 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.

Overall, uncertainty for N_2O emissions estimates is considerably higher than for CH_4, CO, NO_x, or NMVOCs. All these gases, however, 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 that it is all used to fuel aircraft. However, some fuel purchased by airlines is not necessarily 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.

In calculating CH_4 emissions from aircraft, an average emission factor is applied to total jet fuel consumption. This average emission factor takes into account the fact that CH_4 emissions occur only during the landing and take-off (LTO) cycles, with no CH_4 being emitted during the cruise cycle. While some evidence exists that fuel emissions in cruise conditions may actually destroy CH_4, the average emission factor used does not take this into account.

Lastly, in EPA (2001), U.S. aircraft emission estimates for CO, NO_x, and NMVOCs are based upon LTO cycles and, consequently, only estimate 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 total emissions because they exclude emissions from aircraft on domestic flight segments at cruising altitudes.

Coal Mining

All underground and surface coal mining liberates CH_4 as part of the normal mining operations. The amount of CH_4 liberated depends on the amount that remains in the coal ("*in situ*") and surrounding strata when mining occurs. The in-situ CH_4 content depends upon the amount of CH_4 created during the coal formation (i.e., coalification) process, and the geologic characteristics of the coal seams. During coalification, deeper deposits tend to generate more CH_4 and retain more of the gas afterwards. Accordingly, deep underground coal seams generally have higher CH_4 contents than shallow coal seams or surface deposits.

Three types of coal mining related activities release CH_4 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. Underground coal mines contribute the largest share of CH_4 emissions. All underground coal mines employ ventilation systems to ensure that CH_4 levels remain within safe concentrations. These systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Additionally, twenty-one 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 CH_4 before, during, or after mining. In 2001, ten coal mines collected CH_4 from degasification systems and sold this gas to a pipeline, thus reducing emissions to the atmosphere. Surface coal mines also release CH_4 as the overburden is removed and the coal is exposed, but the level of emissions is much lower than from underground mines. Finally, some of the CH_4 retained in the coal after mining is released during processing, storage, and transport of the coal.

Total CH_4 emissions in 2001 were estimated to be 60.7 Tg CO_2 Eq. (2,893 Gg), declining 30 percent since 1990 (see Table 2-23 and Table 2-24). Of this amount, underground mines accounted for 63 percent, surface mines accounted for 16 percent, and post-mining emissions accounted for 21 percent. With the exception of 1994 and 1995, total CH_4 emissions declined in each successive year during this period. In 1993, CH_4 generated from underground mining dropped, primarily due to labor strikes at many large underground mines. In 1995, there was an increase in CH_4 emissions from underground mining due to significantly increased emissions at the highest-emitting coal mine in the country. The decline in CH_4 emissions from underground mines in 2001 is the result of the mining of less gassy coal, and an increase in CH_4 recovered and used. Surface mine emissions and post-mining emissions remained relatively constant from 1990 to 2001.

Methodology

The methodology for estimating CH_4 emissions from coal mining consists of two parts. The first part involves estimating CH_4 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 emission factors.

Underground mines. Total CH_4 emitted from underground mines was estimated as the sum of CH_4 liberated from ventilation systems and CH_4 liberated by means of degasification systems, minus CH_4 recovered and used. The Mine Safety and Heath Administration (MSHA) samples CH_4 emissions from ventilation systems for all mines with detectable[40] CH_4 concentrations. These mine-by-mine measurements are used to estimate CH_4 emissions from ventilation systems.

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[40] 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 2-23: CH$_4$ Emissions from Coal Mining (Tg CO$_2$ Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Underground Mining	62.1	51.2	45.3	44.3	44.4	41.6	39.4	38.1
Liberated	67.6	63.3	59.8	55.7	58.6	54.4	54.0	54.2
Recovered & Used	(5.6)	(12.0)	(14.5)	(11.4)	(14.2)	(12.7)	(14.7)	(16.0)
Surface Mining	10.2	8.9	9.2	9.5	9.4	8.9	8.8	9.5
Post- Mining (Underground)	13.1	11.9	12.4	12.8	12.6	11.7	11.3	11.6
Post-Mining (Surface)	1.7	1.5	1.5	1.5	1.5	1.4	1.4	1.5
Total	**87.1**	**73.5**	**68.4**	**68.1**	**67.9**	**63.7**	**60.9**	**60.7**

Note: Totals may not sum due to independent rounding.

Table 2-24: CH$_4$ Emissions from Coal Mining (Gg)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Underground Mining	2,956	2,439	2,158	2,111	2,117	1,982	1,877	1816
Liberated	3,220	3,012	2,850	2,654	2,791	2,589	2,573	2580
Recovered & Used	(265)	(574)	(692)	(543)	(674)	(607)	(698)	(764)
Surface Mining	488	425	436	451	446	424	420	453
Post- Mining (Underground)	626	569	590	609	600	557	538	550
Post-Mining (Surface)	79	69	71	73	72	69	68	74
Total	**4,149**	**3,502**	**3,255**	**3,244**	**3,235**	**3,033**	**2,902**	**2,893**

Note: Totals may not sum due to independent rounding.

Some of the higher-emitting underground mines also use degasification systems (e.g., wells or boreholes) that remove CH$_4$ before, during, or after mining. This CH$_4$ can then be collected for use or vented to the atmosphere. Various approaches were employed to estimate the quantity of CH$_4$ collected by each of the twenty-one mines using these systems, depending on available data. For example, some mines report to EPA the amount of CH$_4$ liberated from their degasification systems. For mines that sell recovered CH$_4$ to a pipeline, pipeline sales data were used to estimate degasification emissions. For those mines for which no other data are available, default recovery efficiency values were developed, depending on the type of degasification system employed.

Finally, the amount of CH$_4$ recovered by degasification systems and then used (i.e., not vented) was estimated. This calculation was complicated by the fact that most CH$_4$ is not recovered and used during the same year in which the particular coal seam is mined. In 2001, ten active coal mines sold recovered CH$_4$ into the local gas pipeline networks. Emissions avoided for these projects were estimated using gas sales data reported by various state agencies. For most mines with recovery systems, companies and state agencies provided individual well production information, which was used to assign gas sales to a particular year. For the few remaining mines, coal mine operators supplied information regarding the number of years in advance of mining that gas recovery occurs.

Surface Mines and Post-Mining Emissions. Surface mining and post-mining CH$_4$ emissions were estimated by multiplying basin-specific coal production by basin-specific emission factors. Surface mining emission factors were developed by assuming that surface mines emit two times as much CH$_4$ as the average *in situ* CH$_4$ content of the coal. This accounts for CH$_4$ released from the strata surrounding the coal seam. For post-mining emissions, the emission factor was assumed to be 32.5 percent of the average *in situ* CH$_4$ content of coals mined in the basin.

Data Sources

The Mine Safety and Health Administration provided mine-specific information on CH$_4$ liberated from ventilation systems at underground mines. The primary sources of data for estimating emissions avoided at underground mines were gas sales data published by state petroleum and natural gas agencies, information supplied by mine operators

Table 2-25: 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	378,964	634,864	1,013,828
1999	355,433	642,877	998,310
2000	338,173	635,592	973,765
2001	345,303	677,735	1,023,039

regarding the number of years in advance of mining that gas recovery occurred, and reports of gas used on-site. Annual coal production data were taken from the Energy Information Administration's *Coal Industry Annual* (see Table 2-25) (EIA 2002). Data on *in situ* CH_4 content and emissions factors are taken from EPA (1990).

Uncertainty

The emission estimates from underground ventilation systems were based on actual measurement data, which are believed to have relatively low uncertainty. A degree of imprecision was introduced because the measurements were not continuous but rather an average of quarterly instantaneous readings. Additionally, the measurement equipment used possibly resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky and Wang 2000). Estimates of CH_4 liberated and recovered by degasification systems are also relatively certain because many coal mine operators provided information on individual well gas sales and mined through dates. Many of the recovery estimates use data on wells within 100 feet of a mined area. A level of uncertainty currently exists concerning the radius of influence of each well. The number of wells counted, and thus the avoided emissions, may increase if the drainage area is found to be larger than currently estimated. EPA is currently working to determine the proper drainage radius and may include additional mines in the recovery estimate in the future. Compared to underground mines, there is considerably more uncertainty associated with surface mining and post-mining emissions because of the difficulty in developing accurate emission factors from field measurements. EPA plans to update the basin-specific surface mining emission factors. Additionally, EPA plans to re-evaluate the post-mining emission factors for the impact of CH_4 not released before combustion. Because underground emissions comprise the majority of total coal mining emissions, the overall uncertainty is preliminarily estimated to be roughly ±15 percent. Currently, the estimate does not include emissions from abandoned coal mines because of limited data. EPA is conducting research on the feasibility of including an estimate in future years.

Natural Gas Systems

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. Overall, natural gas systems emitted 117.3 Tg CO_2 Eq. (5,588 Gg) of CH_4 in 2001, a slight decrease over emissions in 1990 (see Table 2-26 and Table-2-27). Improvements in management practices and technology, along with the replacement of older equipment, have helped to stabilize emissions (EPA 2001).

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 engines 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. Below is a characterization of the four major stages of the natural gas system. Each of the stages is described and the different factors affecting CH_4 emissions are discussed.

Field Production. In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, gathering pipelines, and well-site gas treatment facilities 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 26 percent of CH_4 emissions from natural gas systems between 1990 and 2001.

Processing. In this stage, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Fugitive emissions from compressors, including compressor seals, are the primary emission source from this stage. Processing plants account for about 12 percent of CH_4 emissions from natural gas systems.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities, which contain large reciprocating and turbine compressors, are used to move the gas throughout the United States transmission system. Fugitive emissions from these compressor stations and from metering and regulating stations account for the majority of the emissions from this stage. Pneumatic devices and engine exhaust are also sources of emissions from transmission facilities. Methane emissions from transmission account for approximately 33 percent of the emissions from natural gas systems.

Natural gas is also injected and stored in underground formations during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Compressors and dehydrators are the primary contributors to emissions from these storage facilities. Approximately one percent of total emissions from natural gas systems can be attributed to storage facilities.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through mains and service lines to individual end users. There were over 1,117,351 miles of distribution mains in 2001, an increase from just over 837,000 miles in 1990 (OPS 2002a). Distribution system emissions, which account for approximately 28 percent of emissions from natural gas systems, result mainly from fugitive emissions from gate stations and non-plastic piping (cast iron, steel).[41] An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced the growth in emissions from this stage. Distribution system emissions in 2001 were slightly higher than 1990 levels.

Methodology

The basis for estimates of CH_4 emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute and EPA (EPA/GRI 1996). The EPA/GRI study developed over 100 emission and activity factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The study was based on a combination of process engineering studies and measurements at representative gas facilities. From this analysis, EPA developed a 1992 base-year emission

Table 2-26: CH_4 Emissions from Natural Gas Systems (Tg CO_2 Eq.)

Stage	1990	1995	1996	1997	1998	1999	2000	2001
Field Production	30.4	33.2	32.3	33.1	33.7	30.7	31.3	30.8
Processing	14.7	14.9	14.9	14.9	14.4	14.2	14.3	14.5
Transmission and Storage	46.7	46.1	46.7	45.8	44.9	43.7	43.1	39.3
Distribution	30.2	33.0	33.6	32.2	31.0	31.7	32.6	32.7
Total	**122.0**	**127.2**	**127.4**	**126.0**	**124.0**	**120.3**	**121.2**	**117.3**

Note: Totals may not sum due to independent rounding.

Table 2-27: CH_4 Emissions from Natural Gas Systems (Gg)

Stage	1990	1995	1996	1997	1998	1999	2000	2001
Field Production	1,445	1,583	1,537	1,577	1,605	1,463	1,488	1,467
Processing	702	709	709	710	684	675	680	692
Transmission and Storage	2,223	2,196	2,223	2,183	2,140	2,082	2,053	1,870
Distribution	1,440	1,572	1,600	1,532	1,475	1,508	1,551	1,559
Total	**5,810**	**6,059**	**6,069**	**6,001**	**5,903**	**5,728**	**5,772**	**5,588**

Note: Totals may not sum due to independent rounding.

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[41] The percentages of total emissions from each stage may not add to 100 because of independent rounding.

estimate using the emission and activity factors. For other years, EPA has developed a set of industry activity factor drivers that can be used to update activity factors. These drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations.

See Annex G for more detailed information on the methodology and data used to calculate CH_4 emissions from natural gas systems.

Data Sources

Activity factor data were taken from the following sources: American Gas Association (AGA 1991-1998); American Petroleum Institute (API 2002); Minerals and Management Service (DOI 1998-2002); Natural Gas Annual (EIA 1993, 1996, 1997, 1998a, 2002d, 2002f, 1998g); Natural Gas Monthly (EIA 2002 b, 2001, 2002c, 2001, 2002e); Office of Pipeline Safety (OPS 2002 a,b); Oil and Gas Journal (OGJ 1999 through 2002). The Gas Systems Analysis model was used to aid in collecting data for non-associated and associated wells (GSAM 1997). All emissions factors were taken from EPA/GRI (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 is preliminarily 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, CH_4 is released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. Total CH_4 emissions from petroleum systems in 2001 were 21.2 Tg CO_2 Eq. (1,011 Gg). Since 1990, emissions declined due to a decline in domestic oil production and industry efforts to make reductions. (See Table 2-28 and Table 2-29.) The various sources of emissions are detailed below.

Production Field Operations. Production field operations account for approximately 97 percent of total CH_4 emissions from petroleum systems. Vented CH_4 from oil wells, storage tanks, and related production field processing equipment account for the vast majority of the emissions from production, with field storage tanks and natural-gas-powered pneumatic devices being the dominant sources. The emissions from storage tanks occur when the CH_4 entrained in crude oil under high pressure volatilizes once the crude oil is dumped into storage tanks at atmospheric pressure. The next largest sources of vented emissions are chemical injection pumps and vessel blowdown. The remaining emissions from production can be attributed to fugitives and combustion.

Crude Oil Transportation. Crude transportation activities account for approximately one half percent of total CH_4 emissions from the oil industry. Venting from tanks and marine vessel loading operations accounts for the majority of CH_4 emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for the remainder.

Crude Oil Refining. Crude oil refining processes and systems account for only two percent of total CH_4 emissions from the oil industry because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. Within refineries, vented emissions account for about 87 percent of the emissions, while fugitive and combustion emissions account for approximately 6 percent each. Refinery system blowdowns for maintenance and the process of asphalt blowing—with air to harden it—are the primary venting contributors. Most of the fugitive emissions from refineries are from leaks in the fuel gas system. Refinery combustion emissions accumulate from small amounts of unburned CH_4 in process heater stack emissions and from unburned CH_4 in engine exhausts and flares.

Methodology

The methodology for estimating CH_4 emissions from petroleum systems is based on a comprehensive study of CH_4 emissions from U.S. petroleum systems, *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report)* (EPA 1999) and *Methane Emissions from the U.S. Petroleum Industry* (Radian 1996a-d). These studies combined emission estimates 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 H explains the emission estimates for these 70 activities in greater detail. The estimates of CH_4 emissions from petroleum systems do not include emissions downstream from oil refineries because these emissions are very small compared to CH_4 emissions upstream from oil refineries.

The methodology for estimating CH_4 emissions from the 70 oil industry activities employs emission factors initially developed in EPA (1999) and activity factors that are based on EPA (1999) and Radian (1996a-d). Emissions are estimated 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 provides emission factors and activity factors for all activities except those related to offshore oil production. For offshore oil production, an emission factor was calculated by dividing an emission estimate from the Minerals Management Service (MMS) by the number of platforms. Emission factors were held constant for the period 1990 through 2001.

Activity factors for 1990 through 2001 were collected from a wide variety of statistical resources. For some years, complete activity factor data were not available. In such cases, one of three approaches was employed. Where appropriate, the activity factor was calculated from related statistics using ratios developed for Radian (1996a-d). For example, Radian (1996a-d) found that the number of heater treaters (a source of CH_4 emissions) is related to both number of producing wells and annual production. To estimate the activity factor for heater treaters, reported statistics for wells and production are used, along with the ratios developed for Radian (1996a-d). In other cases, the activity factor is held constant from 1990 through 2001 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable.

See Annex H for additional detail.

Data Sources

Nearly all emission factors were taken from Radian (1996e). The remaining emission factors were taken from the following sources: the American Petroleum Institute (API 1996), EPA default values, MMS reports (MMS 1995 and 1999), the Exploration and

Table 2-28: CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Production Field Operations	**26.8**	**23.6**	**23.2**	**22.9**	**22.2**	**20.9**	**20.5**	**20.6**
Tank venting	11.7	9.2	8.9	8.6	8.2	7.3	7.2	7.3
Pneumatic device venting	11.0	10.4	10.4	10.4	10.2	9.9	9.7	9.7
Wellhead fugitives	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Combustion & process upsets	2.2	2.1	2.1	2.1	2.0	1.9	1.9	1.9
Misc. venting & fugitives	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Crude Oil Transportation	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Refining	**0.5**	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Total	**27.5**	**24.2**	**23.9**	**23.6**	**22.9**	**21.6**	**21.2**	**21.2**

Note: Totals may not sum due to independent rounding.

Table 2-29: CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Production Field Operations	**1,278**	**1,122**	**1,107**	**1,090**	**1,058**	**996**	**977**	**979**
Tank venting	558	439	425	409	390	349	343	345
Pneumatic device venting	525	497	496	495	485	470	460	460
Wellhead fugitives	26	25	25	25	25	24	22	22
Combustion & process upsets	103	98	98	98	96	92	91	91
Misc. venting & fugitives	65	63	63	63	62	61	60	60
Crude Oil Transportation	**7**	**6**	**6**	**6**	**6**	**6**	**5**	**5**
Refining	**25**	**25**	**26**	**27**	**27**	**27**	**28**	**27**
Total	**1,309**	**1,153**	**1,138**	**1,123**	**1,090**	**1,029**	**1,010**	**1,011**

Note: Totals may not sum due to independent rounding.

Production (E&P) Tank model (API and GRI), reports by the Canadian Association of Petroleum Producers (CAPP 1992 and 1993), and the consensus of industry peer review panels.

Among the more important references used to obtain activity factors are the Energy Information Administration annual and monthly reports (EIA 1995-2001), the API *Basic Petroleum Data Book* (API 2000), *Methane Emissions from the Natural Gas Industry* prepared for the Gas Research Institute (GRI) and EPA (Radian 1996a-d), consensus of industry peer review panels, MMS reports (MMS 1995 and 1999), and the *Oil & Gas Journal* (OGJ 1990 through 2001). Annex H provides a complete list of references.

Uncertainty

The detailed, bottom-up analysis used to evaluate U.S. petroleum systems reduces the uncertainty related to the CH_4 emission estimates in comparison with a top-down approach. However, a number of uncertainties remain. Emission factors and activity factors are based on a combination of measurements, equipment design data, engineering calculations and studies, surveys of selected facilities and statistical reporting. Statistical uncertainties arise from natural variation in measurements, equipment types, operational variability and survey and statistical methodologies. Published activity factors are not available every year for all 70 activities analyzed for petroleum systems; therefore, some are estimated. Because of the dominance of six of major sources, which account for 90 percent of the total emissions, a process is underway to examine and develop uncertainty estimates for them and for total emissions from the petroleum systems.

Municipal Solid Waste Combustion

Combustion is used to manage about 7 to 17 percent of the municipal solid wastes (MSW) generated in the United States, depending on the source of the estimate and the scope of materials included in the definition of solid waste (EPA 2000c, Goldstein and Matdes 2001). Almost all combustion of MSW in the United States occurs at waste-to-energy facilities where energy is recovered, and thus emissions from waste combustion are accounted for in the Energy chapter. Combustion of MSW results in conversion of the organic inputs to CO_2. According to the IPCC Guidelines, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste combustion are calculated by estimating the quantity of waste combusted and the fraction of the waste that is carbon derived from fossil sources.

Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), and have their net carbon flows accounted for under the Land-Use Change and Forestry chapter (see Box 2-3). However, some components—plastics, synthetic rubber, and synthetic fibers—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in MSW are predominantly from clothing and home furnishings. Tires are also considered a “non-hazardous” waste and are included in the MSW combustion estimate, though waste disposal practices for tires differ from the rest of MSW.

Approximately 26 million metric tons of MSW were combusted in the United States in 2001. Carbon dioxide emissions from combustion of MSW rose 91 percent since 1990, to an estimated 26.9 Tg CO_2 Eq. (26,907 Gg) in 2001, as the volume of plastics and other fossil carbon-containing materials in MSW increased (see Table 2-30 and Table 2-31). Waste combustion is also a source of N_2O emissions (De Soete 1993). Nitrous oxide emissions from MSW combustion were estimated to be 0.2 Tg CO_2 Eq. (1 Gg) in 2001, and have not changed significantly since 1990.

Ambient air pollutants were emitted during waste incineration and open burning and are shown in Table 2 32. These emissions are a relatively small portion of the overall ambient air pollutant emissions, remaining below 5 percent for each gas over the entire time series.

Methodology

Emissions of CO_2 from MSW combustion include CO_2 generated by the combustion of plastics, synthetic fibers, and synthetic rubber, as well as the combustion of synthetic rubber and carbon black in tires. These emissions were calculated by multiplying the amount of each material combusted by the carbon content of the material and the fraction oxidized (98 percent). Plastics combusted in MSW were categorized into seven plastic resin types, each material having a discrete carbon content. Similarly, synthetic rubber is categorized into three product types, and synthetic fibers were categorized into four product types, each having a discrete carbon content. Scrap tires contain several types of

Box 2-3: Biogenic Emissions and Sinks of Carbon

For many countries, CO_2 emissions from the combustion or degradation of biogenic materials are 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 paper). The carbon contained in paper was originally stored in trees during photosynthesis. Under natural conditions, this material 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 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.

Carbon dioxide emissions from biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis 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. However, CH_4 emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills, and are consequently included in this inventory.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin 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 153 Tg CO_2 Eq. and 12 Tg CO_2 Eq. on average per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in the Land-Use Change and Forestry chapter, as recommended in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) regarding the tracking of carbon flows.

Table 2-30: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Tg CO_2 Eq.)

Gas/Waste Product	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**14.1**	**18.5**	**19.4**	**21.2**	**22.5**	**23.9**	**25.4**	**26.9**
Plastics	10.3	11.1	11.5	12.5	12.9	13.6	14.2	15.0
Synthetic Rubber in Tires	0.2	1.5	1.6	1.9	2.1	2.4	2.6	2.9
Carbon Black in Tires	0.4	2.3	2.6	2.9	3.3	3.7	4.1	4.5
Synthetic Rubber in MSW	1.6	1.7	1.7	1.8	1.8	1.9	2.0	2.1
Synthetic Fibers	1.5	1.9	2.0	2.1	2.2	2.3	2.4	2.5
N_2O	**0.3**	**0.3**	**0.3**	**0.3**	**0.2**	**0.2**	**0.2**	**0.2**
Total	**14.4**	**18.7**	**19.7**	**21.4**	**22.7**	**24.1**	**25.6**	**27.1**

Table 2-31: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Waste Product	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**14,068**	**18,472**	**19,418**	**21,173**	**22,454**	**23,903**	**25,351**	**26,907**
Plastics	10,320	11,077	11,459	12,484	12,929	13,580	14,232	14,975
Synthetic Rubber in Tires	246	1,465	1,642	1,852	2,130	2,377	2,624	2,871
Carbon Black in Tires	383	2,284	2,561	2,889	3,321	3,707	4,092	4,478
Synthetic Rubber in MSW	1,584	1,708	1,737	1,807	1,841	1,910	1,979	2,055
Synthetic Fibers	1,535	1,938	2,018	2,141	2,233	2,329	2,424	2,527
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Table 2-32: NO_x, CO, and NMVOC Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
NO_x	**82**	**88**	**135**	**140**	**145**	**142**	**149**	**149**
Waste Incineration	44	48	46	48	49	48	50	50
Open Burning	38	40	89	92	96	94	99	99
CO	**978**	**1,073**	**2,628**	**2,668**	**2,826**	**2,833**	**2,914**	**2,916**
Waste Incineration	337	392	66	68	69	69	70	72
Open Burning	641	681	2,562	2,600	2,757	2,764	2,844	2,844
NMVOCs	**222**	**237**	**304**	**313**	**326**	**326**	**332**	**333**
Waste Incineration	44	49	23	23	23	20	20	21
Open Burning	178	189	281	290	303	306	312	312

Note: Totals may not sum due to independent rounding.

Table 2-33: 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
1999	347,318,833	7.0
2000	371,316,526	7.0
2001	371,316,526	7.0

EPA (2003) provided emission estimates for NOx, CO, and NMVOCs from waste incineration and open burning.

synthetic rubber, as well as carbon black. Each type of synthetic rubber has a discrete carbon content, and carbon black is 100 percent carbon. Emissions of CO_2 were calculated based on the number of scrap tires used for fuel and the synthetic rubber and carbon black content of the tires.

Combustion of municipal solid waste also results in emissions of N_2O. These emissions were calculated as a function of the total estimated mass of MSW combusted and an emission factor.

More detail on the methodology for calculating emissions from each of these waste combustion sources is provided in Annex I.

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

Data Sources

For each of the methods used to calculate CO_2 emissions from MSW combustion, data on the quantity of product combusted and the carbon content of the product are needed. It was estimated that approximately 26 million metric tons of MSW were combusted in the United States in 2001 (Goldstein and Madtes 2001). Waste combustion and percent incinerated for 2001 was assumed to be the same as for 2000. For plastics, synthetic rubber, and synthetic fibers, the amount of material in MSW and its portion combusted was taken from the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c, 2002a). For synthetic rubber and carbon black in scrap tires, this information was provided by the *Scrap Tire Use/Disposal Study 1998/1999 Update* (STMC 1999) and *Scrap Tires, Facts and Figures* (STMC 2000, 2001, 2002).

Average carbon contents for the "Other" plastics category, synthetic rubber in scrap tires, synthetic rubber in MSW, and synthetic fibers were calculated from recent production statistics, which divide their respective markets by chemical compound. The plastics production data set was taken from the website of the American Plastics Council (APC 2000); synthetic rubber production was taken from the website of the International Institute of Synthetic Rubber Producers (IISRP 2000); and synthetic fiber production was taken from the website of the Fiber Economics Bureau (FEB 2000). Personal communications with the APC (Eldredge-Roebuck 2000) and the FEB (DeZan 2000) validated the website information. All three sets of production data can also be found in Chemical and Engineering News, "Facts & Figures for the Chemical Industry." Lastly, information about scrap tire composition was taken from the Scrap Tire Management Council's Internet web site entitled "Scrap Tire Facts and Figures" (STMC 2002).

The assumption that 98 percent of organic carbon is oxidized (which applies to all municipal solid waste combustion categories for CO_2 emissions) was reported in the EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 2002b).

The N_2O emission estimates are based on different data sources. The N_2O emissions are a function of total waste combusted, as reported in the December 2001 issue of *BioCycle* (Goldstein and Matdes 2001). Table 2-33 provides MSW generation and percentage combustion data for the total waste stream. The emission factor of N_2O emissions per quantity of MSW combusted was taken from Olivier (1993).

Uncertainty

Uncertainties in the waste combustion emission estimates arise from both the assumptions applied to the data and from the quality of the data.

- *MSW Combustion Rate*. A source of uncertainty affecting both fossil CO_2 and N_2O emissions is the estimate of the MSW combustion rate. The EPA (2000c, 2002a) estimates of materials generated, discarded, and combusted carry considerable uncertainty associated with the material flows methodology used to generate them. Similarly, the *BioCycle* (Glenn 1999, Goldstein and Matdes 2000, Goldstein and Matdes 2001) estimate of total waste combustion — used for the N_2O emissions 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— the EPA's Office of Solid Waste (EPA 2000c, 2002a) and *BioCycle* (Glenn 1999, Goldstein and Matdes 2000, Goldstein and Matdes 2001)—provide estimates of total solid waste combusted that are relatively consistent (see Table 2-34).

- *Fraction Oxidized.* Another source of uncertainty for the CO_2 emissions estimate is fraction oxidized. 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.
- *Missing Data on MSW Composition.* Disposal rates have been interpolated when there is an incomplete interval within a time series. Where data are not available for more recent years (2000, 2001), they are extrapolated from the most recent years for which estimates are available. In addition, the ratio of landfilling to combustion was assumed to be constant for the entire period (1990 to 2001) based on the 1998 ratio (EPA 2000c, 2002a).
- *Average Carbon Contents.* Average carbon contents were applied to the mass of "Other" plastics combusted, synthetic rubber in tires and MSW, and synthetic fibers. These average values were estimated from the average carbon content of the known products recently produced. The true carbon content of the combusted waste may differ from this estimate depending on differences in the formula between the known and unspecified materials, and differences between the composition of the material disposed and that produced. For rubber, this uncertainty is probably small since the major elastomers' carbon contents range from 77 to 91 percent; for plastics, where carbon contents range from 29 to 92 percent, it may be more significant. Overall, this is a small source of uncertainty.
- *Synthetic/Biogenic Assumptions.* A portion of the fiber and rubber in MSW is biogenic in origin. Assumptions have been made concerning the allocation between synthetic and biogenic materials based primarily on expert judgment.

Table 2-34: 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	31,218,818	25,506,752
1999	30,945,455	24,312,318
2000	NA	25,992,157
2001	NA	25,992,157[a]

NA (Not Available)

[a] Used 2000 data as proxy, as 2001 data was not yet available.

- *Combustion Conditions Affecting N_2O Emissions.* Because insufficient data exist 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 value used to estimate N_2O emissions from facilities worldwide (Olivier 1993). As such, it has a range of uncertainty that spans an order of magnitude (between 25 and 293 g N_2O/metric ton MSW combusted) (Watanabe, et al., 1992). Due to a lack of 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.

Natural Gas Flaring and Ambient Air Pollutant Emissions from Oil and Gas Activities

The flaring of natural gas from oil wells is a small source of CO_2. In addition, oil and gas activities also release small amounts of NO_x, CO, and NMVOCs. This source accounts for only a small proportion of overall emissions of each of these gases. Emissions of NO_x, and CO from petroleum and natural gas production activities were both less than 1 percent of national totals, while NMVOC and SO_2 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

Table 2-35: CO_2 Emissions from Natural Gas Flaring

Year	Tg CO_2 Eq.	Gg
1990	5.5	5,514
1995	8.7	8,729
1996	8.2	8,233
1997	7.6	7,565
1998	6.3	6,250
1999	6.7	6,679
2000	5.5	5,525
2001	5.2	5,179

Table 2-36: NO_x, NMVOCs, and CO Emissions from Oil and Gas Activities (Gg)

Year	NO_x	CO	NMVOCs
1990	139	302	555
1995	100	316	582
1996	126	321	433
1997	130	333	442
1998	130	332	440
1999	113	152	376
2000	115	152	348
2001	117	153	357

Table 2-37: Total Natural Gas Reported Vented and Flared (Million Ft^3) and Thermal Conversion Factor (Btu/Ft^3)

Year	Vented and Flared (original)	Vented and Flared (revised)*	Thermal Conversion Factor
1990	150,415	91,130	1,106
1991	169,909	92,207	1,108
1992	167,519	83,363	1,110
1993	226,743	108,238	1,106
1994	228,336	109,493	1,105
1995	283,739	144,265	1,106
1996	272,117	135,709	1,109
1997	256,351	124,918	1,107
1998	103,019	103,019	1,109
1999	110,285	110,285	1,107
2000	91,232	91,232	1,107
2001	85,678	85,678	1,105

* Wyoming venting and flaring estimates were revised. See text for further explanation.

total reported U.S. venting and flaring, approximately 20 percent may be vented, with the remaining 80 percent flared, but it is now believed that flaring accounts for an even greater proportion. Methane emissions from venting are accounted for under Petroleum Systems. For 2001 CO_2 emissions from flaring were estimated to be approximately 5.2Tg CO_2 Eq. (5,179 Gg), a decrease of 6 percent since 1990 (see Table 2-35).

Ambient air pollutant emissions from oil and gas production, transportation, and storage, constituted a relatively small portion of the total emissions of these gases from the 1990 to 2001 (see Table 2 36).

Methodology

Estimates of CO_2 emissions were prepared using an emission factor of 54.71 Tg CO_2 Eq./QBtu of flared gas, and an assumed flaring efficiency of 100 percent.

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

Data Sources

Total natural gas vented and flared was taken from EIA's *Natural Gas Annual* (EIA 2003). It was assumed that all reported vented and flared gas was flared. This assumption is consistent with that used by EIA in preparing their emission estimates, under the assumption that many states require flaring of natural gas (EIA 2000b).

There is a discrepancy in the time series for natural gas vented and flared as reported in EIA (2003). One facility in Wyoming had been incorrectly reporting CO_2 vented as CH_4. EIA corrected these data in the *Natural Gas Annual 2000* (EIA 2001) for the years 1998 and 1999 only. Data for 1990 through 1997 were adjusted by assuming a proportionate share of CO_2 in the flare gas for those years as for 1998 and 1999. The adjusted values are provided in Table 2-37. The emission and thermal conversion factors were also provided by EIA (2003) and are included in Table 2-37.

Emission estimates for NO_x, CO, and NMVOCs from petroleum refining, petroleum product storage and transfer, and petroleum marketing operations were taken directly from EPA data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2003). Included are gasoline, crude oil and distillate fuel oil storage and transfer operations, gasoline bulk terminal and bulk plants operations, and retail gasoline service stations operations.

Uncertainty

Uncertainties in CO_2 emission estimates primarily arise from assumptions concerning the flaring efficiency and the correction factor applied to 1990 through 1997 venting and flaring data. Uncertainties in ambient air 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.[42] 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).[43]

Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4, N_2O, CO, NO_x, NMVOCs, particulate matter, and sulfur dioxide (SO_2).[44] Two transport modes are addressed under the IPCC definition of 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.[45]

Emissions of CO_2 from aircraft are essentially a function of fuel use. Methane, N_2O, CO, NO_x, and NMVOC emissions also 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 stratospheric ozone depletion.[46] At the cruising altitudes of subsonic aircraft, however, NO_x emissions contribute to the formation of tropospheric ozone. At these lower altitudes, the positive radiative forcing effect of ozone has enhanced the anthropogenic greenhouse gas forcing.[47] The vast majority of aircraft NO_x emissions occur at these lower cruising altitudes of commercial subsonic aircraft (NASA 1996).[48]

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

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[42] 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).

[43] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[44] 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 United States, 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.

[45] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

[46] Currently there are only around a dozen civilian supersonic aircraft in service around the world that fly at these altitudes, however.

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

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

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 2001 from the combustion of international bunker fuels from both aviation and marine activities were 98.3 Tg CO_2 Eq., or 14 percent below emissions in 1990 (see Table 2-38). Although emissions from international flights departing from the United States have increased significantly (26 percent), emissions from international shipping voyages departing the United States have decreased by 43 percent since 1990. Increased military activity during the Persian Gulf War resulted in an increased level of military marine emissions in 1990 and 1991 and again in 1998 with further U.S. military activity in Iraq; civilian marine emissions during this period exhibited a similar trend.[49] The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 and N_2O were also emitted. Emissions of NO_x by aircraft during idle, take-off, landing and at cruising altitudes are of primary concern because of their effects on ground-level ozone formation (see Table 2-39).

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.[50]

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 J for a specific discussion 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 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, Annex B, and Annex J. Heat content and density conversions were taken from EIA (2002) and USAF (1998). Emission factors used in the calculations of CH_4, N_2O, CO, NO_x, and NMVOC emissions were obtained 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: 0.32 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 1991 through 2002). 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. U.S. general aviation aircraft jet fuel consumption data were obtained from the Federal Aviation Administration (FAA 1995 through 2002). 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 1991 through 2002). Approximate average fuel prices paid by air carriers for aircraft on international

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

[50] 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).

Table 2-38: Emissions from International Bunker Fuels (Tg CO_2 Eq.)

Gas/Mode	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**113.9**	**101.0**	**102.3**	**109.9**	**112.9**	**105.3**	**99.3**	**97.3**
Aviation	46.6	51.1	52.2	55.9	55.0	58.8	58.4	58.9
Marine	67.3	49.9	50.1	54.0	57.9	46.4	40.9	38.5
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	+	+	+	+	+	+	+	+
Marine	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**1.0**	**0.9**	**0.9**	**1.0**	**1.0**	**0.9**	**0.9**	**0.9**
Aviation	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6
Marine	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.3
Total	**115.0**	**102.1**	**103.3**	**111.0**	**114.0**	**106.3**	**100.3**	**98.3**

+ Does not exceed 0.05 Tg CO_2 Eq.

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

Table 2-39: Emissions from International Bunker Fuels (Gg)

Gas/Mode	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**113,863**	**101,037**	**102,272**	**109,858**	**112,859**	**105,262**	**99,268**	**97,346**
Aviation	46,591	51,117	52,164	55,898	54,959	58,833	58,409	58,869
Marine	67,272	49,921	50,109	53,960	57,900	46,429	40,859	38,478
CH_4	**8**	**6**	**6**	**7**	**7**	**6**	**6**	**5**
Aviation	1	1	1	2	2	2	2	2
Marine	7	5	5	5	6	5	4	4
N_2O	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Aviation	1	2	2	2	2	2	2	2
Marine	2	1	1	1	1	1	1	1
CO	**116**	**113**	**115**	**124**	**124**	**124**	**120**	**120**
Aviation	77	84	86	92	91	97	96	97
Marine	39	29	29	32	34	27	24	22
NO_x	**1,987**	**1,541**	**1,549**	**1,667**	**1,771**	**1,478**	**1,326**	**1,263**
Aviation	184	202	207	221	218	233	231	233
Marine	1,803	1,339	1,343	1,446	1,553	1,244	1,094	1,030
NMVOC	**59**	**48**	**49**	**52**	**55**	**48**	**44**	**42**
Aviation	11	13	13	14	14	15	14	15
Marine	48	36	36	38	41	33	29	27

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

flights was taken from DOT (1991 through 2002) and used to convert the BEA expenditure data to gallons of fuel consumed. Data on U.S. Department of Defense (DoD) aviation bunker fuels and total jet fuel consumed by the U.S. military was supplied by the Office of the Under Secretary of Defense (Installations and Environment), 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. Military aviation bunker fuel emissions were estimated using military fuel and operations data synthesized from unpublished data by the Defense Energy Support Center, under DoD's Defense Logistics Agency (DESC 2002). Together, the data allow the quantity of fuel used in military international operations to be estimated. Densities for each jet fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 2-40. See Annex J 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 of the U.S. Department of Commerce's Bureau of the Census (DOC 1991 through 2002). Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided

Table 2-40: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990	1995	1996	1997	1998	1999	2000	2001
U.S. Carriers	1,982	2,256	2,329	2,482	2,363	2,638	2,740	2,662
Foreign Carriers	2,062	2,549	2,629	2,918	2,935	3,085	2,949	3,034
U.S. Military	862	581	540	493	496	479	469	510
Total	**4,905**	**5,385**	**5,497**	**5,893**	**5,793**	**6,203**	**6,158**	**6,206**

Note: Totals may not sum due to independent rounding.

by DESC (2002). 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 2-41.

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.[51] 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 (1991 through 2002) 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 (1991 through 2002) 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.[52]

Uncertainties exist with regard to the total fuel used by military aircraft and ships, and in the activity data on military operations and training that were used to estimate percentages of total fuel use reported as bunker fuel emissions. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the Navy and Air Force from the Defense Logistics Agency. These data may slightly over or under estimate actual total fuel use in aircraft and ships because each Service may have procured fuel from, and/or may have sold to, traded with, and/or given fuel to other ships, aircraft, governments, or other entities. There are uncertainties in aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities reported as bunker fuel emissions had to be estimated based on a combination of available data and expert judgment. Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data, which reports fuel used while underway and fuel used while not underway. This approach does not capture some voyages that would be classified as domestic for a commercial vessel. Conversely, emissions from fuel used while not underway preceding an international voyage are reported as domestic rather than international as would be done for a commercial vessel. There is uncertainty

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

[52] 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.

Table 2-41: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001
Residual Fuel Oil	4,781	3,495	3,583	3,843	3,974	3,272	2,967	2,846
Distillate Diesel Fuel & Other	617	573	456	421	627	308	290	204
U.S. Military Naval Fuels	522	334	367	484	518	511	329	318
Total	**5,920**	**4,402**	**4,406**	**4,748**	**5,119**	**4,091**	**3,586**	**3,368**

Note: Totals may not sum due to independent rounding.

associated with jet fuel use for 1997 through 2001. Small fuel quantities are used in ground vehicles or equipment rather than in aircraft.

There are also uncertainties in fuel end-uses by fuel-type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995. All assumptions used to develop the estimate were based on process knowledge, Department and military Service data, and expert judgments. The magnitude of the potential errors related to the various uncertainties has not been calculated, but is believed to be small. The uncertainties associated with future military bunker fuel emissions estimates could be reduced through additional data collection.

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.[53]

There is also concern as to the reliability of the existing DOC (1991 through 2002) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

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 CO_2. However, in the long run the CO_2 emitted from biomass consumption does not increase atmospheric CO_2 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 2001, CO_2 emissions due to burning of woody biomass within the industrial and residential/commercial sectors and by electricity generation were about 173.4 Tg CO_2 Eq. (174,991 Gg) (see Table 2-42 and Table 2-43). As the largest consumer of woody biomass, the industrial sector in 2001 was responsible for 73 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, making up 19 percent of total emissions from woody biomass. The commercial end-use sector and electricity generation 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 grown in the

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[53] It should be noted that in the EPA (2003), 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 (2003) is also likely to include emissions from ocean-going vessels departing from U.S. ports on international voyages.

Table 2-42: CO_2 Emissions from Wood Consumption by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1995	1996	1997	1998	1999	2000	2001
Industrial	115.6	132.0	134.5	128.3	128.1	128.3	130.7	126.3
Residential	46.4	47.6	47.5	33.1	30.9	33.1	34.6	32.5
Commercial	3.1	3.7	4.0	4.2	3.8	4.2	4.2	3.4
Electricity Generation	9.9	10.0	11.0	11.0	10.9	11.0	10.7	11.2
Total	**175.0**	**193.3**	**197.1**	**176.6**	**173.8**	**176.6**	**180.3**	**173.4**

Note: Totals may not sum due to independent rounding.

Table 2-43: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	1990	1995	1996	1997	1998	1999	2000	2001
Industrial	115,589	132,006	134,517	128,311	128,120	128,311	130,715	126,280
Residential	46,424	47,622	47,542	33,070	30,933	33,070	34,626	32,522
Commercial	3,086	3,684	4,029	4,179	3,846	4,179	4,247	3,424
Electricity Generation	9,893	10,021	11,015	11,029	10,923	11,029	10,733	11,200
Total	**174,991**	**193,333**	**197,104**	**176,589**	**173,822**	**176,589**	**180,321**	**173,426**

Note: Totals may not sum due to independent rounding.

Table 2-44: CO_2 Emissions from Ethanol Consumption

Year	Tg CO_2 Eq.	Gg
1990	4.4	4,380
1995	8.1	8,099
1996	5.8	5,809
1997	7.4	7,356
1998	8.1	8,128
1999	8.5	8,451
2000	9.7	9,667
2001	10.2	10,226

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 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 2001, the United States consumed an estimated 147 trillion Btus of ethanol. Emissions of CO_2 in 2001 due to ethanol fuel burning were estimated to be approximately 10.2 Tg CO_2 Eq. (10,226 Gg) (see Table 2-44).

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). Since the low in 1996, production has continued to grow.

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 90 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 by EIA (2001) (see Table 2-45). Estimates of wood biomass consumption for fuel combustion do not include liquors, municipal solid waste, tires, etc. that are reported as biomass by EIA. 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 (2002) (see Table 2-46). The carbon coefficient used was provided by OTA (1991).

Uncertainty

The fraction oxidized (i.e., combustion efficiency) factor used is believed to underestimate 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.

Table 2-45: Woody Biomass Consumption by Sector (Trillion Btu)

Year	Industrial	Residential	Commercial	Electric Generation
1990	1,447	581	39	124
1991	1,410	613	41	126
1992	1,461	645	44	140
1993	1,484	548	46	150
1994	1,580	537	46	152
1995	1,652	596	46	125
1996	1,683	595	50	138
1997	1,606	414	52	138
1998	1,603	387	48	137
1999	1,606	414	52	138
2000	1,636	433	53	134
2001	1,580	407	43	140

Table 2-46: Ethanol Consumption

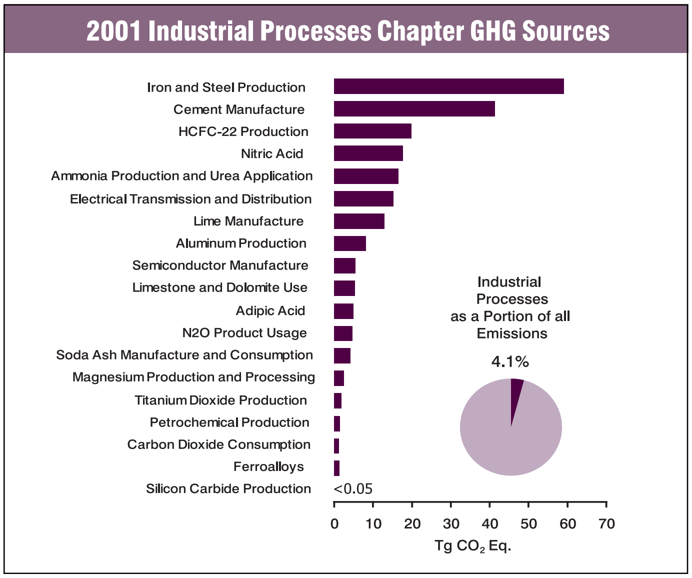
Year	Trillion Btu
1990	63
1991	73
1992	83
1993	97
1994	109
1995	117
1996	84
1997	106
1998	117
1999	122
2000	139
2001	147

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 iron and steel production, cement production, ammonia manufacture and urea application, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and use, titanium dioxide production, ferroalloy production, CO_2 consumption, aluminum production, petrochemical production, silicon carbide production, nitric acid production, adipic acid production, and N_2O from product usage (see Figure 3-1).

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, many of them will continue to accumulate in the atmosphere as long as emissions continue. Usage of HFCs for the substitution of ozone depleting substances 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. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated.

Figure 3-1


2001 Industrial Processes Chapter GHG Sources

In 2001, industrial processes generated emissions of 287.6 Tg CO_2 Eq., or 4.1 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 147.9 Tg CO_2 Eq. (147,864 Gg) in 2001. This amount accounted for only 2.6 percent of national CO_2 emissions. Methane emissions from petrochemical and silicon carbide production resulted in emissions of approximately 1.5 Tg CO_2 Eq. (71 Gg) in 2001, which was 0.2 percent of U.S. CH_4 emissions. Nitrous oxide emissions from adipic acid and nitric acid production and N_2O from product usage were 27.3 Tg CO_2 Eq. (88 Gg) in 2001, or 6.4

Table 3-1: Emissions from Industrial Processes (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**169.3**	**165.7**	**161.4**	**166.6**	**165.0**	**161.3**	**160.1**	**147.9**
Iron and Steel Production	85.4	74.4	68.3	71.9	67.4	64.4	65.8	59.1
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.2	41.4
Ammonia Manufacture & Urea Application	19.3	20.5	20.3	20.7	21.9	20.6	19.6	16.6
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3	12.9
Limestone and Dolomite Use	5.5	7.0	7.6	7.1	7.3	7.7	5.8	5.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2	4.1
Aluminum Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4	4.1
Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	1.9	1.9
Ferroalloy Production	2.0	1.9	2.0	2.0	2.0	2.0	1.7	1.3
Carbon Dioxide Consumption	0.9	1.1	1.1	1.2	1.2	1.2	1.2	1.3
CH_4	**1.2**	**1.5**	**1.6**	**1.6**	**1.7**	**1.7**	**1.7**	**1.5**
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7	1.7	1.5
Silicon Carbide Production	+	+	+	+	+	+	+	+
N_2O	**37.3**	**41.6**	**42.2**	**36.3**	**31.7**	**30.4**	**29.9**	**27.3**
Nitric Acid Production	17.8	19.9	20.7	21.2	20.9	20.1	19.1	17.6
Adipic Acid Production	15.2	17.2	17.0	10.3	6.0	5.5	6.0	4.9
N_2O Product Usage	4.3	4.5	4.5	4.8	4.8	4.8	4.8	4.8
HFCs, PFCs, and SF_6	**94.4**	**99.5**	**113.6**	**116.8**	**127.6**	**120.3**	**121.0**	**111.0**
Substitution of Ozone Depleting Substances	0.9	21.7	30.4	37.7	44.5	50.9	57.3	63.7
HCFC-22 Production	35.0	27.0	31.1	30.0	40.2	30.4	29.8	19.8
Electrical Transmission and Distribution	32.1	27.5	27.7	25.2	20.9	16.4	15.4	15.3
Aluminum Production	18.1	11.8	12.5	11.0	9.0	8.9	7.9	4.1
Semiconductor Manufacture	2.9	5.9	5.4	6.5	7.3	7.7	7.4	5.5
Magnesium Production and Processing	5.4	5.6	6.5	6.3	5.8	6.0	3.2	2.5
Total	**302.2**	**308.3**	**318.8**	**321.4**	**325.9**	**313.7**	**312.6**	**287.6**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

percent of total U.S. N_2O emissions. In 2001, combined emissions of HFCs, PFCs and SF_6 totaled 111.0 Tg CO_2 Eq. Overall, emissions from industrial processes decreased by 5 percent from 1990 to 2001, which was the result of decreases in emissions from several industrial processes—such as iron and steel, electrical transmission and distribution, HCFC-22 production, and aluminum production—which was partially offset by increases in emissions in other industrial processes, the largest being substitutes for ozone depleting substances.

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—is believed to be an industrial source of N_2O emissions. However, emissions for this and other sources have not been estimated 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.[1]

The general method employed to estimate emissions for industrial processes, as recommended by the Intergovernmental Panel on Climate Change (IPCC), involves 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 teragrams of CO_2 equivalents (Tg CO_2 Eq.), while unweighted gas emissions in gigagrams (Gg) are provided in Table 3-2.

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[1] See Annex X for a discussion of emission sources excluded.

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

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CO_2	**169,346**	**165,697**	**161,362**	**166,589**	**164,975**	**161,291**	**160,072**	**147,864**
Iron and Steel Production	85,414	74,357	68,324	71,864	67,429	64,376	65,755	59,074
Cement Manufacture	33,278	36,847	37,079	38,323	39,218	39,991	41,190	41,357
Ammonia Manufacture & Urea Application	19,306	20,453	20,282	20,650	21,934	20,615	19,587	16,588
Lime Manufacture	11,238	12,804	13,495	13,685	13,914	13,466	13,315	12,859
Limestone and Dolomite Use	5,470	7,042	7,615	7,055	7,331	7,671	5,763	5,281
Soda Ash Manufacture and Consumption	4,141	4,304	4,239	4,354	4,325	4,217	4,181	4,147
Aluminum Production	6,315	5,265	5,580	5,621	5,792	5,895	5,410	4,114
Titanium Dioxide Production	1,308	1,670	1,657	1,836	1,819	1,853	1,918	1,857
Ferroalloy Production	1,980	1,866	1,954	2,038	2,027	1,996	1,719	1,329
Carbon Dioxide Consumption	895	1,088	1,138	1,162	1,186	1,210	1,233	1,257
CH_4	**57**	**73**	**76**	**78**	**79**	**80**	**80**	**71**
Petrochemical Production	56	72	75	77	78	80	79	71
Silicon Carbide Production	1	1	1	1	1	1	1	0
N_2O	**120**	**134**	**136**	**117**	**102**	**98**	**96**	**88**
Nitric Acid Production	58	64	67	68	67	65	62	57
Adipic Acid Production	49	56	55	33	19	18	19	16
N_2O Product Usage	14	14	14	15	15	15	15	15
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M
HCFC-22 Production[a]	3	2	3	3	3	3	3	2
Electrical Transmission and Distribution[b]	1	1	1	1	1	1	1	1
Aluminum Production	M	M	M	M	M	M	M	M
Semiconductor Manufacture	M	M	M	M	M	M	M	M
Magnesium Production and Processing[b]	+	+	+	+	+	+	+	+

\+ Does not exceed 0.5 Gg
M (Mixture of gases)
[a] HFC-23 emitted
[b] SF_6 emitted
Note: Totals may not sum due to independent rounding.

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 (iron ore) with metallurgical coke in a blast furnace to produce pig iron (impure iron containing about 3 to 5 percent carbon by weight). Metallurgical coke is manufactured in a coke plant using coal as a raw material. Coke oven gas and coal tar are carbon by-products of the coke manufacturing process. The metallurgical coke is a raw material supplied to the blast furnace. Coke oven gas is generally burned as a fuel within the steel mill. Coal tar is used as a raw material in the manufacture of anodes used for primary aluminum production and for other electrolytic processes.

Carbon dioxide is produced as the metallurgical coke used in the blast furnace process is oxidized. Steel (containing less than 2 percent carbon by weight) is produced from pig iron in a variety of specialized steel making furnaces. The majority of CO_2 emissions from the iron and steel process come from the use of coke in the production of pig iron, with smaller amounts evolving from the removal of carbon from pig iron used to produce steel. Some carbon is also stored in the finished iron and steel products.

Emissions of CO_2 from iron and steel production in 2001 were 59.1 Tg CO_2 Eq. (59,074 Gg). Emissions have fluctuated significantly from 1990 to 2001 due to changes in domestic economic conditions and changes in product imports and exports (see Table 3-3). For the past several years, pig iron production has experienced a downward trend. Despite recovering somewhat in 2000, domestic production fell again in 2001. Pig iron production in 2001 was 12 percent lower than in 2000 and 18 percent below 1995 levels. A slowdown in the domestic and worldwide economy and the availability of low-priced imports limit growth in domestic production (USGS 2001a).

Table 3-3: CO_2 Emissions from Iron and Steel Production

Year	Tg CO_2 Eq.	Gg
1990	85.4	85,414
1995	74.4	74,357
1996	68.3	68,324
1997	71.9	71,864
1998	67.4	67,429
1999	64.4	64,376
2000	65.8	65,755
2001	59.1	59,074

Methodology

Since coke is consumed as a reducing agent during the manufacture of pig iron, the corresponding quantity of coal consumed during coking operations was identified. This quantity of coal is considered a non-energy use. Data were also collected on the amount of imported coke consumed in the blast furnace process. These data were converted to their energy equivalents. The carbon content of the combusted coal and imported coke was estimated by multiplying their energy consumption by material specific carbon-content coefficients. The carbon-content coefficients used are presented in Annex A.

Emissions from the re-use of scrap steel and imported pig iron in the steel production process were calculated by assuming that all the associated carbon-content of these materials are released on combustion. Steel has an associated carbon-content of approximately 0.4 percent, while pig iron is assumed to contain 4 percent carbon by weight.

Emissions from carbon anodes, used during the production of steel in electric arc furnaces (EAF), were also estimated. Emissions of CO_2 were calculated by multiplying the annual production of steel in electric arc furnaces by an emission factor (4.4 kg CO_2/ton $steel_{EAF}$). It was assumed that the carbon anodes are composed of 80 percent petroleum coke and 20 percent coal tar pitch (DOE 1997). Since coal tar pitch is a by-product of the coking process and its carbon related emissions are already accounted for during the estimation of emissions from coal combustion, the emission factor was reduced by 20 percent to avoid double counting.

Similarly, an adjustment was made to account for the coal tar pitch component of carbon anodes consumed during the production of aluminum. Again, it was assumed that the carbon anodes have a composition of 80 percent petroleum coke and 20 percent coal tar. These coal tar emissions are accounted for in the aluminum production section of this chapter. To prevent double counting, 20 percent of the emissions reported in the aluminum section have been subtracted from the estimates for iron and steel production.

Carbon storage was accounted for by assuming that all domestically manufactured steel had a carbon content of 0.4 percent. Furthermore, any pig iron that was not consumed during steel production, but fabricated into finished iron products, was assumed to have a carbon content by weight of 4 percent.

Data Sources

Data relating to the amount of coal consumed at coke plants, for the production of coke for domestic consumption in blast furnaces, as well as the quantity of coke imported for iron production were taken from Energy Information Administration (EIA), *Quarterly Coal Report* January-March 2002 (EIA 2002); *U.S. Coal Domestic and International Issues* (EIA 2001); *Mineral Yearbook: Iron and Steel* (USGS 2001a, 2000a, 1999, 1997, 1995a, 1993) and American Iron and Steel Institute (AISI), *Annual Statistical* were obtained from *IPCC Good Practice Guidance and Uncertainty Management* (IPCC 2000). Aluminum production data for 1990 through 2001 were obtained from *Mineral Industry Surveys: Aluminum Annual Report* (USGS 2002, 2001b, 2000b, 1998, 1995b). The CO_2 emission factor for carbon anode emissions from aluminum production was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Estimates for the composition of carbon anodes used during steel and aluminum production were obtained from *Energy and Environmental Profile of the U.S. Aluminum Industry* (DOE 1997).

Uncertainty

Estimating CO_2 emissions from coal and coke combustion is based on energy consumption data, average carbon contents, and the fraction of carbon oxidized produce a relatively accurate estimate of CO_2 emissions. However, there are uncertainties associated with each of these factors. For example, carbon oxidation factors may vary depending on inefficiencies in the combustion process, where varying degrees of ash or soot can remain unoxidized.

Simplifying assumptions were made concerning the composition of carbon anodes (80 percent petroleum coke and 20 percent coal tar). For example, within the aluminum industry, the coal tar pitch content of anodes can vary from 15 percent in prebaked anodes to 24 to 28 percent in Soderberg anode pastes (DOE 1997). An average value was assumed and applied to all carbon anodes utilized during aluminum and steel production. The assumption is also made that all coal tar used during anode production originates as a by-product of the domestic coking process. Similarly, it was assumed that all pig iron and crude steel have carbon contents of 4 percent and 0.4 percent, respectively. The carbon content of pig iron can vary between 3 and 5 percent, while crude steel can have a carbon content of up to 2 percent, although it is typically less than 1 percent (IPCC 2000).

There is uncertainty in the most accurate CO_2 emission factor for carbon anode consumption in aluminum production. Emissions vary depending on the specific technology used by each plant (Prebake or Soderberg). The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provide CO_2 emission factors for each technology type. Using information gathered from the Voluntary Aluminum Industrial Partnership (VAIP) program, it was assumed that production was split 80 percent prebake and 20 percent Soderberg for the whole time series. Similarly, the carbon anode emission factor for steel production can vary between 3.7 and 5.5 kg CO_2/ton steel (IPCC 2000). For this analysis, the upper bound value was used.

Cement Manufacture

Cement manufacture is an energy and raw material intensive process resulting in the generation of CO_2 from both the energy consumed in making the cement and the chemical process itself.[2] Cement production has accounted 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 U.S. state. 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.

Table 3-4: CO_2 Emissions from Cement Production*

Year	Tg CO_2 Eq.	Gg
1990	33.3	33,278
1995	36.8	36,847
1996	37.1	37,079
1997	38.3	38,323
1998	39.2	39,218
1999	40.0	39,991
2000	41.2	41,190
2001	41.4	41,357

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

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 category's total. They are presented here for informational purposes only.

In 2001, U.S. clinker production—including Puerto Rico—totaled 79,979 thousand metric tons, and U.S. masonry cement production was estimated to be 4,450 thousand metric tons (USGS 2002). The resulting emissions of CO_2 from clinker production were estimated to be 41.4 Tg CO_2 Eq. (41,357 Gg) (see Table 3-4). Emissions from masonry production from clinker raw material were estimated to be 0.1 Tg CO_2 Eq. (100 Gg) in 2001, 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 2001, emissions increased by 24 percent. In 2001, output by cement plants increased by less than 1

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[2] 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.

percent over 2000, to 79,979 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, have had considerable influence on cement production.

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 2000) and a constant reflecting the mass of CO_2 released per unit of lime. This calculation yields an emission factor of 0.507 tons of CO_2 per ton of clinker produced, which was determined 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 2000).

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.

Table 3-5: Cement Production (Gg)

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	75,842	3,989
1999	77,337	4,375
2000	79,656	4,332
2001	79,979	4,450

Data Sources

The activity data for clinker and masonry cement production (see Table 3-5) were obtained from U.S. Geological Survey (USGS 1992, 1995a, 1995b, 1996, 1997, 1998, 1999, 2000, 2001, 2002). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants.

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 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.

Ammonia Manufacture and Urea Application

Emissions of CO_2 occur during the production of synthetic ammonia. In the United States, roughly 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas. The remainder is produced using naphtha (a petroleum fraction) as a feedstock or through the electrolysis of brine at chlorine plants (EPA 1997). The natural gas-based and naphtha-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. The brine electrolysis process does not lead to CO_2 emissions.

There are five principal process steps in synthetic ammonia production from natural gas feedstock. The primary reforming step converts CH_4 to CO_2, carbon monoxide (CO), and H_2 in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. The CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air in the shift conversion step. Carbon dioxide is removed from the process gas by the shift conversion process, and the hydrogen gas is combined with the nitrogen gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released.

The conversion process for conventional steam reforming of CH_4, including primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88\,CH_4 + 1.26\,Air + 1.24\,H_2O \xrightarrow{\text{(catalyst)}} 0.88\,CO_2 + N_2 + 3\,H_2$$

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$

Not all of the CO_2 produced in the production of ammonia is emitted directly to the atmosphere. Both ammonia and carbon dioxide are used as raw materials in the production of urea [$CO(NH_2)_2$], which is another type of nitrogenous fertilizer that contains carbon as well as nitrogen. The chemical reaction that produces urea is:

$$2\,NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

The carbon in the urea that is produced and assumed to be subsequently applied to agricultural land as a nitrogenous fertilizer is ultimately released into the environment as CO_2; therefore, the CO_2 produced by ammonia production and subsequently used in the production of urea does not change overall CO_2 emissions. However, the CO_2 emissions are allocated to the ammonia and urea production processes in accordance to the amount of ammonia and urea produced.

Net emissions of CO_2 from ammonia production in 2001 were 9.1 Tg CO_2 Eq. (9,104 Gg). Carbon dioxide emissions from this source are summarized in Table 3-6. Emissions of CO_2 from urea application in 2001 totaled 7.5 Tg CO_2 Eq. (7,485 Gg). Carbon dioxide emissions from this source are summarized in Table 3-7.

Table 3-6: CO_2 Emissions from Ammonia Manufacture

Year	Tg CO_2 Eq.	Gg
1990	12.6	12,553
1995	13.5	13,546
1996	13.8	13,825
1997	14.0	14,028
1998	14.2	14,215
1999	12.9	12,948
2000	12.1	12,100
2001	9.1	9,104

Table 3-7: CO_2 Emissions from Urea Application

Year	Tg CO_2 Eq.	Gg
1990	6.8	6,753
1995	6.9	6,907
1996	6.5	6,457
1997	6.6	6,622
1998	7.7	7,719
1999	7.7	7,667
2000	7.5	7,488
2001	7.5	7,485

Table 3-8: Ammonia Production

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	16,761
1999	15,728
2000	14,342
2001	11,374

Table 3-9: Urea Production

Year	Thousand Metric Tons
1990	8,124
1991	7,373
1992	8,142
1993	7,557
1994	7,584
1995	7,363
1996	7,755
1997	7,430
1998	8,042
1999	8,080
2000	6,969
2001	6,199

Methodology

The calculation methodology for non-combustion CO_2 emissions from production of nitrogenous fertilizers is based on a CO_2 emission factor published by the European Fertilizer Manufacturers Association (EFMA). The CO_2 emission factor (1.2 tons CO_2/ton NH_3) is applied to the total annual domestic ammonia production. Emissions of CO_2 from ammonia production are then adjusted to account for the use of some of the CO_2 produced from ammonia production as a raw material in the production of urea. For each ton of urea produced, 8.8 of every 12 tons of CO_2 are consumed and 6.8 of every 12 tons of ammonia are consumed. The CO_2 emissions reported for ammonia production are therefore reduced by a factor of 0.73 multiplied by total annual domestic urea production, and that amount of CO_2 emissions is allocated to urea fertilizer application. Total CO_2 emissions resulting from nitrogenous fertilizer production does not change as a result of this calculation, but some of the CO_2 emissions are attributed to ammonia production and some of the CO_2 emissions are attributed to urea application.

The calculation of the total non-combustion CO_2 emissions from nitrogenous fertilizers accounts for CO_2 emissions from the application of imported and domestically produced urea. For each ton of imported urea applied, 0.73 tons of CO_2 are emitted to the atmosphere. The amount of imported urea applied is calculated based on the net of urea imports and exports.

All ammonia production and subsequent urea production was assumed to be from the same process—conventional catalytic reforming of natural gas feedstock. Further, ammonia and urea are assumed to be manufactured in the same manufacturing complex, as both the raw materials needed for urea production are produced by the ammonia production process.

Data Sources

The emission factor of 1.2 ton CO_2/ton NH_3 was taken from the European Fertilizer Manufacturers Association Best Available Techniques publication, *Production of Ammonia* (EFMA 1995). The EFMA reported an emission factor range of 1.15 to 1.30 ton CO_2/ton NH_3, with 1.2 ton CO_2/ton NH_3 as a typical value. The EFMA reference also indicates that more than 99 percent of the CH_4 feedstock to the catalytic reforming process is ultimately converted to CO_2. Ammonia and urea production data (see Table 3-8 and Table 3-9, respectively) were obtained from the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991, 1992, 1993, 1994, 1998, 1999, 2000, 2001a, 2001b, 2002a, 2002b, 2002c) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Import and export data were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual reports (U.S. Census Bureau) for 1997 through 2001, The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992.

Uncertainty

It is uncertain how accurately the emission factor used represents an average across all ammonia plants. The EFMA reported an emission factor range of 1.15 to 1.30 ton CO_2/ton NH_3, with 1.2 ton CO_2/ton NH_3 reported as a typical value. The actual emission factor depends upon the amount of air used in the ammonia production process, with 1.15 ton CO_2/ton NH_3 being the approximate stoichiometric minimum that is achievable for the conventional reforming process. By using natural gas consumption data for each ammonia plant, more accurate estimates of CO_2 emissions from ammonia production could be calculated. However, these consumption data are often considered confidential. Also, natural gas is consumed at ammonia plants both as a feedstock to the reforming process and for generating process heat and steam. Natural gas consumption data, if available, would need to be divided into feedstock use (non-energy) and process heat and steam (fuel) use, as CO_2 emissions from fuel use and non-energy use are calculated separately.[3]

Natural gas feedstock consumption data for the U.S. ammonia industry as a whole is available from the Energy Information Administration (EIA) *Manufacturers Energy Consumption Survey* (MECS) for the years 1985, 1988, 1991, 1994 and 1998 (EIA 1994; EIA 1998). These feedstock consumption data collectively correspond to an effective average emission factor of 1.0 ton CO_2/ton NH_3, which appears to be below the stoichiometric minimum that is achievable for the conventional steam reforming process. The EIA data for natural gas consumption for the years 1994 and 1998 correspond more closely to the CO_2 emissions calculated using the EFMA emission factor than do data for previous years. The 1994 and 1998 data alone yield an effective emission factor of 1.1 ton CO_2/ton NH_3, corresponding to CO_2 emissions estimates that are approximately 1.5 Tg CO_2 Eq. below the estimates calculated using the EFMA emission factor of 1.2 ton CO_2/ton NH_3. Natural gas feedstock consumption data are not available from EIA for other years, and data for 1991 and previous years may underestimate feedstock natural gas consumption, and therefore the emission factor was used to estimate CO_2 emissions from ammonia production, rather than EIA data.

Table 3-10: Urea Net Imports

Year	Thousand Metric Tons
1990	1,086
1991	648
1992	656
1993	2,305
1994	2,249
1995	2,055
1996	1,051
1997	1,600
1998	2,483
1999	2,374
2000	3,241
2001	4,008

All ammonia production and subsequent urea production was assumed to be from the same process—conventional catalytic reforming of natural gas feedstock. However, actual emissions may differ because processes other than catalytic steam reformation and feedstocks other than natural gas may have been used for ammonia production. Urea is also used for other purposes than as a nitrogenous fertilizer. It was assumed that 100 percent of the urea production and net imports are used as fertilizer or in otherwise emissive uses. It is also assumed that ammonia and urea are produced at collocated plants from the same natural gas raw material.

Lime Manufacture

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Its major uses are in steel making, flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction,

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[3] It appears, for example, that the IPCC emission factor for ammonia production of 1.5 ton CO_2 per ton ammonia may include both CO_2 emissions from the natural gas feedstock to the process and some CO_2 emissions from the natural gas used to generate process heat and steam for the process. Table 2-5, Ammonia Production Emission Factors, in Volume 3 of the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual (IPCC 1997) includes two emission factors, one reported for Norway and one reported for Canada. The footnotes to the table indicate that the factor for Norway does not include natural gas used as fuel but that it is unclear whether the factor for Canada includes natural gas used as fuel. However, the factors for Norway and Canada are nearly identical (1.5 and 1.6 tons CO_2 per ton ammonia, respectively) and it is likely that if one value includes fuel use the other value also does. Further, for the conventional steam reforming process, the EFMA reports an emission factor range for feedstock CO_2 of 1.15 to 1.30 ton per ton (with a typical value of 1.2 ton per ton) and an emission factor for fuel CO_2 of 0.5 tons per ton. This corresponds to a total CO_2 emission factor for the ammonia production process, including both feedstock CO_2 and process heat CO_2, of 1.7 ton per ton which is closer to the emission factors reported in the IPCC 1996 Reference Guidelines than to the feedstock-only CO_2 emission factor of 1.2 ton CO_2 per ton ammonia reported by the EFMA.

Table 3-11: Net CO_2 Emissions from Lime Manufacture

Year	Tg CO_2 Eq.
1990	11.2
1995	12.8
1996	13.5
1997	13.7
1998	13.9
1999	13.5
2000	13.3
2001	12.9

Table 3-12: CO_2 Emissions from Lime Manufacture (Gg)

Year	Potential	Recovered*	Net Emissions
1990	11,730	(493)	11,238
1995	13,701	(896)	12,804
1996	14,347	(852)	13,495
1997	14,649	(964)	13,685
1998	14,975	(1,061)	13,914
1999	14,655	(1,188)	13,466
2000	14,548	(1,233)	13,315
2001	14,016	(1,156)	12,859

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

and water purification. Lime has historically ranked fifth in total production of all chemicals in the United States. For U.S. operations, the term "lime" actually refers to a variety of chemical compounds. These include calcium oxide (CaO), or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

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)[4] 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 18,957 thousand metric tons in 2001 (USGS 2002). This resulted in estimated CO_2 emissions of 12.9 Tg CO_2 Eq. (12,859 Gg) (see Table 3-11 and Table 3-12).

At the turn of the 20th Century, over 80 percent of lime consumed in the United States went for construction uses. The contemporary quicklime market is distributed across its four end-use categories as follows: metallurgical uses, 35 percent; environmental uses, 27 percent; chemical and industrial uses, 24 percent; and construction uses, 13 percent. Construction end-uses account for the largest segment of the hydrated lime market, however, hydrated lime constitutes less than 10 percent of the total lime market (USGS 2002).

Lime production in 2001 declined 3 percent from 2000, the third consecutive drop in annual production. Overall, from 1990 to 2001, lime production increased by 20 percent. The increase in production is attributed in part to growth in demand for environmental applications, especially flue gas desulfurization (FGD) technologies. In 1993, the U.S. Environmental Protection Agency (EPA) completed regulations under the Clean Air Act capping sulfur dioxide (SO_2) emissions from electric utilities. Lime scrubbers' high efficiencies and increasing affordability have allowed the FGD end-use to expand from 10 percent of total lime consumption in 1990 to 15 percent in 2001 (USGS 1992, 2002).

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. To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors. The emission factor 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 (95 percent for both types of lime). The emission factors were calculated as follows:

For high-calcium lime:

$$[(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.75 \text{ g } CO_2\text{/g lime}$$

For dolomitic lime:

$$[(88.02 \text{ g/mole } CO_2) \div (96.39 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.87 \text{ g } CO_2\text{/g lime}$$

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

Production is adjusted to remove the mass of chemically combined water found in hydrated lime, using the midpoint of default ranges provided by the *IPCC Good Practice Guidance* (IPCC 2000). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 24 percent for dolomitic hydrated lime.

Lime production in the United States was 18,957 thousand metric tons in 2001 (USGS 2002), resulting in potential CO_2 emissions of 14.0 Tg CO_2. 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 1,939 thousand metric tons in 2001, generating 1.4 Tg CO_2. It was assumed that approximately 80 percent of the CO_2 involved in sugar refining and PCC was recovered, resulting in actual CO_2 emissions of 12.9 Tg CO_2.

Data Sources

The activity data for lime manufacture and lime consumption by sugar refining and PCC production for 1990 through 2001 (see Table 3-13) were obtained from USGS (1992, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002). The CaO and CaO•MgO contents of lime were obtained from the *IPCC Good Practice Guidance* (IPCC 2000). Since data for the individual lime types was not provided prior to 1997, total lime production for 1990 through 1996 was allocated according to the 1997 distribution. For sugar refining and PCC, it was assumed that 100 percent of lime manufacture and consumption was high-calcium, based on communication with the National Lime Association (Males 2003).

Uncertainty

Uncertainties in the emission estimate can be attributed to slight differences in the chemical composition of these products. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, 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.

Table 3-13: Lime Production and Lime Use for Sugar Refining and PCC (Thousand Metric Tons)

Year	High-Calcium Production[a]	Dolomite Production[a,b]	Use
1990	12,947	2,895	826
1991	12,840	2,838	964
1992	13,307	2,925	1,023
1993	13,741	3,024	1,279
1994	14,274	3,116	1,374
1995	15,193	3,305	1,503
1996	15,856	3,434	1,429
1997	16,120	3,552	1,616
1998	16,750	3,423	1,779
1999	16,110	3,598	1,992
2000	15,850	3,621	2,067
2001	15,730	3,227	1,939

[a] Includes hydrated limes.
[b] Includes dead-burned dolomite.

Table 3-14: Hydrated Lime Production (Thousand Metric Tons)

Year	High-Calcium Hydrate	Dolomitic Hydrate
1990	1,781	319
1991	1,841	329
1992	1,892	348
1993	1,908	342
1994	1,942	348
1995	2,027	363
1996	1,858	332
1997	1,820	352
1998	1,950	383
1999	2,010	298
2000	1,550	421
2001	2,030	447

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 PCC reacts with CO_2; whereas most of the lime used in steel making 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.[5] As more information becomes available, this emission estimate will be adjusted accordingly.

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[5] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

In some cases, lime is generated from calcium carbonate by-products at paper mills and water treatment plants.[6] 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. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin, and therefore would not be included in Inventory totals.

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 ($CaCO_3MgCO_3$)[7] are basic raw materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass manufacture, and environmental pollution control.

Table 3-15: CO_2 Emissions from Limestone & Dolomite Use (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Flux Stone	3.0	3.7	4.1	4.8	5.0	5.5	2.5	2.1
Glass Making	0.2	0.5	0.4	0.3	0.1	+	0.4	0.1
FGD	1.4	1.7	2.0	1.5	1.3	1.3	1.8	2.6
Magnesium Production	0.1	+	0.1	0.1	0.1	0.1	0.1	0.1
Other Miscellaneous Uses	0.8	1.1	1.1	0.4	0.9	0.8	1.0	0.5
Total	**5.5**	**7.0**	**7.6**	**7.1**	**7.3**	**7.7**	**5.8**	**5.3**

+ Does not exceed 0.05 Tg CO_2 Eq.
Notes: Totals may not sum due to independent rounding. Other miscellaneous uses include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Table 3-16: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Flux Stone	**2,954**	**3,709**	**4,052**	**4,803**	**4,992**	**5,538**	**2,506**	**2,062**
Limestone	2,554	3,098	3,375	4,063	4,496	4,499	1,885	1,640
Dolomite	401	610	677	741	497	1,039	621	422
Glass Making	**214**	**494**	**389**	**327**	**123**	**+**	**383**	**113**
Limestone	189	413	299	327	68	+	383	113
Dolomite	25	81	90	+	54	+	+	+
FGD	**1,433**	**1,674**	**2,017**	**1,462**	**1,287**	**1,308**	**1,847**	**2,551**
Magnesium Production	**64**	**41**	**73**	**73**	**73**	**73**	**73**	**53**
Other Miscellaneous Uses	**804**	**1,125**	**1,084**	**389**	**856**	**752**	**953**	**501**
Total	**5,470**	**7,042**	**7,614**	**7,055**	**7,331**	**7,671**	**5,763**	**5,281**

+ Does not exceed 0.5 Gg.
Notes: Totals may not sum due to independent rounding. Other miscellaneous uses include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

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[6] 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.

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

Table 3-17: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Flux Stone	**6,632**	**8,303**	**9,069**	**10,764**	**11,244**	**12,372**	**5,567**	**4,599**
Limestone	5,804	7,042	7,671	9,234	10,218	10,225	4,285	3,728
Dolomite	828	1,261	1,399	1,530	1,026	2,147	1,282	871
Glass Making	**482**	**1,105**	**865**	**743**	**268**	**0**	**871**	**258**
Limestone	430	939	679	743	155	0	871	258
Dolomite	52	166	186	0	112	0	0	0
FGD	**3,258**	**3,805**	**4,583**	**3,324**	**2,924**	**2,974**	**4,199**	**5,799**
Other Miscellaneous Uses	**1,800**	**2,557**	**2,445**	**873**	**1,935**	**1,709**	**2,167**	**1,138**

NA (Not Available)

Note: "Other miscellaneous uses" includes chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

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 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 and magnesium production.

In 2001, approximately 10,923 thousand metric tons of limestone and 871 thousand metric tons of dolomite were consumed for these applications. Overall, usage of limestone and dolomite resulted in aggregate CO_2 emissions of 5.3 Tg CO_2 Eq. (5,281 Gg) (see Table 3-15 and Table 3-16). Emissions in 2001 decreased 8 percent from the previous year and have decreased 2 percent since 1990.

Methodology

Carbon dioxide emissions were calculated by multiplying the quantity of limestone or dolomite consumed by the average carbon content, approximately 12.0 percent for limestone and 13.2 percent for dolomite (based on stoichiometry). This assumes that all carbon is oxidized and released. This methodology was used for flux stone, glass manufacturing, FGD systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining and then converting to CO_2 using a molecular weight ratio.

Two magnesium production methods were in use in the United States during 2001. One plant produced magnesium metal from the dolomitic process, while the only other plant in the United States produced magnesium from magnesium chloride (electrolytic reduction). During the dolomitic process, CO_2 emissions during the thermic reduction of dolomite ($CaMg\ (CO_3)_2$) to magnesium metal vapor was estimated based on magnesium production capacity and the magnesium to carbon molar ratio. Capacity fluctuations are due to variable furnace availability. Operation at maximum operational capacity is assumed, which results in an overestimation of emissions. The assumption of emissions based on the magnesium to carbon molar ratio underestimates emissions from less than ideal (chemically) production. According to the reaction stoichiometry, two carbon molecules are emitted per magnesium molecule.

Data Sources

Consumption data for 1990 through 2001 of limestone and dolomite used for flux stone, glass manufacturing, FGD systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining (see Table 3-17) were obtained from personal communication with Valentine Tepordei of the USGS regarding data in the *Minerals Yearbook: Crushed Stone Annual Report* (Tepordei 2002 and USGS 1993, 1995a, 1995b, 1996a, 1997a, 1998a, 1999a, 2000a, 2001a). The production capacity data for 1990 through 2001 of dolomitic magnesium metal (see Table 3-18) also came from the USGS (1995c, 1996b, 1997b, 1998b, 1999b, 2000b, 2001b). During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Consumption figures for 1990 were estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1990 total use figure. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total figure.

Table 3-18: Dolomitic Magnesium Metal Production Capacity (Metric Tons)

Year	Production Capacity
1990	35,000
1991	35,000
1992	14,909
1993	12,964
1994	21,111
1995	22,222
1996	40,000
1997	40,000
1998	40,000
1999	40,000
2000	40,000
2001	29,167

Additionally, each year the USGS withholds certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. On average between 1990 and 2001 the USGS withheld estimates for two limestone and dolomite end-uses. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

Finally, 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 for emissive end uses. 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.[8]

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. Also, some of the limestone reported as "limestone" is believed to actually be dolomite, which has a higher carbon content. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, the uncertainty of the estimates for limestone used in glass making is especially high. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. However, since glass making accounts for a small percent of consumption, its contribution to the overall emissions estimate is low.

Soda Ash Manufacture and Consumption

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 three States produce natural soda ash: Wyoming, California, and Colorado. Of these three States, only Wyoming has net emissions of CO_2. This difference is a result of the production processes employed in each state.[9] During the

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[8] This approach was recommended by USGS.

[9] 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 not emitted.

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 is generated as a by-product of this reaction, and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed.

In 2001, CO_2 emissions from the manufacture of soda ash from trona were approximately 1.5 Tg CO_2 Eq. (1,500 Gg). Soda ash consumption in the United States generated 2.6 Tg CO_2 Eq. (2,648 Gg) in 2001. Total emissions from this source in 2001 were 4.1 Tg CO_2 Eq. (4,147 Gg) (see Table 3-19 and Table 3-20). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 2001 decreased by 1 percent from the previous year, and have increased overall by less than 1 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 2001 was glass making, 50 percent; chemical production, 27 percent; soap and detergent manufacturing, 11 percent; distributors, 6 percent; flue gas desulfurization and pulp and paper production, 2 percent each; and water treatment and miscellaneous, 1 percent each (USGS 2002).

The domestic market for soda ash continued to decrease in 2001, but was partially offset by an increase in exports. This increase followed the closure of a synthetic soda ash plant in Japan. Although the United States continues to be the major supplier of world soda ash, China's soda ash manufacturing capacity is rapidly increasing. This will likely cause greater competition in Asian markets in the future. The world market for soda ash is expected to grow 1.5 to 2 percent annually.

A new major soda ash plant that uses a new feedstock—nahcolite, a natural sodium bicarbonate found in deposits in Colorado's Piceance Creek Basin—came online in 2001. The new facility will have an annual capacity of 900,000 tons of soda ash and began operation in October 2001 (USGS 2001). Part of this production process involves the stripping of CO_2. At this point, however, it is unknown whether any CO_2 will be released to the atmosphere or captured and used for conversion back to sodium bicarbonate.

Table 3-19: CO_2 Emissions from Soda Ash Manufacture and Consumption

Year	Tg CO_2 Eq.
1990	4.1
1995	4.3
1996	4.2
1997	4.4
1998	4.3
1999	4.2
2000	4.2
2001	4.1

Table 3-20: CO_2 Emissions from Soda Ash Manufacture and Consumption (Gg)

Year	Manufacture	Consumption	Total
1990	1,431	2,710	4,141
1995	1,607	2,698	4,304
1996	1,587	2,652	4,239
1997	1,665	2,689	4,354
1998	1,607	2,718	4,325
1999	1,548	2,668	4,217
2000	1,529	2,652	4,181
2001	1,500	2,648	4,147

Note: Totals may not sum due to independent rounding.

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:

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

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2. Thus, the 15.4 million metric tons of trona mined in 2001 for soda ash production (USGS 2002) resulted in CO_2 emissions of approximately 1.5 Tg CO_2 Eq. (1,500 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 3-21) were taken from USGS (1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002). 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.

Table 3-21: Soda Ash Manufacture and Consumption (Thousand Metric Tons)

Year	Manufacture*	Consumption
1990	14,700	6,530
1991	14,700	6,280
1992	14,900	6,320
1993	14,500	6,280
1994	14,600	6,260
1995	16,500	6,500
1996	16,300	6,390
1997	17,100	6,480
1998	16,500	6,550
1999	15,900	6,430
2000	15,700	6,390
2001	15,400	6,380

* Soda ash manufactured from trona ore only.

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.

Titanium Dioxide Production

Titanium dioxide (TiO_2) is a metal oxide manufactured from titanium ore, and is principally used as a pigment. Titanium dioxide is a principal ingredient in white paint, and TiO_2 is also used as a pigment in the manufacture of white paper, foods, and other products. There are two processes for making TiO_2, the chloride process and the sulfate process. Carbon dioxide is emitted from the chloride process, which uses petroleum coke and chlorine as raw materials and emits process-related CO_2. The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2. In 2001, approximately 95 percent of the titanium dioxide production capacity was chloride process and the remainder was sulfate process.

The chloride process is based on the following chemical reactions:

$$2\,FeTiO_3 + 7\,Cl_2 + 3\,C \rightarrow 2\,TiCl_4 + 2\,FeCl_3 + 3\,CO_2$$

$$2\,TiCl_4 + 2\,O_2 \rightarrow 2\,TiO_2 + 4\,Cl_2$$

The carbon in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (the Ti-containing ore) to form CO_2. The majority of U.S. TiO_2 was produced in the United States through the chloride process, and a special grade of petroleum coke is manufactured specifically for this purpose. Emissions of CO_2 from titanium dioxide production in 2001 were 1.9 Tg CO_2 Eq. (1,857 Gg), an increase of 42 percent from 1990 due to increasing production within the industry (see Table 3-22).

Table 3-22: CO_2 Emissions from Titanium Dioxide

Year	Tg CO_2 Eq.	Gg
1990	1.3	1,308
1995	1.7	1,670
1996	1.7	1,657
1997	1.8	1,836
1998	1.8	1,819
1999	1.9	1,853
2000	1.9	1,918
2001	1.9	1,857

Methodology

Emissions of CO_2 from titanium dioxide production were calculated by multiplying annual titanium dioxide production by chlorine process-specific emission factors.

Data were obtained for the total amount of titanium dioxide produced each year, and it was assumed that 95 percent of the total production in 2001 was produced using the chloride process. An emission factor of 0.4 metric tons

C/metric ton TiO_2 was applied to the estimated chloride process production. It was assumed that all titanium dioxide produced using the chloride process was produced using petroleum coke, although some titanium dioxide may have been produced with graphite or other carbon inputs. The amount of petroleum coke consumed annually in titanium dioxide production was calculated based on the assumption that petroleum coke used in the process is 90 percent carbon and 10 percent inert materials.

Data Sources

The emission factor for the titanium dioxide chloride process was taken from the report *Everything You've Always Wanted to Know about Petroleum Coke* (Onder and Bagdoyan 1993). Titanium dioxide production data for 1990 through 2000 (see Table 3-23) were obtained from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Titanium Annual Report* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001). Data for 2001 were obtained from U.S. Census Bureau (2002) *Current Industrial Reports: Titanium Dioxide, November 2002*. Data for the percentage of the total titanium dioxide production capacity that is chloride process for 1994 through 2000 were also taken from the USGS *Minerals Yearbook*. Percentage chloride process data were not available for 1990 through 1993, and data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate-process plant closed in September 2001, the chloride process percentage for 2001 was estimated based on a discussion with Joseph Gambogi, USGS Commodity Specialist (2002). The composition data for petroleum coke were obtained from Onder and Bagdoyan (1993).

Table 3-23: Titanium Dioxide Production

Year	Metric Tons
1990	979,000
1991	992,000
1992	1,140,000
1993	1,160,000
1994	1,250,000
1995	1,250,000
1996	1,230,000
1997	1,340,000
1998	1,330,000
1999	1,350,000
2000	1,400,000
2001	1,330,000

Uncertainty

Although some titanium dioxide may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs may generate differing amounts of CO_2 per unit of titanium dioxide produced compared to the use of petroleum coke. The most accurate method for these estimates would be basing calculations on the amount of reducing agent used in the process, rather than the amount of titanium dioxide produced. These data were not available, however.

Also, annual titanium production is not reported by USGS by the type of production process used (chloride or sulfate). Only the percentage of total production capacity is reported. It was assumed that titanium dioxide was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. This assumes that the chloride process plants and sulfate process plants operate at the same level of utilization. Finally, the emission factor was applied uniformly to all chloride process production, and no data were available to account for differences in production efficiency among chloride process plants. In calculating the amount of petroleum coke consumed in chloride process titanium dioxide production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the titanium dioxide chloride process, however this composition information was not available.

Ferroalloy Production

Carbon dioxide is emitted from the production of several ferroalloys. Ferroalloys are composites of iron and other elements such as 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 (25 to 55 percent and 56 to 95 percent silicon), silicon metal (about 98 percent silicon), and miscellaneous alloys (36 to 65 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 in the United States. Subsequently, government information disclosure rules prevent the publication of production data for these

Table 3-24: CO_2 Emissions from Ferroalloy Production

Year	Tg CO_2 Eq.	Gg
1990	2.0	1,980
1995	1.9	1,866
1996	2.0	1,954
1997	2.0	2,038
1998	2.0	2,027
1999	2.0	1,996
2000	1.7	1,719
2001	1.3	1,329

Table 3-25: Production of Ferroalloys (Metric Tons)

Year	Ferrosilicon 25%-55%	Ferrosilicon 56%-95%	Silicon Metal	Misc. Alloys (32%-65%)
1990	321,385	109,566	145,744	72,442
1995	184,000	128,000	163,000	99,500
1996	182,000	132,000	175,000	110,000
1997	175,000	147,000	187,000	106,000
1998	162,000	147,000	195,000	99,800
1999	252,000	145,000	195,000	NA
2000	229,000	100,000	184,000	NA
2001	167,000	89,000	137,000	NA

NA (Not Available)

production facilities. 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 to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon is given below:

$$Fe_2O_3 + 2SiO_2 + 7C \longrightarrow 2FeSi + 7CO$$

Emissions of CO_2 from ferroalloy production in 2001 were 1.3 Tg CO_2 Eq. (1,329 Gg) (see Table 3-24), a 23 percent reduction from the previous year.

Methodology

Emissions of CO_2 from ferroalloy production were calculated by multiplying annual ferroalloy production by material-specific emission factors. Emission factors taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) were applied to ferroalloy production. For ferrosilicon alloys containing 25 to 55 percent silicon and miscellaneous alloys (including primarily magnesium-ferrosilicon, but also including other silicon alloys) containing 32 to 65 percent silicon, an emission factor for 50 percent silicon ferrosilicon (2.35 tons CO_2/ton of alloy produced) was applied. Additionally, for ferrosilicon alloys containing 56 to 95 percent silicon, an emission factor for 75 percent silicon ferrosilicon (3.9 tons CO_2 per ton alloy produced) was applied. The emission factor for silicon metal was assumed to be 4.3 tons CO_2/ton metal produced. It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke using an electric arc furnace process (IPCC/UNEP/OECD/IEA 1997), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon and 10 percent inert material.

Data Sources

Emission factors for ferroalloy production were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Ferroalloy production data for 1990 through 2001 (see Table 3-25) were obtained from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Silicon Annual Report* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002). Until 1999, the USGS reported production of ferrosilicon containing 25 to 55 percent silicon separately from production of miscellaneous alloys containing 32 to 65 percent silicon; beginning in 1999, the USGS reported these as a single category (see Table 3-25). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

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 or other biomass would not be counted under this source because wood-based carbon is of biogenic origin.[10] Emissions from ferroalloys produced with coking coal or graphite inputs would be counted in

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[10] Emissions and sinks of biogenic carbon are accounted for in the Land-Use Change and Forestry chapter.

national trends, but may generate differing amounts of CO_2 per unit of ferroalloy produced compared to the use of petroleum coke. The most accurate method for these estimates would be basing calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data were not available, however.

Also, annual ferroalloy production is now reported by the USGS in three broad categories: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal. It was assumed that the IPCC emission factors apply to all of the ferroalloy production processes, including miscellaneous alloys. Finally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing company proprietary data. Emissions from this production category, therefore, were not estimated.

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 be released to 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.

Table 3-26: CO_2 Emissions from Carbon Dioxide Consumption

Year	Tg CO_2 Eq.	Gg
1990	0.9	895
1995	1.1	1,088
1996	1.1	1,138
1997	1.2	1,162
1998	1.2	1,186
1999	1.2	1,210
2000	1.2	1,233
2001	1.3	1,257

In 2001, CO_2 emissions from this source not accounted for elsewhere were 1.3 Tg CO_2 Eq. (1,257 Gg) (see Table 3-26). This amount represents an increase of 2 percent from the previous year and an increase of 40 percent from emissions in 1990.

Methodology

Carbon dioxide emission estimates were based on CO_2 consumption, and assume 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 6,287 thousand metric tons in 2001. The Freedonia Group estimates that, in the United States, there is an 80 percent to 20 percent split between CO_2 produced as a by-product and CO_2 produced from natural wells. Thus, emissions from this source are equal to 20 percent of CO_2 consumption. The remaining 80 percent was assumed to 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 3-27) were obtained from *Industrial Gases to 2006*, a report published by the Freedonia Group, Inc. (2002). The Freedonia Group, Inc.

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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.

Table 3-27: Carbon Dioxide Consumption

Year	Thousand Metric Tons
1990	4,476
1991	4,652
1992	4,683
1993	4,935
1994	5,186
1995	5,438
1996	5,690
1997	5,809
1998	5,929
1999	6,048
2000	6,167
2001	6,287

report contains actual data for 2001, 1996, and 1992. Data for 1990 through 1991, 1993 through 1995, and 1997 through 2000 were obtained by extrapolating the trend created by the 2001, 1996, and 1992 values. The percent of CO_2 produced from natural wells was obtained from Freedonia Group, Inc. (1991).

Uncertainty

Uncertainty exists in the assumed allocation of CO_2 produced from fossil fuel by-products (80 percent) and CO_2 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. Further research is required to determine the quantity, if any, that may be recovered.

Petrochemical Production

Methane is released, in small amounts, 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 generated by the incomplete combustion of an aromatic petroleum feedstock. Most carbon black produced in the United States 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 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 2001 were 1.5 Tg CO_2 Eq. (71 Gg) (see Table 3-28), a decrease of 11 percent from the previous year.

Table 3-28: CH_4 Emissions from Petrochemical Production

Year	Tg CO_2 Eq.	Gg
1990	1.2	56
1995	1.5	72
1996	1.6	75
1997	1.6	77
1998	1.6	78
1999	1.7	80
2000	1.7	79
2001	1.5	71

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,[12] 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 CH_4 emissions, there were not sufficient data to estimate their emissions.

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[12] 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 ($C_2H_4Cl_2$).

Table 3-29: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	1990	1995	1996	1997	1998	1999	2000	2001
Carbon Black	1,306	1,524	1,560	1,588	1,610	1,642	1,674	1,583
Ethylene	16,542	21,215	22,217	23,088	23,474	25,118	24,971	22,521
Ethylene Dichloride	6,282	7,829	9,303	10,324	11,080	10,308	9,866	9,294
Styrene	3,637	5,166	5,402	5,171	5,183	5,410	5,420	4,277
Methanol	3,785	4,992	5,280	5,743	5,860	5,303	5,221	5,053

Data Sources

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Annual production data for 1990 (see Table 3-29) were obtained from the Chemical Manufacturer's Association *Statistical Handbook* (CMA 1999). Production data for 1991 through 2001 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (2002).

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 CH_4 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 carbon 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, these emissions are already accounted for under CO_2 from Fossil Fuel Combustion in the Energy chapter. Emissions of CH_4 from silicon carbide production in 2001 (see Table 3-30) were 0.5 Gg CH_4 (0.01 Tg CO_2 Eq.).

Table 3-30: CH_4 Emissions from Silicon Carbide Production

Year	Tg CO_2 Eq.	Gg
1990	+	1
1995	+	1
1996	+	1
1997	+	1
1998	+	1
1999	+	1
2000	+	+

+ Does not exceed 0.05 Tg CO_2 Eq. or 0.5 Gg

Methodology

Emissions of CH_4 were calculated by multiplying annual 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 2001 (see Table 3-31) were obtained from the *Minerals Yearbook: Volume I-Metals and Minerals, Manufactured Abrasives* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002).

Table 3-31: 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
1999	65,000
2000	45,000
2001	40,000

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.

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.

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 NO_x, 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. 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 emissions.

Nitrous oxide emissions from this source were estimated at 17.6 Tg CO_2 Eq. (56.8 Gg) in 2001 (see Table 3-32). Emissions from nitric acid production have decreased 1.4 percent since 1990, with the trend in the time series closely tracking the changes in production.

Methodology

Nitrous oxide emissions were calculated by multiplying nitric acid production by the amount of N_2O emitted per unit of nitric acid produced. The emissions factor was determined as a weighted average of 2 kg N_2O / metric ton HNO_3 for plants using non-selective catalytic reduction (NSCR) systems and 9.5 kg N_2O / metric ton HNO_3 for plants not equipped with NSCR (Choe et al. 1993). In the process of destroying NO_x, NSCR systems destroy 80 to 90 percent of the N_2O, which is accounted for in the emission factor of 2 kg N_2O / metric ton HNO_3. An estimated 20 percent of HNO_3 plants in the United States are equipped with NSCR (Choe et al. 1993). Hence, the emission factor is equal to (9.5 x 0.80) + (2 x 0.20) = 8 kg N_2O per metric ton HNO_3.

Data Sources

Nitric acid production data for 1990 (see Table 3-33) was obtained from *Chemical and Engineering News*, “Facts and Figures” (C&EN 2001). Nitric acid production data for 1991 through 2001 (see Table 3-33) were obtained from *Chemical and Engineering News*, “Facts and Figures” (C&EN 2002). The emission factor range was taken from Choe, et al. (1993).

Table 3-32: N_2O Emissions from Nitric Acid Production

Year	Tg CO_2 Eq.	Gg
1990	17.8	57.6
1995	19.9	64.2
1996	20.7	66.8
1997	21.2	68.5
1998	20.9	67.4
1999	20.1	64.9
2000	19.1	61.5
2001	17.6	56.8

Table 3-33: 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	8,423
1999	8,115
2000	7,692
2001	7,097

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 explosives manufacturing. As a result, only a small volume of nitric acid is sold on the market making production quantities 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.

Adipic Acid Production

Adipic acid production is an anthropogenic source of nitrous oxide (N_2O) emissions. Worldwide, few adipic acid plants exist. The United States is the major producer with three companies in four locations accounting for approximately one-third 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. Food grade adipic acid is also used to provide some foods with a "tangy" flavor (Thiemems and Trogler 1991). Approximately 90 percent of all adipic acid produced in the United States is used in the production of nylon 6,6 (CMR 2001).

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 (Thiemens and Trogler 1991). Process emissions from the production of adipic acid 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 had N_2O abatement technologies in place and as of 1998, the three major adipic acid production facilities had control systems in place.[13] Only one small plant, representing approximately two percent of production, does not control for N_2O (Reimer 1999).

Table 3-34: N_2O Emissions from Adipic Acid Production

Year	Tg CO_2 Eq.	Gg
1990	15.2	49.0
1995	17.2	55.5
1996	17.0	55.0
1997	10.3	33.3
1998	6.0	19.3
1999	5.5	17.7
2000	6.0	19.5
2001	4.9	15.9

Nitrous oxide emissions from this source were estimated to be 4.9 Tg CO_2 Eq. (15.9 Gg) in 2001 (see Table 3-34).

National adipic acid production has increased by approximately 14 percent over the period of 1990 through 2001, to approximately 0.8 million metric tons. At the same time, emissions have been significantly reduced due to the widespread installation of pollution control measures.

Methodology

For two production plants, 1990 to 2001 emission estimates were obtained directly from the plant engineer and account for reductions due to control systems in place at these plants during the time series. For the other two plants, N_2O 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 mt of N_2O per metric ton of product. Emissions are estimated using the following equation:

$$N_2O \text{ emissions} = [\text{production of adipic acid (mt of adipic acid)}] \times [0.3 \text{ mt } N_2O / \text{mt adipic acid}] \times [1 - (N_2O \text{ destruction factor} \times \text{abatement system utility factor})]$$

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[13] During 1997, the N_2O emission controls installed by the third plant operated for approximately a quarter of the year.

Table 3-35: Adipic Acid Production

Year	Thousand Metric Tons
1990	735
1991	708
1992	723
1993	769
1994	821
1995	830
1996	839
1997	871
1998	862
1999	907
2000	925
2001	835

The "N_2O destruction factor" represents the percentage of N_2O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the abatement equipment operates during the annual production period. Overall, in the United States, two of the plants employ catalytic destruction, one plant employs thermal destruction, and the smallest plant uses no N_2O abatement equipment. The N_2O abatement system destruction factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer et al. 1999, Reimer 1999).

Data Sources

National adipic acid production data (see Table 3-35) for 1990 through 2001 were obtained from the American Chemical Council (ACC 2002). Plant capacity data for 1990 through 1994 were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992, 1993, 1994, 1995). Plant capacity data for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacity data were taken from *Chemical Market Reporter* "Chemical Profile: Adipic Acid" (CMR 1998). The 1998 plant capacity data for all four plants and 1999 plant capacity data for three of the plants were obtained from *Chemical Week*, Product focus: adipic acid/adiponitrile (CW 1999). Plant capacity data for 2000 and 2001 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). Plant capacity data for 1999, 2000, and 2001 for the one remaining plant was kept the same as 1998. The emission factor was taken from Thiemens and Trogler (1991). The national production and plant capacities were utilized for two of the four plants. Information for the other two plants was taken directly from the plant engineer (Childs 2002).

Uncertainty

In order to calculate emissions for the two plants where emissions were not provided by the plant engineer, production data on a plant-specific basis was needed. However, these production data are considered confidential and were not available from the plants. As a result, plant-specific production figures for the two plants were calculated by allocating national adipic acid production using existing plant capacities. This allocation creates a degree of uncertainty in the adipic acid production data as all plants are assumed to operate at equivalent utilization levels as represented by their capacities.

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.

Nitrous Oxide Product Usage

Nitrous oxide is a clear, colorless, oxidizing liquefied gas, with a slightly sweet odor. Nitrous oxide is produced by thermally decomposing ammonium nitrate (NH_4NO_3), a chemical commonly used in fertilizers and explosives. The decomposition creates steam (H_2O) and N_2O by a low pressure, low-temperature (500°F) reaction. Once the steam is condensed out, the N_2O is purified, compressed, dried, and liquefied for storage and distribution. Two manufacturers of N_2O exist in the United States (CGA 2002).

Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia and as an anesthetic in various dental and veterinary applications. As such, it is used to treat short-term pain, for sedation in minor elective surgeries and as an induction anesthetic. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O are also used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2001 was approximately 17.0 thousand metric tons. Nitrous oxide emissions were 4.8 Tg CO_2 Eq. (15.5 Gg) in 2001 (see Table 3-36). Production of N_2O has stabilized over the past decade because medical markets have found other substitutes for anesthetics, and more medical procedures are being performed on an outpatient basis using local anesthetics. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs.

Methodology

Emissions from N_2O product usage were calculated by first multiplying the total amount of N_2O produced in the United States by the share of the total quantity of N_2O that is used by each sector. This value was then multiplied by the associated emissions rate for each sector. After the emissions were calculated for each sector, they were added together to obtain a total estimate of N_2O product usage emissions. Emissions were determined using the following equation:

$$\text{Nitrous Oxide Product Usage Emissions} = \sum_i [\text{Total U.S. Production of Nitrous Oxide}] \times [\text{Share of Total Quantity of } N_2O \text{ Usage by Sector}] \times [\text{Emissions Rate for Sector}]$$

where,

i = each sector

The share of total quantity of N_2O usage by sector represents the share of national N_2O produced that is used by the given sector. For example, in 2001, the medicine/dentistry industry used an estimated 87 percent of total N_2O produced, followed by food processing propellants at 6 percent. All other categories combined used the remaining 7 percent of the N_2O produced (Tupman 2002). This sector breakdown has changed only slightly over the past decade. For instance, the small share of N_2O usage in the production of sodium azide has declined significantly during the decade of the 1990's. Due to the lack of information on the specific time period of the phase-out in this market sector, it was assumed that most of the N_2O usage for sodium azide production ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dentistry consumption sector. Once the N_2O is allocated across these sectors, a usage emissions rate is then applied for each sector to estimate the amount of N_2O emitted.

Table 3-36: N_2O Emissions from Nitrous Oxide Product Usage

Year	Tg CO_2 Eq.	Gg N_2O
1990	4.3	13.9
1995	4.5	14.4
1996	4.5	14.4
1997	4.8	15.5
1998	4.8	15.5
1999	4.8	15.5
2000	4.8	15.5
2001	4.8	15.5

Only the medical/dentistry and food propellant sectors are estimated to release emissions into the atmosphere, and therefore these sectors are the only usage sectors with emission rates. For the medicine/dentistry sector, due to the poor solubility of N_2O in blood and other tissues, approximately 97.5 percent of the N_2O is not metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emissions factor of 97.5 percent is used for this sector (Tupman 2002). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere resulting in an emissions factor of 100 percent for this sector (Heydorn 1997). For the remaining sectors all of the N_2O is consumed/reacted during the process, and therefore the emissions rate is considered to be zero percent (Tupman 2002).

Data Sources

The 1990 through 1992 and 1996 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). These data were provided as a range. For example, in 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. An industry expert was able to provide a narrower range for 1996 that falls within the production bounds described by Heydorn (1997). These data are considered more industry specific and current (Tupman 2002). The midpoint of the narrower production range (15.9 to 18.1 thousand metric tons) was used to estimate N_2O emissions for years 1993 through 2001.

The 1996 share of the total quantity of N_2O used by each sector was obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each sector was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The emissions rate for the food processing propellant industry was obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997), and confirmed by a N_2O industry expert (Tupman 2002). The emissions rate for all other sectors was obtained from communication with a N_2O industry expert (Tupman 2002). The emissions rate for the medicine/dentistry sector was substantiated by the *Encyclopedia of Chemical Technology* (Othmer 1990).

Uncertainty

Since plant specific N_2O production data is confidential, emissions are based on national production statistics, which were provided as a range. Based on the N_2O production ranges described by Heydorn (1997) and Tupman (2002), uncertainty associated with the production estimate used to develop industry emissions for 1993 through 2001 are within –20 percent and +7 percent. For 1990 through 1992, the uncertainty in the production data is ± 3 percent. Information regarding the industry specific use of N_2O is also confidential. Thus, the predicted share of the total quantity of N_2O used by each sector is somewhat uncertain because it is based on industry expert opinion. In particular, the exact timeframe for the market decline in N_2O use during sodium azide production is unknown. The emissions rate for the medicine/dentistry industry is an estimate also based on industry opinion and does not have a published source that confirms the percent of emissions released into the environment.

Table 3-37: N_2O Production (Thousand Metric Tons)

Year	Thousand Metric Tons
1990	16.3
1991	15.9
1992	15.0
1993	17.0
1994	17.0
1995	17.0
1996	17.0
1997	17.0
1998	17.0
1999	17.0
2000	17.0
2001	17.0

Substitution of Ozone Depleting Substances

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used 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.[14] 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 to the stratospheric ozone layer, they are potent greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 3-38 and Table 3-39.

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-404A.[15] In 1993, the use of HFCs in foam production and as an aerosol propellant 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 has been increasing from small amounts in 1990 to 63.7 Tg CO_2 Eq. in 2001. This increase was in large

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[14] [42 U.S.C § 7671, CAA § 601]

[15] R-404A contains HFC-125, HFC-143a, and HFC-134a.

Table 3-38: Emissions of HFCs and PFCs from ODS Substitution (Tg CO_2 Eq.)

Gas	1990	1995	1996	1997	1998	1999	2000	2001
HFC-23	+	0.1	0.1	0.2	0.2	0.3	0.4	0.5
HFC-32	+	+	+	+	+	+	0.1	0.2
HFC-125	+	1.3	1.9	2.5	3.1	3.6	4.4	5.2
HFC-134a	0.7	15.9	21.1	26.2	30.0	33.9	37.6	41.0
HFC-143a	+	0.4	0.8	1.3	1.9	2.6	3.4	4.3
HFC-236fa	+	+	+	0.1	0.8	1.3	1.9	2.3
CF_4	+	+	+	+	+	+	+	+
Others*	0.2	4.0	6.6	7.5	8.5	9.1	9.6	10.1
Total	**0.9**	**21.7**	**30.4**	**37.7**	**44.5**	**50.9**	**57.3**	**63.7**

+ Does not exceed 0.05 Tg CO_2 Eq.
* Others include HFC-152a, HFC-227ea, HFC-4310mee, and PFC/PFPEs, the latter being 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.

Table 3-39: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	1995	1996	1997	1998	1999	2000	2001
HFC-23	+	5	9	14	19	26	32	39
HFC-32	+	+	3	7	11	17	94	240
HFC-125	+	478	675	889	1,116	1,289	1,559	1,869
HFC-134a	564	12,232	16,211	20,166	23,089	26,095	28,906	31,552
HFC-143a	+	111	209	334	488	676	903	1,142
HFC-236fa	+	+	+	15	120	213	296	370
CF_4	+	+	+	+	+	1	1	1
Others*	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, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely accelerate in the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

Methodology and Data Sources

A detailed vintaging model of ODS-containing equipment and products was used 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. Further information on the Vintaging Model is contained in Annex K.

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 Vintaging Model or the methods outlined in IPCC/UNEP/OECD/IEA (1997). Though the model is more comprehensive than the IPCC default 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. In 2001, the United States was the third largest producer of primary aluminum, with 11 percent of the world total (USGS 2002). 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 process-related emissions of CO_2 and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

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.

Table 3-40: CO_2 Emissions from Aluminum Production

Year	Tg CO_2 Eq.	Gg
1990	6.3	6,315
1995	5.3	5,265
1996	5.6	5,580
1997	5.6	5,621
1998	5.8	5,792
1999	5.9	5,895
2000	5.4	5,410
2001	4.1	4,114

Process emissions of CO_2 from aluminum production were estimated at 4.1 Tg CO_2 Eq. (4,114 Gg) in 2001 (see Table 3-40). The carbon anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke, and is accounted for in the Industrial Processes chapter and not with Fossil Fuel Combustion emissions in the Energy chapter. Similarly, the coal tar pitch portion of these CO_2 process emissions is subtracted from the Iron and Steel section—where it would otherwise be counted—to avoid double-counting.

In addition to CO_2 emissions, the aluminum production industry is also the second largest source (after semiconductor manufacturing) 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. As the anode effects become longer and more frequent, there is a corresponding rise in emission levels.

Primary aluminum production-related emissions of PFCs are estimated to have declined 77 percent since 1990. Since 1990, emissions of CF_4 and C_2F_6 have declined 77 and 76 percent, respectively, to 3.6 Tg CO_2 Eq. of CF_4 (0.6 Gg CF_4) and 0.6 Tg CO_2 Eq. of C_2F_6 (0.1 Gg C_2F_6) in 2001, as shown in Table 3-41 and Table 3-42. This decline was due to both reductions in domestic aluminum production and actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects.

U.S. primary aluminum production for 2001—totaling 2,637 thousand metric tons—decreased by 24 percent from 2000. This decrease is attributed to the curtailment of production at several U.S. smelters, due to high electric power costs in various regions of the country. The transportation industry remained the largest domestic consumer of aluminum, accounting for about 35 percent (USGS 2002).

Table 3-41: PFC Emissions from Aluminum Production (Tg CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	15.8	2.3	18.1
1995	10.5	1.3	11.8
1996	11.1	1.4	12.5
1997	9.8	1.2	11.0
1998	8.1	0.9	9.0
1999	8.0	0.9	8.9
2000	7.1	0.8	7.9
2001	3.6	0.6	4.1

Note: Totals may not sum due to independent rounding.

Table 3-42: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.4	0.2
1995	1.6	0.1
1996	1.7	0.1
1997	1.5	0.1
1998	1.2	0.1
1999	1.2	0.1
2000	1.1	0.1
2001	0.6	0.1

Methodology

Carbon dioxide is generated during alumina reduction to aluminum metal following the reaction below:

$$2Al_2O_3 + 3C \longrightarrow 4Al + 3CO_2$$

The CO_2 emission factor employed was estimated from the production of primary aluminum metal and the carbon consumed by the process. Emissions vary depending on the specific technology used by each plant (e.g., Prebake or Soderberg). The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provide CO_2 emission factors for each technology type. During alumina reduction in a prebake anode cell process, approximately 1.5 metric tons of CO_2 are emitted for each metric ton of aluminum produced (IPCC/UNEP/OECD/IEA 1997). Similarly, during alumina reduction in a Soderberg cell process, approximately 1.8 metric tons of CO_2 are emitted per metric ton of aluminum produced (IPCC/UNEP/OECD/IEA 1997). Based on information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, production was assumed to be split 80 percent prebake and 20 percent Soderberg for the whole time series.

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:

$$\text{PFC } (CF_4 \text{ or } C_2F_6) \text{ kg/metric ton Al} = S \times \text{Anode Effect Minutes/Cell-Day}$$

where,

S = Slope coefficient

Anode Effect Minutes/Cell-Day = Anode Effect Frequency × Anode Effect Duration

For 8 out of the 23 U.S. smelters (4 out of the 18 smelters operating in 2001), smelter-specific slope coefficients based on field measurements were used. For the remaining smelters, technology-specific slope coefficients from *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) were used. The slope coefficients were combined with smelter anode effect data, collected by aluminum companies and reported to the VAIP, to estimate emission factors over time. Where smelter-specific anode effect data were not available (2 out of 23 smelters), industry averages were used. Emissions factors were multiplied by annual production to estimate annual emissions at the smelter level. Smelter-specific production data was available for 20 of the 23 smelters (15 of the 18 smelters operating in 2001); production at the remaining smelters was estimated based on national aluminum production and capacity data (USGS). Emissions were then aggregated across smelters to estimate national emissions. The methodology used to estimate emissions is consistent with the methodologies recommended by the *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

Data Sources

Primary aluminum production data for 1990 through 1999 and 2001 (see Table 3-43) were obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000, 2002). The USGS requested data from the 11 domestic producers, all of whom responded. Primary aluminum production data for 2000 were obtained by using information from VAIP program submittals and from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 2001). Comparing a subset of smelter specific production data from EPA's VAIP program and the USGS *Mineral Industry Surveys:*

Table 3-43: 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
1999	3,779
2000	3,468
2001	2,637

Aluminum Annual Report (USGS 2001), it was observed that in 2000 the VAIP program data was approximately 200 thousand metric tons less than the USGS production total. The data from VAIP were believed to provide a more accurate estimate of U.S. aluminum production and therefore were used to calculate emissions for 2000. The CO_2 emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Emission estimates of PFCs were provided by aluminum smelters participating in the VAIP program. Where smelter-specific slope coefficients were not available, technology-specific coefficients were drawn from the IPCC's *Good Practice Guidance* (IPCC 2000). Information on the average frequency and duration of anode effects was taken from the International Aluminum Institute's anode effect survey (IAI 2000).

Uncertainty

Carbon dioxide emissions vary depending on the specific technology used by each plant. A more accurate method would be to calculate CO_2 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.

Using IPCC Good Practice Guidance Tier 1 methodology, the overall uncertainty associated with the 2001 CF_4 and C_2F_6 emissions estimates is ± 16 and ± 18 percent, respectively, using a 95 percent confidence interval. For the 2000 PFC emission estimates, the uncertainty of the CF_4 estimate is estimated to be ± 11 percent and the uncertainty of the C_2F_6 estimate is estimated to be ± 13 percent. For the 1991 estimates, the corresponding uncertainties are ± 8 percent and ± 11 percent. For each smelter, uncertainty associated with the quantity of aluminum produced, the frequency and duration of anode effects, and the slope factor was estimated. Error propagation analysis was then applied to estimate the overall uncertainty of the emissions estimate for each smelter and for the U.S. aluminum industry as a whole. The uncertainty of aluminum production estimates ranged between 1 percent and 25 percent, depending on whether a smelter's production was reported or estimated. The uncertainty of the frequency and duration of anode effects ranged between 2 percent and 78 percent, depending on whether these parameters were reported or were estimated using industry-wide averages. Given the limited uncertainty data on site-specific slope coefficients (i.e., those developed using IPCC Tier 3b methodology), it was assumed that the overall uncertainty associated with the slope coefficients would be similar to that given by the IPCC guidance for technology-specific slope coefficients. Consequently, the uncertainty assigned to the slope coefficients ranged between 7 percent and 35 percent, depending upon the gas and the smelter technology type. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Occasionally, SF_6 is also used by the aluminum industry as a cover gas or a fluxing and degassing agent in experimental and specialized casting operations. In its application as a cover gas, SF_6 is mixed with nitrogen or CO_2 and injected above the surface of molten aluminum; as a fluxing and degassing agent, SF_6 is mixed with argon, nitrogen, and/or chlorine and blown through molten aluminum. These practices are not employed extensively by primary aluminum producers and are believed to be isolated to secondary casting firms. The aluminum industry in the United States and Canada was estimated to use 230 Mg of SF_6 per year (Maiss and Brenninkmeijer 1998); however, this estimate is highly uncertain.

Historically, SF_6 from aluminum activities has been omitted from estimates of global SF_6 emissions, with the caveat that any emissions would be insignificant (Ko et al. 1993, Victor and MacDonald 1998). Emissions are believed to be insignificant, given that the concentration of SF_6 in the mixtures is small and a portion of the SF_6 is decomposed in the process (MacNeal et al. 1990, Gariepy and Dube 1992, Ko et al. 1993, Ten Eyck and Lukens 1996, Zurecki 1996).

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 in its uses as a degassing agent or cover gas.

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, its production for non-feedstock uses is scheduled to be phased out by 2020 under the U.S. Clean Air Act.[16] Feedstock production, however, 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. The 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 by-product, or may be captured for use in a limited number of applications.

Emissions of HFC-23 in 2001 were estimated to be 19.8 Tg CO_2 Eq. (1.7 Gg). This quantity represents a 33 percent decrease from emissions in 2000, and a 43 percent decrease from emissions in 1990 (see Table 3-44). Although HCFC-22 production has increased by 10 percent since 1990, the intensity of HFC-23 emissions (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined by 48 percent over the same period, lowering emissions. Four HCFC-22 production plants operated in the United States in 2001, two of which used thermal oxidation to significantly lower (and in at least one case, virtually eliminate) their HFC-23 emissions.

Table 3-44: HFC-23 Emissions from HCFC-22 Production

Year	Tg CO_2 Eq.	Gg
1990	35.0	3.0
1995	27.0	2.3
1996	31.1	2.7
1997	30.0	2.6
1998	40.2	3.4
1999	30.4	2.6
2000	29.8	2.6
2001	19.8	1.7

In the future, production of HCFC-22 in the United States is expected to decline as non-feedstock HCFC production is phased-out. Feedstock production is anticipated to continue growing, mainly for manufacturing fluorinated polymers.

Methodology

The methodology employed for estimating emissions is based upon measurements at individual HCFC-22 production plants. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. The other plants periodically measure HFC-23 concentrations in the output stream using gas chromotography. This information is combined with information on quantities of critical feed components (e.g., HF) and/or products (HCFC-22) to estimate HFC-23 emissions using a material balance approach. HFC-23 concentrations are determined at the point the gas leaves the chemical reactor; therefore, estimates also include fugitive emissions.

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[16] 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 3-45: HCFC-22 Production

Year	Gg
1990	138.9
1991	142.7
1992	149.6
1993	132.4
1994	146.8
1995	154.7
1996	166.1
1997	164.5
1998	182.8
1999	165.5
2000	186.9
2001	152.4

Data Sources

Emission estimates were provided by the EPA's Global Programs Division in cooperation with the U.S. manufacturers of HCFC-22. Annual estimates of U.S. HCFC-22 production are presented in Table 3-45.

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 believed that the emissions reported are roughly within 10 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. More simplistic emission estimates generally assume that HFC-23 emissions are between 2 and 4 percent of HCFC-22 production on a mass ratio basis.

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 conducting material to connect individual circuit components in silicon wafers, using HFCs, PFCs, SF_6 and other gases in plasma form. The etching process uses plasma-generated 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 use 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 (i.e., 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 emissions of unreacted gases, these compounds can also be transformed in the plasma processes into a different HFC or PFC compound,

Table 3-46: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq.)

Year	1990	1995	1996	1997	1998	1999	2000	2001
CF_4	0.7	1.5	1.4	1.7	1.8	1.9	1.9	1.4
C_2F_6	1.5	3.2	2.9	3.5	3.9	4.2	4.0	3.0
C_3F_8	0.1	0.2	0.2	0.2	0.2	0.3	0.2	0.2
HFC-23	0.1	0.2	0.2	0.2	0.2	0.3	0.2	0.2
SF_6	0.4	0.8	0.8	1.0	1.0	1.1	1.1	0.7
NF_3*	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Total	**2.9**	**5.9**	**5.4**	**6.5**	**7.3**	**7.7**	**7.4**	**5.5**

Note: Totals may not sum due to independent rounding.
*NF_3 emissions are presented for informational purposes, using a GWP of 8,000, and are not included in totals.

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 generated and emitted as a process by-product.

For 2001, total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were estimated to be 5.5 Tg CO_2 Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 3-46 and Table 3-47. The rapid growth of this industry and the increasing complexity of semiconductor products that use more PFCs in the production process have led to an increase in emissions of 93 percent since 1990. However, the growth rate in emissions began to slow in 1997, and emissions declined by 28 percent between 1999 and 2001. This decline is due both to a drop in production (with silicon consumption declining by 21 percent between 2000 and 2001) and to the initial implementation of PFC emission reduction methods, such as process optimization.

Methodology

Emissions from semiconductor manufacturing were estimated using two sets of data. For 1990 through 1994, emission estimates were based on the historical consumption of silicon (i.e., 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 participants in EPA's PFC Emission Reduction Partnership for the Semiconductor Industry in 1995 and later years. For the three years for which gas sales data were available (1992 to 1994), the estimates derived using this method are within 10 percent of the estimates derived using gas sales data and average values for emission factors and global warming potentials (GWPs).

For 1995 through 2001, total U.S. emissions were extrapolated from the total annual emissions reported by the participants in the PFC Emission Reduction Partnership for the Semiconductor Industry. The emissions from the participants were multiplied by the ratio of the total layer-weighted capacity of all of the semiconductor plants in the United States and the total layer-weighted capacity of the plants operated by the participants. The layer-weighted capacity of a plant (or group of plants) consists of the silicon capacity of that plant multiplied by the number of layers used in the chips produced by that plant. This method assumes that participants and non-participants have similar capacity utilizations and per-layer emission factors.

From 1995 through 1999, the per-layer emission factor calculated for participants remained fairly constant and was assumed to be applicable to the non-participants. In 2000 and 2001, the per-layer emission factor of participants declined significantly, presumably reflecting efforts to reduce PFC emissions. However, non-participants were assumed to emit PFCs at the historic per-layer rate during the years 2000 and 2001. The 2000 and 2001 U.S. emissions estimates were adjusted accordingly.

Chemical-specific emission estimates were based on data submitted for the year by participants, which were the first reports to provide emissions by chemical. It was assumed that emissions from non-participants and emissions from previous years were distributed among the chemicals in the same proportions as in these 2001 participant reports. This assumption is supported by chemical sales information from previous years and chemical-specific emission factors.

Table 3-47: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Mg)

Year	1990	1995	1996	1997	1998	1999	2000	2001
CF_4	111	229	211	254	282	300	286	217
C_2F_6	167	345	318	383	424	452	431	326
C_3F_8	14	28	26	31	35	37	35	26
HFC-23	8	17	16	19	21	22	21	16
SF_6	17	35	32	39	43	46	44	31
NF_3	9	19	17	21	23	24	23	23

Participants estimate their emissions using a range of methods. For 2001, all participants used a method at least as accurate as the IPCC's method 2c, recommended in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). The partners with relatively high emissions typically use the more accurate IPCC 2b or 2a methods, multiplying estimates of their PFC consumption by process-specific emission factors that they have either measured or obtained from tool suppliers.

Data Sources

Aggregate emissions estimates from the semiconductor manufacturers participating in the EPA's PFC Emission Reduction Partnership were used to develop these estimates. Estimates of the capacities and characteristics of plants operated by participants and non-participants were derived from the Semiconductor Equipment and Materials International (SEMI) *World Fab Watch* (formerly *International Fabs on Disk*) database (1996 to 2002). Estimates of silicon consumed by line-width from 1990 through 1994 were derived from information from VLSI Research (2001), and the number of layers per line-width was obtained from International SEMATECH's *International Technology Roadmap: 2000 Update.*

Uncertainty

Emission estimates for this source category have improved, but are still relatively uncertain. Emissions vary depending upon the total amount of gas used and the tool and process employed. Much of this information is tracked by semiconductor manufacturers participating in the EPA's PFC Emission Reduction Partnership; however, there is some uncertainty associated with the data collected. In addition, not all semiconductor manufacturers track this information. Total U.S. emissions were extrapolated from the information submitted by the participants, introducing additional uncertainty.

Electrical Transmission and Distribution

Sulfur hexafluoride's largest use, both domestically and internationally, is as an electrical insulator in equipment that transmits and distributes electricity (RAND 2000). 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.

Fugitive emissions of SF_6 can escape from gas-insulated substations and switch gear through seals, especially from older equipment. The gas can also be released during equipment installation, servicing, and disposal. In the past, some electric utilities vented SF_6 to the atmosphere during servicing and disposal; however, 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 15.3 Tg CO_2 Eq. (0.6 Gg) in 2001. This quantity represents a 51 percent decrease below the estimate for 1990 (see Table 3-48). This decrease, which is reflected in the atmospheric record, is believed to be a response to increases in the price of SF_6 and to growing awareness of the environmental impact of SF_6 emissions.

Table 3-48: SF_6 Emissions from Electrical Transmission and Distribution

Year	Tg CO_2 Eq.	Gg
1990	32.1	1.3
1995	27.5	1.1
1996	27.7	1.2
1997	25.2	1.1
1998	20.9	0.9
1999	16.4	0.7
2000	15.4	0.6
2001	15.3	0.6

Methodology

The 2001 estimate of SF_6 emissions from electrical equipment, 15.3 Tg CO_2 Eq., is comprised of (1) estimated emissions of approximately 14.6 Tg CO_2 Eq. from U.S. electric power systems, and (2) estimated emissions of approximately 0.7 Tg CO_2 Eq. from U.S. electrical equipment manufacturers (original equipment manufacturers, or OEMs). The 2001 estimate of emissions from electric power systems is based on the reported 2001 emissions (5.5 Tg CO_2) of participating utilities in EPA's SF_6 Emissions Reduction Partnership for Electric Power Systems, which began in 1999. These emissions were scaled up to the national level using the results of a regression analysis that indicated that utilities' emissions are strongly correlated with their transmission miles. The 2001 emissions estimate for OEMs of 0.7 Tg CO_2 is derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF_6 charged into new equipment. The quantity of SF_6 charged into new equipment is estimated based on statistics compiled by the National Electrical Manufacturers Association. (In the absence of statistics for 2001, the quantity of SF_6 used to fill new equipment in 2001 was assumed to be the same as in 2000.) The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (P. O'Connell, et al., Study Committee 23). Emissions for 1999 and 2000 were estimated similarly.

Because most participating utilities reported emissions only for 1999 through 2001, and only one reported emissions for more than three years, it was necessary to model "backcast" electric power system SF_6 emissions for the years 1990 through 1998. It was assumed that SF_6 purchases were strongly related to emissions. To estimate 1990 through 1998 emissions, aggregate world sales of SF_6 (RAND 2000) for each year from 1990 through 1999 were divided by the world sales from 1999. The result was a time series that gave each year's sales as a multiple of 1999 sales. Each year's normalized sales were then multiplied by the estimated U.S. emissions of SF_6 from electric power systems in 1999, which was estimated to be 15.8 Tg CO_2 Eq., to estimate U.S. emissions of SF_6 from electrical equipment in that year. This yielded a time series that was related to statistics for both SF_6 emissions and SF_6 sales. Emissions from OEM were estimated for 1990-1998 using OEM statistics for this period.

Data Sources

Emission estimates were provided by EPA's Global Programs Division in cooperation with companies that participate in the SF_6 Emissions Reduction Partnership for Electric Power Systems and with producers of SF_6.

Uncertainty

There is uncertainty involved in extrapolating total U.S. emissions from the emissions reported by participants in EPA's SF_6 Emissions Reduction Partnership for Electric Power Systems, and in extrapolating 1990 through 1998 emissions from 1999 emissions. The regression equations used to extrapolate U.S. emissions from participant reports have a variance (at the 95 percent confidence level) of +/- 2 Tg CO_2 for 1999 through 2001. In addition, emission rates for utilities that were not participants, which accounted for approximately 65 percent of U.S. transmission miles, may differ from those that were participants. Global sales of SF_6 appear to closely reflect global emissions; global sales declined by 24 percent between 1995 and 1998, while atmospheric measurements indicate that world emissions of SF_6 declined by 27 percent during the same period. However, U.S. emission patterns may differ from global emission patterns.

Magnesium Production and Processing

The magnesium metal production and casting industry uses SF_6 as a cover gas to prevent the violent oxidation of molten magnesium in the presence of air. A dilute gaseous mixture of SF_6 with dry air and/or CO_2 is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A minute portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride. It is assumed that the amount of SF_6 reacting in magnesium production and processing is negligible and thus all SF_6 used is emitted into the atmosphere. Sulfur hexafluoride has been used in this application around the world for the last twenty years. It has largely replaced salt fluxes and sulfur dioxide (SO_2), which are more toxic and corrosive than SF_6.

The magnesium industry emitted 2.5 Tg CO_2 Eq. (0.1 Gg) of SF_6 in 2001 (see Table 3-49). This represents a significant decline from previous years. The decline is attributable to declines in production, casting, and estimated emission factors. One of the two primary U.S. producers closed in October 2001. There are no significant plans for expansion of primary magnesium production in the United States, but demand for magnesium metal by U.S. casting companies has grown as auto manufacturers design more lightweight magnesium parts into vehicle models. Foreign magnesium producers are expected to meet the growing U.S. demand for primary magnesium.

Methodology

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. These participating companies represent 100 percent of U.S. primary production and over 80 percent of the casting sector.

Table 3-49: SF_6 Emissions from Magnesium Production and Processing

Year	Tg CO_2 Eq.	Gg
1990	5.4	0.2
1995	5.6	0.2
1996	6.5	0.3
1997	6.3	0.3
1998	5.8	0.2
1999	6.0	0.3
2000	3.2	0.1
2001	2.5	0.1

Table 3-50: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Secondary	Die Casting	Gravity	Wrought	Anodes
1999	1	2.14	2	1	1
2000	1	0.71	2	1	1
2001	1	0.74	2	1	1

The 1999 through 2001 emissions from primary production, some secondary production, and a large fraction of die casting were reported by participants. The 1999 through 2001 emissions from the remaining secondary production and casting were estimated by multiplying industry emission factors (kg SF_6 per metric ton of Mg produced or processed) by the amount of metal produced or consumed in the five major processes (other than primary production) that require SF_6 melt protection; 1) secondary production, 2) die casting, 3) gravity casting, 4) wrought products and, 5) anodes. The emission factors are provided in Table 3-50. Because there were less than three primary producers in the United States in 2001, the emission factor for primary production is withheld to protect production information. However, the emission factor has not risen above the 1995 value of 1.1 kg per metric ton.

The 1999 through 2001 emission factors for die casting, which is believed to account for about half of non-primary U.S. SF_6 emissions, were derived from information from industry participants. The average 2001 emission factor for die casting was estimated to be 0.74 kg SF_6 per metric ton of magnesium cast. However, to estimate total U.S. emissions from die-casting, it was assumed that die casters who did not provide information were similar to participants who cast small parts, with an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. The emission factors for the other industry sectors were based on discussions with industry representatives.

To estimate 1990 to 1998 emissions, industry emission factors were multiplied by the corresponding metal production and consumption statistics from USGS. The primary production emission factors were 1.1 kg per metric ton in both 1994 and 1995, and the die casting factor was 4.1 kg per metric ton. It was assumed that these emission factors had remained constant throughout the early 1990s. However, it was assumed that after 1996 the emission factors for primary production and die casting declined linearly to the level estimated based on Partner reports. This assumption is consistent with the trend in sales to the magnesium sector that is reported in the RAND survey of major SF_6 manufacturers, which shows a decline of 70 percent between 1996 and 1999 (RAND 2000). The emission factors for the other processes, about which less is known, were assumed to remain constant.

Data Sources

Emission estimates were provided by EPA's Climate Protection Division in cooperation with the U.S. EPA SF_6 Emission Reduction Partnership for the Magnesium Industry and the USGS. U.S. magnesium metal production (primary and secondary) and consumption (casting) data from 1990 to 2001 are available from the USGS.[17] Emission factors from 1990 to 1998 were based on a number of sources. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995, and an emission factor for die casting was available for the mid-1990s from an international survey (Gjestland & Magers 1996).

Uncertainty

There are a number of uncertainties in these estimates, including the assumption that SF_6 neither reacts nor decomposes during use. It is possible that the melt surface reactions and high temperatures associated with molten magnesium cause some gas degradation. EPA is currently pursuing a measurement campaign in cooperation with magnesium producers and processors to ascertain the extent of such degradation. As is the case for other sources of SF_6 emissions, total SF_6 consumption data for magnesium production and processing in United States were not available. Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with a high magnesium content; however, it is unknown to what extent this technique is used in the United States.

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[17] See <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis>.

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/UNEP/OECD/IEA 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. In this case, actual emissions equal potential emissions.

Table 3-51 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances, HFCs, PFCs, and SF_6 from semiconductor manufacture, and SF_6 from magnesium production and processing, and electrical transmission and distribution.[18] 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. Estimates of HFCs, PFCs, and SF_6 consumed by semiconductor manufacture were developed by dividing chemical-by-chemical emissions by the appropriate chemical-specific emission factors from the IPCC Good Practice Guidance (Tier 2c). Estimates of CF_4 consumption were adjusted to account for the conversion of other chemicals into CF_4 during the semiconductor manufacturing process, again using the default factors from the IPCC Good Practice Guidance. U.S. utility purchases of SF_6 for electrical equipment from 1999 through 2001 were estimated based on reports by participants in EPA's SF_6 Emission Reduction Program for Electric Power Systems. U.S. utility purchases of SF_6 for electrical equipment from 1990 through 1998 were backcasted based on world sales of SF_6 to utilities. Purchases of SF_6 by utilities were added to SF_6 purchases by electrical equipment manufacturers to obtain total SF_6 purchases by the electrical equipment sector.

Table 3-51: 2001 Potential and Actual Emissions of HFCs, PFCs, and SF_6 from Selected Sources (Tg CO_2 Eq.)

Source	Potential	Actual
Substitution of Ozone Depleting Substances	224.7	63.7
Aluminum Production	-	4.1
HCFC-22 Production	-	19.8
Semiconductor Manufacture	8.1	5.5
Magnesium Production and Processing	2.5	2.5
Electrical Transmission and Distribution	24.1	15.3

\- Not applicable.

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[18] See Annex X for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

Table 3-52: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
NO_x	**591**	**607**	**596**	**629**	**637**	**605**	**631**	**662**
Chemical & Allied Product Manufacturing	152	144	113	115	117	102	104	106
Metals Processing	88	89	75	81	81	79	82	87
Storage and Transport	3	5	14	15	15	9	9	10
Other Industrial Processes	343	362	393	417	424	415	435	458
Miscellaneous*	5	7	1	1	1	1	1	1
CO	**4,124**	**3,958**	**3,016**	**3,153**	**3,163**	**2,145**	**2,214**	**2,327**
Chemical & Allied Product Manufacturing	1,074	1,109	954	971	981	326	335	346
Metals Processing	2,395	2,159	1,451	1,551	1,544	1,118	1,155	1,230
Storage and Transport	69	22	64	64	65	145	151	158
Other Industrial Processes	487	566	509	528	535	517	536	556
Miscellaneous*	101	102	39	38	38	39	37	37
NMVOCs	**2,426**	**2,643**	**1,997**	**2,038**	**2,047**	**1,890**	**1,845**	**1,829**
Chemical & Allied Product Manufacturing	575	599	352	352	357	265	269	277
Metals Processing	111	113	66	71	71	60	62	65
Storage and Transport	1,356	1,499	1,174	1,205	1,204	1,104	1,039	1,043
Other Industrial Processes	364	409	395	397	402	449	465	434
Miscellaneous*	20	23	10	13	13	12	11	10

* Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, cooling towers, and fugitive dust. It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.
Note: Totals may not sum due to independent rounding.

Industrial Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of ambient 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 2001 are reported in Table 3-52.

Methodology and Data Sources

The emission estimates for this source were taken directly from the EPA (2003). 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.

Box 2-4: Formation of CO_2 Through Atmospheric CH_4 Oxidation

Methane emitted to the atmosphere will eventually oxidize into CO_2, which remains in the atmosphere for up to 200 years. The global warming potential (GWP) of CH_4, however, does not account for the radiative forcing effects of the CO_2 formation that results from this CH_4 oxidation. The IPCC Guidelines for Greenhouse Gas Inventories (IPCC/UNEP/OECD/IEA 1997) do not explicitly recommend a procedure for accounting for oxidized CH_4, but some of the resulting CO_2 is, in practice, included in the inventory estimates because of the intentional "double-counting" structure for estimating CO_2 emissions from the combustion of fossil fuels. According to the IPCC Guidelines, countries should estimate emissions of CH_4, CO, and NMVOCs from fossil fuel combustion, but also assume that these compounds eventually oxidize to CO_2 in the atmosphere. This is accomplished by using CO_2 emission factors that do not factor out carbon in the fuel that is released as in the form of CH_4, CO, and NMVOC molecules. Therefore, the carbon in fossil fuel is intentionally double counted, as an atom in a CH_4 molecule and as an atom in a CO_2 molecule.[54] While this approach does account for the full radiative forcing effect of fossil fuel-related greenhouse gas emissions, the timing is not accurate because it may take up to 12 years for the CH_4 to oxidize and form CO_2.

There is no similar IPCC approach to account for the oxidation of CH_4 emitted from sources other than fossil fuel combustion (e.g., landfills, livestock, and coal mining). Methane from biological systems contains carbon that is part of a rapidly cycling biological system, and therefore any carbon created from oxidized CH_4 from these sources is matched with carbon removed from the atmosphere by biological systems – likely during the same or subsequent year. Thus, there are no additional radiative forcing effects from the oxidation of CH_4 from biological systems. For example, the carbon content of CH_4 from enteric fermentation is derived from plant matter, which itself was created through the conversion of atmospheric CO_2 to organic compounds.

The remaining anthropogenic sources of CH_4 (e.g., fugitive emissions from coal mining and natural gas systems, industrial process emissions) do increase the long-term CO_2 burden in the atmosphere, and this effect is not captured in the inventory. The following tables provide estimates for the equivalent CO_2 production that results from the atmospheric oxidation of CH_4 from these remaining sources. The estimates for CH_4 emissions are gathered from the respective sections of this report, and are presented in Table 2-47. The CO_2 estimates are summarized in Table 2-48.

The estimates of CO_2 formation are calculated by applying a factor of 44/16, which is the ratio of molecular weight of CO_2 to the molecular weight of CH_4. For the purposes of the calculation, it is assumed that CH_4 is oxidized to CO_2 in the same year that it is emitted. As discussed above, this is a simplification, because the average atmospheric lifetime of CH_4 is approximately 12 years.

Carbon dioxide formation can also result from the oxidation of CO and NMVOCs. However, the resulting increase of CO_2 in the atmosphere is explicitly included in the mass balance used in calculating the storage and emissions from non-energy uses of fossil fuels, with the carbon components of CO and NMVOC counted as CO_2 emissions in the mass balance.[55]

Table 2-47: CH_4 Emissions from Non-Combustion Fossil Sources (Gg)

Source	1990	1995	1996	1997	1998	1999	2000	2001
Coal Mining	4,149	3,502	3,255	3,244	3,235	3,033	2,902	2,893
Natural Gas Systems	5,810	6,059	6,069	6,001	5,903	5,728	5,772	5,588
Petroleum Systems	1,309	1,153	1,138	1,123	1,090	1,029	1,010	1,011
Petrochemical Production	56	72	75	77	78	80	79	71
Silicon Carbide Production	1	1	1	1	1	1	1	+
Total	**11,325**	**10,786**	**10,538**	**10,446**	**10,308**	**9,869**	**9,764**	**9,563**

Note: These emissions are accounted for under their respective source categories. Totals may not sum due to independent rounding.

Table 2-48: Formation of CO_2 Through Atmospheric CH_4 Oxidation (Tg CO_2 Eq.)

Source	1990	1995	1996	1997	1998	1999	2000	2001
Coal Mining	11.4	9.6	9.0	8.9	8.9	8.3	8.0	8.0
Natural Gas Systems	16.0	16.7	16.7	16.5	16.2	15.8	15.9	15.4
Petroleum Systems	3.6	3.2	3.1	3.1	3.0	2.8	2.8	2.8
Petrochemical Production	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Carbide Production	+	+	+	+	+	+	+	+
Total	**31.1**	**29.7**	**29.0**	**28.7**	**28.3**	**27.1**	**26.9**	**26.3**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 Tg CO_2 Eq.

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[54] It is assumed that 100 percent of the CH_4 emissions from combustion sources are accounted for in the overall carbon emissions calculated as CO_2 for sources using emission factors and carbon mass balances. However, it may be the case for some types of combustion sources that the oxidation factors used for calculating CO_2 emissions do not accurately account for the full mass of carbon emitted in gaseous form (i.e., partially oxidized or still in hydrocarbon form).

[55] See Annex C for a more detailed discussion on accounting for indirect emissions from CO and NMVOCs.

4. Solvent Use

The use of solvents and other chemical products can result in emissions of various ozone precursors (i.e., ambient air 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. Surface coatings accounted for just under a majority of NMVOC emissions from solvent use—41 percent in 2001—while "non-industrial"[2] uses accounted for about 38 percent and degreasing applications for 7 percent. Overall, solvent use accounted for approximately 28 percent of total U.S. emissions of NMVOCs in 2001, and has decreased 13 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 solvent uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (i.e., electronics, etc.), dry cleaning, non-industrial uses (i.e., uses of paint thinner, etc.), and solvent utilization NEC. Because some of these industrial applications also employ thermal incineration as a control technology, combustion by-products (CO and NO_x) 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 2001 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-specific emission factors to the amount 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 solvent laden gas streams from painting booths, printing operations, and oven exhaust.

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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	1995	1996	1997	1998	1999	2000	2001
NO$_x$	**1**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Degreasing	+	+	+	+	+	+	+	+
Graphic Arts	+	1	1	1	1	+	+	+
Dry Cleaning	+	+	+	+	+	+	+	+
Surface Coating	1	2	2	2	2	3	3	3
Other Industrial Processes[a]	+	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+
Other	NA	+	+	+	+	+	+	+
CO	**4**	**5**	**1**	**1**	**1**	**46**	**45**	**44**
Degreasing	+	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+	+
Dry Cleaning	+	1	+	+	+	+	+	+
Surface Coating	+	1	1	1	1	46	45	44
Other Industrial Processes[a]	4	3	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+
Other	NA	NA	+	+	+	+	+	+
NMVOCs	**5,217**	**5,609**	**4,969**	**5,100**	**4,671**	**4,533**	**4,422**	**4,584**
Degreasing	675	716	546	566	337	360	318	334
Graphic Arts	249	307	261	266	272	222	224	230
Dry Cleaning	195	209	140	148	151	265	268	274
Surface Coating	2,289	2,432	2,155	2,228	1,989	1,851	1,782	1,878
Other Industrial Processes[a]	85	87	96	100	101	94	99	104
Non-Industrial Processes[b]	1,724	1,858	1,768	1,790	1,818	1,701	1,690	1,721
Other	+	+	3	3	3	40	41	43

[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.

Data Sources

The emission estimates for this source were taken directly from EPA data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2003). 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 EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). 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.

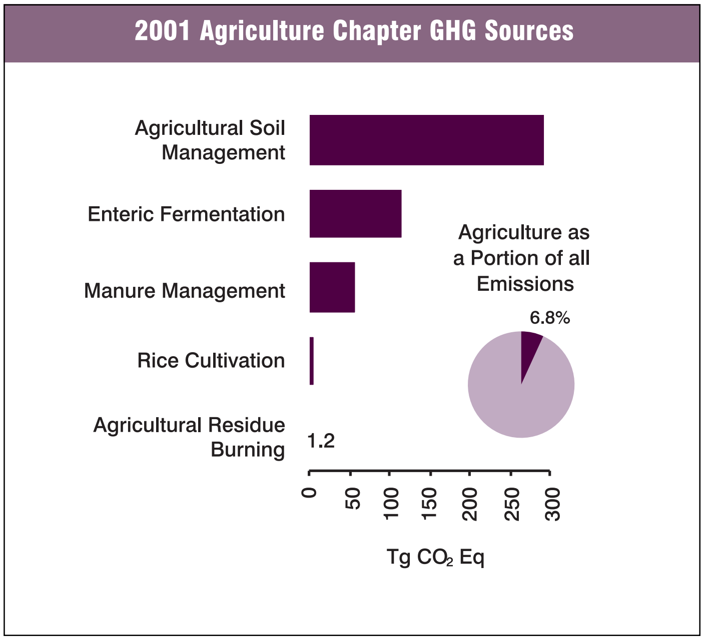
Uncertainty

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 provides an assessment of non-carbon dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues (see Figure 5-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as conversion of grassland to cultivated land, are discussed in the Land-Use Change and Forestry chapter. Carbon dioxide emissions from on-farm energy use are accounted in the Energy chapter.

Figure 5-1



In 2001, agricultural activities were responsible for emissions of 474.9 Tg CO_2 Eq., or 6.8 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 percent and 6 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 CH_4. Rice cultivation and agricultural crop residue burning were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 69 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture chapter. Between 1990 and 2001, CH_4 emissions from agricultural activities increased by 3.3 percent while N_2O emissions increased by 10.1 percent. In addition to CH_4 and N_2O, field burning of agricultural residues was also a minor source of the ambient air pollutants carbon monoxide (CO) and nitrogen oxides (NO_x).

Table 5-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**156.9**	**167.4**	**163.1**	**163.1**	**164.4**	**164.5**	**162.2**	**162.1**
Enteric Fermentation	117.9	123.0	120.5	118.3	116.7	116.6	115.7	114.8
Manure Management	31.3	36.2	34.9	36.6	39.0	38.9	38.2	38.9
Rice Cultivation	7.1	7.6	7.0	7.5	7.9	8.3	7.5	7.6
Field Burning of Agricultural Residues	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8
N_2O	**284.1**	**301.0**	**310.6**	**315.9**	**316.9**	**314.8**	**312.9**	**312.8**
Agricultural Soil Management	267.5	284.1	293.2	298.2	299.2	297.0	294.6	294.3
Manure Management	16.2	16.6	17.0	17.3	17.3	17.4	17.9	18.0
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.5
Total	**441.0**	**468.4**	**473.7**	**479.0**	**481.3**	**479.3**	**475.1**	**474.9**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**7,473**	**7,972**	**7,765**	**7,768**	**7,829**	**7,834**	**7,723**	**7,718**
Enteric Fermentation	5,612	5,855	5,737	5,635	5,557	5,551	5,509	5,468
Manure Management	1,490	1,723	1,661	1,741	1,858	1,852	1,820	1,850
Rice Cultivation	339	363	332	356	376	395	357	364
Field Burning of Agricultural Residues	33	31	36	36	37	36	37	36
N_2O	**916**	**971**	**1,002**	**1,019**	**1,022**	**1,015**	**1,009**	**1,009**
Agricultural Soil Management	863	916	946	962	965	958	950	949
Manure Management	52	53	55	56	56	56	58	58
Field Burning of Agricultural Residues	1	1	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding.

Enteric Fermentation

Methane 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 CH_4 as a by-product, which can be exhaled or eructated by the animal. The amount of CH_4 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 domesticated animal types, ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 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 products that can be metabolized. 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 CH_4 emissions among all animal types.

Non-ruminant domesticated animals (e.g., swine, horses, and mules) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affects CH_4 emissions. In general, a lower feed quality and a higher feed intake leads to higher CH_4 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 provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2001 were 114.8 Tg CO_2 Eq. (5,468 Gg), decreasing slightly since 2000 due to minor decreases in animal populations. Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation,

Table 5-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1995	1996	1997	1998	1999	2000	2001
Beef Cattle	83.2	89.7	88.8	86.6	85.0	84.7	83.5	82.7
Dairy Cattle	28.9	27.7	26.3	26.4	26.3	26.6	27.0	26.9
Horses	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.0
Sheep	1.9	1.5	1.4	1.3	1.3	1.2	1.2	1.2
Swine	1.7	1.9	1.8	1.8	2.0	1.9	1.9	1.9
Goats	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**117.9**	**123.0**	**120.5**	**118.3**	**116.7**	**116.6**	**115.7**	**114.8**

Note: Totals may not sum due to independent rounding.

Table 5-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1995	1996	1997	1998	1999	2000	2001
Beef Cattle	3,961	4,272	4,227	4,124	4,046	4,035	3,976	3,936
Dairy Cattle	1,375	1,320	1,254	1,255	1,251	1,266	1,284	1,282
Horses	91	92	93	93	94	93	94	95
Sheep	91	72	68	64	63	58	56	56
Swine	81	88	84	88	93	90	88	88
Goats	13	11	10	10	10	10	10	10
Total	**5,612**	**5,855**	**5,737**	**5,635**	**5,557**	**5,551**	**5,509**	**5,468**

Note: Totals may not sum due to independent rounding.

accounting for 72 percent in 2001. Emissions from dairy cattle in 2001 accounted for 23 percent, and the remaining 5 percent was from horses, sheep, swine, and goats.

From 1990 to 2001, emissions from enteric fermentation have decreased by 3 percent. Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. During this timeframe, populations of sheep and goats have also decreased, while horse populations increased and the populations of swine fluctuated.

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 CH_4 emissions from livestock in the United States. Cattle production systems in the United States are better characterized in comparison with other livestock production systems. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimating emissions for cattle. Emission estimates for other domesticated animals were handled using a less detailed approach (i.e., IPCC Tier 1).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that describes the quantity of CH_4 produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of livestock population, feeding practices and production characteristics was used to estimate emissions from cattle populations.

National cattle population statistics were disaggregated into the following cattle sub-populations:

Dairy Cattle

- Calves
- Heifer Replacements
- Cows

Beef Cattle

- Calves
- Heifer Replacements
- Heifer and Steer Stockers
- Animals in Feedlots
- Cows
- Bulls

Calf birth estimates, end of year population statistics, detailed feedlot placement information, and slaughter weight data were used in the model to initiate and track cohorts of individual animal types having distinct emissions profiles. The key variables tracked for each of the cattle population categories are described in Annex L. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain.

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values and CH_4 conversion rates (Y_m) for each population category. The IPCC recommends Y_m values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for all other cattle. Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed, rather than using the recommended IPCC values. The diet characterizations and estimation of DE and Y_m values were based on contact with state agricultural extension specialists, a review of published forage quality studies, expert opinion, and modeling of animal physiology. See Annex L for more details on the method used to characterize cattle diets in the United States.

In order to estimate CH_4 emissions from cattle, the population was divided into region, age, sub-type (e.g., calves, heifer replacements, cows, etc.), and production (i.e., pregnant, lactating, etc.) groupings to more fully capture differences in CH_4 emissions from these animal types. Cattle diet characteristics were used to develop regional emission factors for each sub-category. Tier 2 equations from IPCC (2000) were used to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, and heifer feedlot animals. To estimate emissions from cattle, population data were multiplied by the emission factor for each cattle type. More details are provided in Annex L.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2001. 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 L for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Data Sources

Annual cattle population data were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (1995a,b, 1999a,c,d,f, 2000a,c,d,f, 2001a,c,d,f, 2002a,c,d,f). Diet characteristics were used to develop DE and Y_m values for cattle populations. Diet characteristics for dairy cattle were from Donovan (1999), while beef cattle were derived from NRC (2000). DE and Y_m for dairy cows were calculated from diet characteristics using a model simulating ruminant digestion in growing and/or lactating cattle (Donovan and Baldwin 1999). For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. Values from EPA (1993) were used for dairy replacement heifers. For grazing beef cattle, DE values were based on diet information in NRC (2000) and Y_m values were based on Johnson (2002). Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. Annual livestock population data for other livestock types, except horses, as well as feedlot placement information were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1998, 1999b,e, 2000b,e, 2001b,e, 2002b,e). Horse data were obtained from the Food and Agriculture Organization (FAO) statistical database (FAO 2002). Methane emissions from sheep, goats, swine, and horses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC/UNEP/OECD/IEA 1997). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology is the same as that recommended by IPCC (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).

Uncertainty

The basic uncertainties associated with estimating emissions from enteric fermentation are the range of emission factors possible for the different animal types and the number of animals with a particular emissions profile that exist during the year. Although determining an emission factor for all possible cattle sub-groupings and diet characterizations in the United States is not possible, the enteric fermentation model that was used estimates the likely emission factors for the major animal types and diets. The model generates estimates for dairy and beef cows, dairy and beef replacements, beef stockers, and feedlot animals. The analysis departs from the recommended IPCC (2000) DE and Y_m values to account for diets for these different animal types regionally. Based on expert opinion and peer reviewer recommendations, the values supporting the development of emission factors for the animal types studied are more appropriate for the situation in the United States than the IPCC recommended values.

In addition to the uncertainty associated with developing emission factors for different cattle population categories based on estimated energy requirements and diet characterizations, there is uncertainty in the estimation of animal populations by animal type. The model estimates the movement of animal cohorts through the various monthly age and weight classes by animal type. Several inputs affect the precision of this approach, including estimates of births by month, weight gain of animals by age class, and placement of animals into feedlots based on placement statistics and slaughter weight data. However, the model characterizes the changes in U.S. cattle population and captures potential differences related to the emission factors used for different animal types.

The values for Y_m and DE reflect the diet characterizations that are assumed for each cattle group, within each region of the country. While these values try to reflect the general diet characteristics within each region, there is uncertainty associated with local variations in feed and in the way cattle feed intake is managed.

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 QA/QC procedures were implemented. Tier 1 procedures included quality checks on data gathering, input, and documentation, as well as checks on the actual emission calculations. Additionally, Tier 2 procedures included quality checks on emission factors, activity data, and emissions.

Manure Management

The management of livestock manure can produce anthropogenic CH_4 and 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 denitrification of the organic nitrogen in livestock manure and urine.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of materials in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or pits) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. A number of other factors related to how the manure is handled also affect the amount of CH_4 produced. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For example, CH_4 production generally increases with rising temperature and residency time. Also, for non-liquid based manure systems, moist conditions (which are a function of rainfall and humidity) favor CH_4 production. Although the majority of manure is handled as a solid, producing little CH_4, the general trend in manure management, particularly for large dairy and swine producers, is one of increasing use of liquid systems. In addition, use of daily spread systems at smaller dairies is decreasing, due to new regulations limiting the application of manure nutrients, which has resulted in an increase of manure managed and stored on site at these smaller dairies.

The composition of the manure also affects the amount of CH_4 produced. Manure composition varies by animal type, including the animal's digestive system and diet. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. For example, feedlot cattle fed a high-energy grain diet generate manure with a high CH_4-producing capacity. Range cattle fed a low energy diet of forage material produce manure with about 50 percent of the CH_4-producing potential of feedlot cattle manure. However, some higher energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal. Ultimately, a combination of diet characteristics and the growth rate of the animals will affect the total manure produced.

A very small portion of the total nitrogen excreted is expected to convert to N_2O in the waste management system. The production of N_2O from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For N_2O emissions to occur, the manure must first be handled aerobically where ammonia or organic nitrogen is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to nitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman, et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. For example, manure at cattle drylots is deposited on soil, oxidized to nitrite and nitrate, and has the potential to encounter saturated conditions following rain events.

Certain N_2O emissions are accounted for and discussed under Agricultural Soil Management. These are emissions from livestock manure and urine deposited on pasture, range, or paddock lands, as well as emissions 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.).

Table 5-5 and Table 5-6 provide estimates of CH_4 and N_2O emissions from manure management by animal category. Estimates for CH_4 emissions in 2001 were 38.9 Tg CO_2 Eq. (1,850 Gg), 24 percent higher than in 1990. The majority of this increase was from swine and dairy cow manure, which increased 31 and 32 percent respectively, and is attributed to shifts by the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use liquid systems to manage (flush or scrape) and store manure. Thus the shift towards larger facilities is translated into an increasing use of liquid manure management systems. This shift was accounted for by incorporating state-specific weighted CH_4 conversion factor (MCF) values calculated from the 1992 and 1997 farm-size distribution reported in the Census of Agriculture (USDA 1999e). From 2000 to 2001, there was a 1.8 percent increase in CH_4 emissions, due to minor shifts in the animal populations.

As stated previously, smaller dairies are moving away from daily spread systems. Therefore, more manure is managed and stored on site, contributing to additional CH_4 emissions over the time series. A description of the emission estimation methodology is provided in Annex M.

Total N_2O emissions from manure management systems in 2001 were estimated to be 18.0 Tg CO_2 Eq. (58.0 Gg). The 11 percent increase in N_2O emissions from 1990 to 2001 can be partially attributed to a shift in the poultry industry away from the use of liquid manure management systems, in favor of litter-based systems and high rise houses. In addition, there was an overall increase in the population of poultry and swine from 1990 to 2001, although swine populations declined slightly in 1993, 1995, 1996, 1999, and 2000 from previous years and poultry populations decreased in 1995 and 2001 from previous years. Nitrous oxide emissions showed a 0.6 percent increase from 2000 to 2001, due to minor shifts in animal population.

The population of beef cattle in feedlots, which tend to store and manage manure on site, also increased, resulting in increased N_2O emissions from this animal category. Although dairy cow populations decreased overall, the population of dairies managing and storing manure on site—as opposed to using pasture, range, or paddock or daily spread systems—increased. Therefore, the increase in dairies using on-site storage to manage their manure results in a steady level of N_2O emissions. As stated previously, N_2O emissions from livestock manure deposited on pasture, range, or paddock land and manure immediately applied to land in daily spread systems are accounted for under Agricultural Soil Management.

Methodology

The methodologies presented in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000)* form the basis of the CH_4 and N_2O emissions estimates for each animal type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state);
- Amount of nitrogen produced (amount per 1000 pound animal times average weight times number of head);
- Amount of volatile solids produced (amount per 1000 pound animal times average weight times number of head);
- Methane producing potential of the volatile solids (by animal type);
- Extent to which the CH_4 producing potential is realized for each type of manure management system (by state and manure management system);

Table 5-5: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**31.3**	**36.2**	**34.9**	**36.6**	**39.0**	**38.9**	**38.2**	**38.9**
Dairy Cattle	11.4	13.4	12.8	13.4	13.9	14.7	14.6	15.1
Beef Cattle	3.4	3.5	3.5	3.4	3.3	3.3	3.3	3.3
Swine	13.1	16.0	15.3	16.4	18.4	17.6	17.1	17.1
Sheep	0.1	0.1	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+
Poultry	2.7	2.6	2.6	2.7	2.7	2.6	2.6	2.7
Horses	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
N_2O	**16.2**	**16.6**	**17.0**	**17.3**	**17.3**	**17.4**	**17.9**	**18.0**
Dairy Cattle	4.3	4.1	4.0	4.0	3.9	4.0	4.0	3.9
Beef Cattle	4.9	5.3	5.1	5.4	5.5	5.5	5.9	6.1
Swine	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4
Sheep	+	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+
Poultry	6.3	6.5	7.2	7.2	7.2	7.2	7.4	7.3
Horses	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**47.5**	**52.8**	**51.9**	**53.9**	**56.3**	**56.3**	**56.1**	**56.9**

\+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-6: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal Type	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**1,490**	**1,723**	**1,661**	**1,741**	**1,858**	**1,852**	**1,820**	**1,850**
Dairy Cattle	545	640	611	639	661	700	693	719
Beef Cattle	161	164	164	161	158	158	157	155
Swine	623	763	729	781	876	838	813	815
Sheep	3	2	2	2	2	2	2	2
Goats	1	1	1	1	1	1	1	1
Poultry	128	124	125	127	130	124	125	128
Horses	29	29	29	29	30	29	30	30
N_2O	**52**	**53**	**55**	**56**	**56**	**56**	**58**	**58**
Dairy Cattle	14	13	13	13	13	13	13	13
Beef Cattle	16	17	17	17	18	18	19	20
Swine	1	1	1	1	1	1	1	1
Sheep	+	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+
Poultry	21	21	23	23	23	23	24	24
Horses	1	1	1	1	1	1	1	1

\+ Does not exceed 0.5 Gg.

Note: Totals may not sum due to independent rounding.

- Portion of manure managed in each manure management system (by state and animal type); and
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems.

Both CH_4 and N_2O emissions were estimated by first determining activity data, including animal population, waste characteristics, and manure management system usage. For swine and dairy cattle, manure management system usage was determined for different farm size categories using data from USDA (USDA 1996b, 1998d, 2000h) and EPA (ERG 2000a, EPA 2001a, 2001b). For beef cattle and poultry, manure management system usage data was not tied to farm size (ERG 2000a, USDA 2000i). For other animal types, manure management system usage was based on previous EPA estimates (EPA 1992).

Next, MCFs and N_2O emission factors were determined for all manure management systems. MCFs for dry systems and N_2O emission factors for all systems were set equal to default IPCC factors (IPCC 2000). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation (see Annex M for detailed information on MCF derivations for liquid systems). The MCF calculations model the average monthly ambient temperature, a minimum system temperature, the carryover of volatile solids in the system from month to month due to long storage times exhibited by anaerobic lagoon systems, and a factor to account for management and design practices that result in the loss of volatile solids from lagoon systems.

For each animal group—except sheep, goats, and horses—the base emission factors were then weighted to incorporate the distribution of management systems used within each state and thereby to create an overall state-specific weighted emission factor. To calculate this weighted factor, the percent of manure for each animal group managed in a particular system in a state was multiplied by the emission factor for that system and state, and then summed for all manure management systems in the state.

Methane emissions were estimated using the volatile solids (VS) production for all livestock. For poultry and swine animal groups, for example, VS production was calculated using a national average VS production rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. For most cattle groups, regional animal-specific VS production rates that are related to the diet of the animal for each year of the inventory were used (Peterson et al., 2002). The resulting VS for each animal group was then multiplied by the maximum CH_4 producing capacity of the waste (B_o), and the state-specific CH_4 conversion factors.

Nitrous oxide emissions were estimated by determining total Kjeldahl nitrogen (TKN)[1] production for all livestock wastes using livestock population data and nitrogen excretion rates. For each animal group, TKN production was calculated using a national average nitrogen excretion rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. State-specific weighted N_2O emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate N_2O emissions.

See Annex M for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Data Sources

Animal population data for all livestock types, except horses and goats, were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a-g, 2001a-f, 2002a-f). Horse population data were obtained from the FAOSTAT database (FAO 2002). Goat population data were obtained from the Census of Agriculture (USDA 1999d). Information regarding poultry turnover (i.e., slaughter) rate was obtained from State Natural Resource Conservation Service (NRCS) personnel (Lange 2000). Dairy cow and swine population data by farm size for each state, used for the weighted MCF and emission factor calculations, were obtained from the *Census of Agriculture*, which is conducted every five years (USDA 1999e).

Manure management system usage data for dairy and swine operations were obtained from USDA's Centers for Epidemiology and Animal Health (USDA 1996b, 1998d, 2000h) for small operations and from preliminary estimates for EPA's Office of Water regulatory effort for large operations (ERG 2000a; EPA 2001a, 2001b). Data for layers were obtained from a voluntary United Egg Producers' survey (UEP 1999), previous EPA estimates (EPA 1992), and USDA's Animal Plant Health Inspection Service (USDA 2000i). Data for beef feedlots were also obtained from EPA's Office of Water (ERG 2000a; EPA 2001a, 2001b). Manure management system usage data for other livestock were taken from previous EPA estimates (EPA 1992). Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations, and data provided by those personnel (Poe et al. 1999). These organizations include state NRCS offices, state extension services, state universities, USDA National Agriculture Statistics Service (NASS), and other experts (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000,

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[1] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

Sweeten 2000, and Wright 2000). Additional information regarding the percent of beef steer and heifers on feedlots was obtained from contacts with the national USDA office (Milton 2000).

Methane conversion factors for liquid systems were calculated based on average ambient temperatures of the counties in which animal populations were located. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2001, 2002), and the county population data were based on 1992 and 1997 Census data (USDA 1999e). County population data for 1990 and 1991 were assumed to be the same as 1992; county population data for 1998 through 2001 were assumed to be the same as 1997; and county population data for 1993 through 1996 were extrapolated based on 1992 and 1997 data.

The maximum CH_4 producing capacity of the volatile solids, or B_o, was determined based on data collected in a literature review (ERG 2000b). B_o data were collected for each animal type for which emissions were estimated.

Nitrogen excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types. Volatile solids excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for swine, poultry, bulls, and calves not on feed. In addition, volatile solids production rates from Peterson et al., 2002 were used for dairy and beef cows, heifers, and steer for each year of the inventory. Nitrous oxide emission factors and MCFs for dry systems were taken from *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

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 regional location and the exact CH_4 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 1992 and 1997 farm-size data. However, the assumption of a direct relationship between farm size and liquid system usage may not apply in all cases and may vary based on geographic location. In addition, the CH_4 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.

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000) published a default range of MCFs for anaerobic lagoon systems of 0 to 100 percent, which reflects the wide range in performance that may be achieved with these systems. There exist relatively few data points on which to determine country-specific MCFs for these systems. In the United States, many livestock waste treatment systems classified as anaerobic lagoons are actually holding ponds that are substantially organically overloaded and therefore not producing CH_4 at the same rate as a properly designed lagoon. In addition, these systems may not be well operated, contributing to higher loading rates when sludge is allowed to enter the treatment portion of the lagoon or the lagoon volume is pumped too low to allow treatment to occur. Rather than setting the MCF for all anaerobic lagoon systems in the United States based on data available from optimized lagoon systems, an MCF methodology was developed that more closely matches observed system performance and accounts for the affect of temperature on system performance.

However, there is uncertainty related to the new methodology. The MCF methodology used in the inventory includes a factor to account for management and design practices that result in the loss of volatile solids from the management system. This factor is currently estimated based on data from anaerobic lagoons in temperate climates, and from only three systems. However, this methodology is intended to account for systems across a range of management practices. Future work in gathering measurement data from animal waste lagoon systems across the country will contribute to the verification and refinement of this methodology. It will also be evaluated whether lagoon temperatures differ substantially from ambient temperatures and whether the lower bound estimate of temperature established for lagoons and other liquid systems should be revised for use with this methodology.

The IPCC provides a suggested MCF for poultry waste management operations of 1.5 percent. Additional study is needed in this area to determine if poultry high-rise houses promote sufficient aerobic conditions to warrant a lower MCF.

The default N_2O emission factors published in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) were 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 CH_4 at different rates, and would in all likelihood produce N_2O at different rates, although a single N_2O emission factor was used for both system types. In addition, there are little data available to determine the extent to which nitrification-denitrification occurs in animal waste management systems. Ammonia concentrations that are present in poultry and swine systems suggest that N_2O emissions from these systems may be lower than predicted by the IPCC default factors. At this time, there are insufficient data available to develop U.S.-specific N_2O emission factors; however, this is an area of on-going research, and warrants further study as more data become available.

Although an effort was made to introduce the variability in volatile solids production due to differences in diet for beef and dairy cows, heifers, and steer, further research is needed to confirm and track diet changes over time. A methodology to assess variability in swine volatile solids production would be useful in future inventory estimates.

Uncertainty also exists with the maximum CH_4 producing potential of volatile solids excreted by different animal groups (i.e., B_o). The B_o values used in the CH_4 calculations are published values for U.S. animal waste. However, there are several studies that provide a range of B_o values for certain animals, including dairy and swine. The B_o values chosen for dairy assign separate values for dairy cows and dairy heifers to better represent the feeding regimens of these animal groups. For example, dairy heifers do not receive an abundance of high energy feed and consequently, dairy heifer manure will not produce as much CH_4 as manure from a milking cow. However, the data available for B_o values are sparse, and do not necessarily reflect the rapid changes that have occurred in this industry with respect to feed regimens.

An uncertainty analysis was conducted on the manure management inventory considering the issues described above and based on published data from scientific and statistical literature, the IPCC, and experts in the industry. The results of the uncertainty analysis showed that the manure management CH_4 inventory has a 95 percent confidence interval of -18 percent to 20 percent around the inventory value, and the manure management N_2O inventory has a 95 percent confidence interval of -16 percent to 24 percent around the inventory value.

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, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the CH_4 is also leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape 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 CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce CH_4. 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 CH_4 transport pathway to the atmosphere is blocked. The quantities of CH_4 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, CH_4 emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils. All rice in

Table 5-7: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	1995	1996	1997	1998	1999	2000	2001
Primary	**5.1**	**5.6**	**5.0**	**5.6**	**5.8**	**6.3**	**5.5**	**5.9**
Arkansas	2.1	2.4	2.1	2.5	2.7	2.9	2.5	2.9
California	0.7	0.8	0.9	0.9	0.8	0.9	1.0	0.8
Florida	+	+	+	+	+	+	+	+
Louisiana	1.0	1.0	1.0	1.0	1.1	1.1	0.9	1.0
Mississippi	0.4	0.5	0.4	0.4	0.5	0.6	0.4	0.5
Missouri	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4
Texas	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4
Ratoon	**2.1**	**2.1**	**1.9**	**1.9**	**2.1**	**2.0**	**2.0**	**1.7**
Arkansas	0.0	0.0	0.0	0.0	+	+	0.0	0.0
Florida	+	0.1	0.1	0.1	0.1	0.1	0.1	+
Louisiana	1.1	1.1	1.1	1.2	1.2	1.2	1.3	1.1
Texas	0.9	0.8	0.8	0.7	0.8	0.7	0.7	0.6
Total	**7.1**	**7.6**	**7.0**	**7.5**	**7.9**	**8.3**	**7.5**	**7.6**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

the United States is grown under continuously flooded conditions; none is grown under deepwater conditions. Mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, 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, rice variety,[2] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over an entire growing season because the total amount of CH_4 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 CH_4 production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to CH_4, that time is short relative to a growing season, so the dependence of total emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate, and ammonium sulfate) appear to inhibit CH_4 formation.

Rice is cultivated in seven states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Soil types, rice varieties, and cultivation practices for rice vary from state to state, 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 from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow for the stubble to decay aerobically), 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 CH_4 in the United States (Table 5-7 and Table 5-8). In 2001, CH_4 emissions from rice cultivation were 7.6 Tg CO_2 Eq. (364 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2001, ranging from an annual decrease of

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[2] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

Table 5-8: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1995	1996	1997	1998	1999	2000	2001
Primary	**241**	**265**	**240**	**265**	**278**	**300**	**260**	**283**
Arkansas	102	114	99	118	126	138	120	138
California	34	40	43	44	39	43	47	40
Florida	1	2	2	2	2	2	2	1
Louisiana	46	48	45	50	53	52	41	46
Mississippi	21	25	18	20	23	28	19	22
Missouri	7	10	8	10	12	16	14	18
Texas	30	27	25	22	24	22	18	18
Ratoon	**98**	**98**	**92**	**91**	**98**	**95**	**97**	**81**
Arkansas	0	0	0	0	+	+	0	0
Florida	2	4	4	3	3	4	3	2
Louisiana	52	54	51	55	59	58	61	52
Texas	45	40	38	33	36	33	34	27
Total	**339**	**363**	**332**	**356**	**376**	**395**	**357**	**364**

\+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

11 percent to an annual increase of 17 percent, there was an overall increase of 7 percent over the eleven-year period due to an overall increase in harvested area.[3]

The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states. Price is the primary factor affecting rice area in Arkansas, as farmers will plant more of what is most lucrative amongst soybeans, rice, and cotton. Government support programs have also been influential in so much as they affect the price received for a rice crop (Slaton 2001b, Mayhew 1997). California rice area is primarily influenced by price and government programs, but is also affected by water availability (Mutters 2001). In Florida, the state having the smallest harvested rice area, rice acreage is largely a function of the price of rice relative to sugarcane and corn. Most rice in Florida is rotated with sugarcane, but sometimes it is more profitable for farmers to follow their sugarcane crop with sweet corn or more sugarcane instead of rice (Schueneman 1997, 2001b). In Louisiana, rice area is influenced by government support programs, the price of rice relative to cotton, soybeans, and corn, and in some years, weather (Saichuk 1997, Linscombe 2001b). For example, a drought in 2000 caused extensive saltwater intrusion along the Gulf Coast, making over 32,000 hectares unplantable. In Mississippi, rice 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, 2001). 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 rice and soybeans or cotton, and government support programs (Stevens 1997, Guethle 2001). In Texas, rice area is affected mainly by the price of rice, government support programs, and water availability (Klosterboer 1997, 2001b).

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) recommends utilizing harvested rice areas and area-based seasonally integrated emission factors (i.e., amount of CH_4 emitted over a growing season per unit harvested area) to estimate annual CH_4 emissions from rice cultivation. This methodology is followed with the use of United States-specific emission factors derived from rice field measurements. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season. This is consistent with IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

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[3] The 11 percent decrease occurred between 1992 and 1993; the 17 percent increase happened between 1993 and 1994.

Table 5-9: Rice Areas Harvested (Hectares)

State/Crop	1990	1995	1996	1997	1998	1999	2000	2001
Arkansas								
Primary	485,633	542,291	473,493	562,525	600,971	657,628	570,619	656,010
Ratoon*	NO	NO	NO	NO	202	202	NO	NO
California	159,854	188,183	202,347	208,822	185,350	204,371	221,773	190,611
Florida								
Primary	4,978	9,713	8,903	7,689	8,094	7,229	7,801	4,562
Ratoon	2,489	4,856	4,452	3,845	4,047	4,673	3,193	2,752
Louisiana								
Primary	220,558	230,676	215,702	235,937	250,911	249,292	194,253	220,963
Ratoon	66,168	69,203	64,711	70,781	75,273	74,788	77,701	66,289
Mississippi	101,174	116,552	84,176	96,317	108,458	130,716	88,223	102,388
Missouri	32,376	45,326	38,446	47,349	57,871	74,464	68,393	83,772
Texas								
Primary	142,857	128,693	120,599	104,816	114,529	104,816	86,605	87,414
Ratoon	57,143	51,477	48,240	41,926	45,811	41,926	43,302	34,966
Total	**1,273,229**	**1,386,969**	**1,261,068**	**1,380,008**	**1,451,518**	**1,550,106**	**1,361,864**	**1,449,726**

* Arkansas ratooning occurred only in 1998 and 1999.
NO (Not Occurring)
Note: Totals may not sum due to independent rounding.

Data Sources

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 5-9. Primary crop areas for 1990 through 2001 for all states except Florida were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987-1992* (USDA 1994), *Field Crops Final Estimates 1992-1997* (USDA 1998), *Crop Production 2000 Summary* (USDA 2001), and *Crop Production 2001 Summary* (USDA 2002). Harvested rice areas in Florida, which are not reported by USDA, were obtained from Tom Schueneman (1999b, 1999c, 2000, 2001a), a Florida agricultural extension agent, and Dr. Chris Deren (2002) of the Everglades Research and Education Centre at the University of Florida. Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998 and 1999, when the ratooned area was less than 1 percent of the primary area (Slaton 1999, 2000, 2001a). In Florida, the ratooned area was 50 percent of the primary area from 1990 to 1998 (Schueneman 1999a), about 65 percent of the primary area in 1999 (Schueneman 2000), around 41 percent of the primary area in 2000 (Schueneman 2001a), and about 70 percent of the primary area in 2001(Deren 2002). In Louisiana, the percentage of the primary area that was ratooned was constant at 30 percent over the 1990 to 1999 period, but increased to approximately 40 percent in 2000, before returning to 30 percent in 2001 (Linscombe 1999a, 2001a, 2002 and Bollich 2000). In Texas, the percentage of the primary area that was ratooned was constant at 40 percent over the entire 1990 to 1999 period and in 2001, but increased to 50 percent in 2000 due to an early primary crop (Klosterboer 1999, 2000, 2001a, 2002).

To determine what seasonal CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments which involved the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation, 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. The remaining experimental results[4] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with synthetic and organic fertilizer added (Bossio et al. 1999, Cicerone et al. 1992, Sass et al. 1991a and 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with synthetic fertilizer added (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH_4/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare-season.

Uncertainty

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This variability is due to differences in cultivation practices, used here, primary emissions ranged from 22 to 479 kg CH_4/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare-season. Based on these emission ranges, total CH_4 emissions from rice cultivation in 2001 were estimated to range from 1.7 to 17 Tg CO_2 Eq. (80 to 800 Gg).

A second source of uncertainty is the ratooned area data, which are not compiled regularly. However, this is a relatively minor source of uncertainty, as these areas account for less than 10 percent of the total area. Expert judgment was used to estimate these areas.

The last source of uncertainty is in the practice of flooding outside of the normal rice season. According to agriculture extension agents, all of the rice-growing states practice this on some part of their rice acreage. Estimates of these areas range from 5 to 68 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, CH_4 flux measurements have not been undertaken in all of these states or under all representative conditions, so this activity is not included in the emission estimates presented here.

Agricultural Soil Management

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[5] 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 (Figure 5-2). Direct additions occur through various soil management practices and from the deposition of manure on soils by animals on pasture, range, and paddock (i.e., by animals whose manure is not managed). Soil management practices that add nitrogen to soils include fertilizer use, application of managed livestock manure and sewage sludge, production of nitrogen-fixing crops, retention of crop residues, and cultivation of histosols (i.e., soils with a high organic matter content, otherwise known as organic soils).[6] Indirect additions of nitrogen to soils occur through two mechanisms: 1) volatilization and subsequent atmospheric deposition of applied nitrogen;[7] and 2) surface runoff and leaching of applied nitrogen into groundwater and surface water. Other agricultural soil management, 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.

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[4] 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).

[5] Nitrification and denitrification are two processes within the nitrogen cycle that are brought about by certain microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4) to nitrate (NO_3), and denitrification is the anaerobic microbial reduction of nitrate to dinitrogen gas (N_2). Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well understood mechanism (Nevison 2000).

[6] Cultivation of histosols does not, *per se*, “add” nitrogen to soils. Instead, the process of cultivation enhances mineralization of nitrogen-rich organic matter that is present in histosols, thereby enhancing N_2O emissions from histosols.

[7] These processes entail volatilization of applied nitrogen as ammonia (NH_3) and oxides of nitrogen (NO_x), transformations of these gases within the atmosphere (or upon deposition), and deposition of the nitrogen primarily in the form of particulate ammonium (NH_4), nitric acid (HNO_3), and oxides of nitrogen.

Agricultural soil management is the largest source of N_2O in the United States.[8] Estimated emissions from this source in 2001 were 294.3 Tg CO_2 Eq. (949 Gg N_2O) (see Table 5-10 and Table 5-11). Although annual agricultural soil management emissions fluctuated between 1990 and 2001, there was a general increase in emissions over the twelve-year period (see Annex N for a complete time series of emission estimates). This general increase in emissions was due primarily to an increase in synthetic fertilizer use, manure production, and crop and forage production over this period. The year-to-year fluctuations are largely a reflection of annual variations in synthetic fertilizer consumption and crop production. Over the twelve-year period, total emissions of N_2O from agricultural soil management increased by approximately 10 percent.

Estimated direct and indirect N_2O emissions, by subsource, are provided in Table 5-12, Table 5-13, and Table 5-14.

Methodology

The methodology used to estimate emissions from agricultural soil management is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). The Revised 1996 IPCC Guidelines divide this N_2O source category into three components: (1) direct emissions from managed soils due to applied nitrogen and cultivation of histosols; (2) direct emissions from soils due to the deposition of manure by livestock on pasture, range, and paddock; and (3) indirect emissions from soils induced by applied fertilizers, sewage sludge and total livestock manure nitrogen.

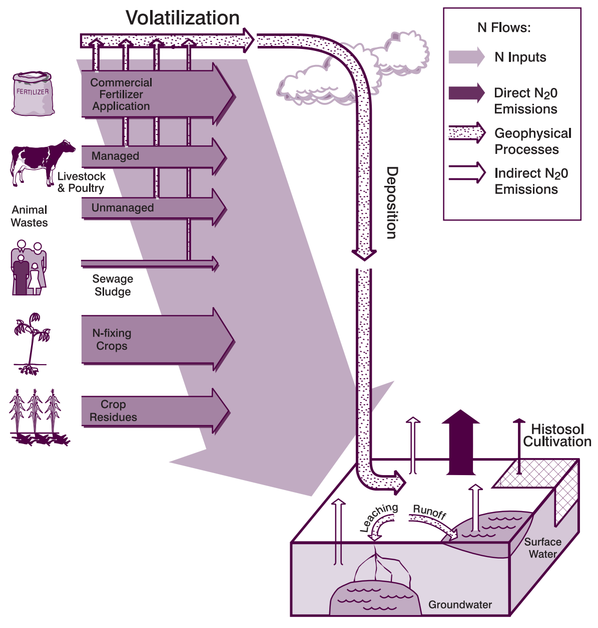
Annex N provides more detailed information on the methodologies and data used to calculate N_2O emissions from each of these three components.

Direct N_2O Emissions from Managed Soils

Direct N_2O emissions from managed soils are composed of two parts, which are estimated separately and then summed. These two parts are 1) emissions due to nitrogen applications, and 2) emissions from histosol cultivation.

Figure 5-2

Direct and Indirect N_2O Emissions from Agricultural Soils



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from agricultural soils in the United States. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Estimates of direct N_2O emissions from nitrogen applications were based on the total amount of nitrogen that is applied to soils annually through the following practices: (a) the application of synthetic and organic commercial fertilizers, (b) the application of livestock manure through both daily spread operations and through the eventual application of manure that had been stored in manure management systems, (c) the application of sewage sludge, (d) the production of nitrogen-fixing crops and forages, and (e) the retention of crop residues (i.e., leaving residues in the field after harvest). For each of these practices, the annual amounts of nitrogen applied were estimated as follows:

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[8] Note that the emission estimates for this source category include applications of nitrogen to all soils (e.g., forest soils, urban areas, golf courses, etc.), but the term "Agricultural Soil Management" is kept for consistency with the reporting structure of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 5-10: N_2O Emissions from Agricultural Soil Management (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Direct	**193.7**	**205.1**	**212.6**	**217.8**	**219.0**	**216.8**	**215.9**	**216.6**
Managed Soils	153.3	161.5	169.1	175.6	177.6	175.9	175.6	176.7
Pasture, Range, & Paddock Livestock	40.4	43.6	43.5	42.2	41.3	40.9	40.3	39.9
Indirect	**73.8**	**79.0**	**80.6**	**80.3**	**80.2**	**80.2**	**78.7**	**77.7**
Total	**267.5**	**284.1**	**293.2**	**298.2**	**299.2**	**297.0**	**294.6**	**294.3**

Note: Totals may not sum due to independent rounding.

Table 5-11: N_2O Emissions from Agricultural Soil Management (Gg)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Direct	**625**	**662**	**685**	**703**	**706**	**700**	**696**	**699**
Managed Soils	495	521	545	567	573	568	566	570
Pasture, Range, & Paddock Livestock	130	141	140	136	133	132	130	129
Indirect	**238**	**255**	**260**	**259**	**259**	**259**	**254**	**251**
Total	**863**	**916**	**946**	**962**	**965**	**958**	**950**	**949**

Note: Totals may not sum due to independent rounding.

Table 5-12: Direct N_2O Emissions from Managed Soils (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Commercial Fertilizers*	55.4	59.2	61.2	61.3	61.4	61.6	59.8	58.6
Livestock Manure	13.0	13.6	13.7	14.0	14.2	14.2	14.4	14.5
Sewage Sludge	0.4	0.6	0.6	0.7	0.7	0.7	0.7	0.7
N Fixation	58.5	61.8	63.9	68.2	69.2	68.2	68.8	70.6
Crop Residue	23.2	23.4	26.8	28.7	29.3	28.3	29.0	29.3
Histosol Cultivation	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9
Total	**153.3**	**161.5**	**169.1**	**175.6**	**177.6**	**175.9**	**175.6**	**176.6**

Note: Totals may not sum due to independent rounding.
* Excludes sewage sludge and livestock manure used as commercial fertilizers.

Table 5-13: Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure (Tg CO_2 Eq.)

Animal Type	1990	1995	1996	1997	1998	1999	2000	2001
Beef Cattle	35.2	38.9	39.0	37.8	37.0	36.7	36.0	35.7
Dairy Cows	1.7	1.5	1.4	1.3	1.3	1.2	1.2	1.2
Swine	0.5	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Sheep	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Goats	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Poultry	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Total	**40.4**	**43.6**	**43.5**	**42.2**	**41.3**	**40.9**	**40.3**	**39.9**

Note: Totals may not sum due to independent rounding.

Table 5-14: Indirect N_2O Emissions from Agricultural Soil Management (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Volatilization & Atm. Deposition	**11.7**	**12.5**	**12.7**	**12.6**	**12.6**	**12.6**	**12.4**	**12.3**
Commercial Fertilizers*	4.9	5.3	5.4	5.4	5.5	5.5	5.3	5.2
Livestock Manure	6.7	7.1	7.1	7.1	7.0	7.0	6.9	6.9
Sewage Sludge	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Surface Leaching & Runoff	**62.1**	**66.5**	**67.9**	**67.7**	**67.6**	**67.6**	**66.3**	**65.4**
Commercial Fertilizers*	36.9	39.5	40.8	40.9	40.9	41.1	39.9	39.1
Livestock Manure	24.9	26.5	26.6	26.3	26.1	26.0	25.9	25.8
Sewage Sludge	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Total	**73.8**	**79.0**	**80.6**	**80.3**	**80.2**	**80.2**	**78.7**	**77.7**

Note: Totals may not sum due to independent rounding.
* Excludes sewage sludge and livestock manure used as commercial fertilizers.

a) Synthetic and organic commercial fertilizer nitrogen applications were derived from annual fertilizer consumption data and the nitrogen content of the fertilizers.

b) Livestock manure nitrogen applications were based on the assumption that all livestock manure is applied to soils except for two components: 1) a small portion of poultry manure that is used as a livestock feed supplement, and 2) the manure from pasture, range, and paddock livestock. The manure nitrogen data were derived from animal population and weight statistics, information on manure management system usage, annual nitrogen excretion rates for each animal type, and information on the fraction of poultry litter that is used as a livestock feed supplement.

c) Sewage sludge nitrogen applications were derived from estimates of annual U.S. sludge production, the nitrogen content of the sludge, and periodic surveys of sludge disposal methods.

d) The amounts of nitrogen made available to soils through the cultivation of nitrogen-fixing crops and forages were based on estimates of the amount of nitrogen in aboveground plant biomass, which were derived from annual crop production statistics, mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents of the plant biomass.

e) Crop residue nitrogen retention data were derived from information about which residues are typically left on the field, the fractions of residues left on the field, annual crop production statistics, mass ratios of aboveground residue to crop product, and dry matter fractions and nitrogen contents of the residues.

After the annual amounts of nitrogen applied were estimated for each practice, each amount of nitrogen was reduced by the fraction that is assumed to volatilize according to the *Revised 1996 IPCC Guidelines* and the *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. The net amounts left on the soil from each practice were then summed to yield total unvolatilized applied nitrogen, which was multiplied by the IPCC default emission factor for nitrogen applications.

Estimates of annual N_2O emissions from histosol cultivation were based on estimates of the total U.S. acreage of histosols cultivated annually for each of two climatic zones: 1) temperate, and 2) sub-tropical. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and tropical regions.[9]

Total annual emissions from nitrogen applications, and annual emissions from histosol cultivation, were then summed to estimate total direct emissions from managed soils.

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[9] Note that the IPCC default emission factors for histosols have been revised in the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). These revised default emission factors (IPCC 2000) were used in these calculations.

Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure

Estimates of N_2O emissions from this component are based on the amount of nitrogen in the manure that is deposited annually on soils by livestock in pasture, range, and paddock. Estimates of annual manure nitrogen from these livestock were derived from animal population and weight statistics; information on the fraction of the total population of each animal type that is on pasture, range, or paddock; and annual nitrogen excretion rates for each animal type. The annual amounts of manure nitrogen from each animal type were summed over all animal types to yield total pasture, range, and paddock manure nitrogen, which was then multiplied by the IPCC default emission factor for pasture, range, and paddock nitrogen to estimate N_2O emissions.

Indirect N_2O Emissions from Soils

Indirect emissions of N_2O are composed of two parts, which are estimated separately and then summed. These two parts are 1) emissions resulting from volatilization and subsequent deposition of the nitrogen in applied fertilizers, applied sewage sludge, and all livestock manure,[10] and 2) leaching and runoff of nitrogen in applied fertilizers, applied sewage sludge, and applied plus deposited livestock manure. The activity data (i.e., nitrogen in applied fertilizers, applied sewage sludge, all livestock manure, and applied plus deposited livestock manure) were estimated in the same way as for the direct emission estimates.

To estimate the annual amount of applied nitrogen that volatilizes, the annual amounts of applied synthetic fertilizer nitrogen, applied sewage sludge nitrogen, and all livestock manure nitrogen, were each multiplied by the appropriate IPCC default volatilization fraction. The three amounts of volatilized nitrogen were then summed, and the sum was multiplied by the IPCC default emission factor for volatilized/deposited nitrogen.

To estimate the annual amount of nitrogen that leaches or runs off, the annual amounts of applied synthetic fertilizer nitrogen, applied sewage sludge nitrogen, and applied plus deposited livestock manure nitrogen were each multiplied by the IPCC default leached/runoff fraction. The three amounts of leached/runoff nitrogen were then summed, and the sum was multiplied by the IPCC default emission factor for leached/runoff nitrogen.

Total annual indirect emissions from volatilization, and annual indirect emissions from leaching and runoff, were then summed to estimate total indirect emissions of N_2O from managed soils.

Data Sources

The activity data used in these calculations were obtained from numerous sources. Annual synthetic and organic fertilizer consumption data for the United States were obtained from annual publications on commercial fertilizer statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000b, 2002). Fertilizer nitrogen contents were taken from these same publications and AAPFCO (2000a). Livestock population data were obtained from USDA publications (USDA 1994b,c; 1995a,b; 1998a,c; 1999a-e; 2000a-g; 2001b-g; 2002b-g), the FAOSTAT database (FAO 2002), and Lange (2000). Manure management information was obtained from Poe et al. (1999), Safley et al. (1992), and personal communications with agricultural experts (Anderson 2000, Deal 2000, Johnson 2000, Miller 2000, Milton 2000, Stettler 2000, Sweeten 2000, Wright 2000). Livestock weight data were obtained from Safley (2000), USDA (1996, 1998d), and ASAE (1999); daily rates of nitrogen excretion from ASAE (1999) and USDA (1996); and information about the fraction of poultry litter used as a feed supplement from Carpenter (1992). Data collected by the EPA were used to derive annual estimates of land application of sewage sludge (EPA 1993, 1999). The nitrogen content of sewage sludge was taken from Metcalf and Eddy, Inc. (1991). Annual production statistics for nitrogen-fixing crops were obtained from USDA reports (USDA 1994a, 1998b, 2000i, 2001a, 2002a), a book on forage crops (Taylor and Smith 1995, Pederson 1995, Beuselinck and Grant 1995, Hoveland and Evers 1995), and personal communications with forage experts (Cropper 2000, Gerrish 2000, Hoveland 2000, Evers 2000, and Pederson 2000). Mass ratios of aboveground

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[10] Total livestock manure nitrogen is used in the calculation of indirect N_2O emissions from volatilization because all manure nitrogen, regardless of how the manure is managed or used, is assumed to be subject to volatilization.

residue to crop product, dry matter fractions, and nitrogen contents for nitrogen-fixing crops were obtained from Strehler and Stützle (1987), Barnard and Kristoferson (1985), Karkosh (2000), Ketzis (1999), and IPCC/UNEP/OECD/IEA (1997). Annual production statistics for crops whose residues are left on the field, except for rice in Florida, were obtained from USDA reports (USDA 1994a, 1998b, 2000i, 2001a, 2002a). Production statistics for rice in Florida are not recorded by USDA, so these were derived from Smith (1999), Schueneman (1999, 2001), and Deren (2002). Aboveground residue to crop mass ratios, residue dry matter fractions, and residue nitrogen contents were obtained from Strehler and Stützle (1987), Turn et al. (1997), Ketzis (1999), and Barnard and Kristoferson (1985). Estimates of the fractions of residues left on the field were based on information provided by Karkosh (2000), and on information about rice residue burning (see the Agricultural Residue Burning section). The annual areas of cultivated histosols were estimated from 1982, 1992, and 1997 statistics in USDA's 1997 *National Resources Inventory* (USDA 2000h, as extracted by Eve 2001, and revised by Ogle 2002).

All emission factors, [11] volatilization fractions, and the leaching/runoff fraction were taken from the Revised 1996 *IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

Uncertainty

The amount of N_2O emitted from managed soils depends not only on N inputs, but also on a large number of variables, including organic carbon availability, O_2 partial pressure, soil moisture content, pH, soil temperature, and soil amendment management practices. However, the effect of the combined interaction of these other variables on N_2O flux is complex and highly uncertain. Therefore, the IPCC default methodology, which is used here, is based only on N inputs and does not utilize these other variables. As noted in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), this is a generalized approach that treats all soils, except cultivated histosols, as being under the same conditions. The estimated ranges around the IPCC default emission factors provide an indication of the uncertainty in the emission estimates due to this simplified methodology. Most of the emission factor ranges are about an order of magnitude, or larger. Developing an emission estimation methodology that explicitly utilizes these other variables will require more scientific research and much more detailed databases, and will likely involve the use of process models (see Box 5-1).

Box 5-1: DAYCENT Model Estimates of N_2O Emissions from Agricultural Soils

U.S. EPA is currently working in collaboration with the Agricultural Research Service and the Natural Resource Ecology Lab at Colorado State University to test the feasibility of using the DAYCENT ecosystem process model to estimate N_2O emissions from agricultural soil management. In countries like the United States that cover large land areas and have a diversity of climate, soils, land use and management systems, the use of an ecosystem process model such as DAYCENT can have great advantages over the single emission factor approach as specified in the IPCC Guidelines for estimating N_2O emissions. Potential advantages of a dynamic simulation based approach include the ability to use actual observed weather, observed annual crop yields, and more detailed soils and management information to drive the estimates of N_2O emissions. One of the greatest challenges involved in this effort will be obtaining the activity data (e.g., synthetic fertilizer and manure nitrogen inputs) at the appropriate spatial scale for use in the DAYCENT model. The goal of the modeling effort is to develop county-level estimates of N_2O emissions from agricultural soils that can be summed to produce a national-level estimate. Emission estimates from this modeling effort are intended for use in the 1990-2002 inventory.

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 non-commercial fertilizers (other than the estimated manure and crop residues) have not been captured. The livestock excretion values, while based on detailed population and weight statistics, were derived using simplifying assumptions concerning the types of management systems employed. Statistics on sewage sludge applied to soils were not available on an annual basis; annual production and application estimates were based on figures and projections that were calculated from surveys that yielded uncertainty levels as high as 14 percent (Bastian 1999). Annual data were obtained by interpolating and extrapolating at constant rates from these

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[11] Note that the emission factor used for cultivated histosols in the sub-tropics is the average of the tropical and temperate default IPCC emission factors.

uncertain figures, though change between the years was unlikely to be constant (Bastian 2001). The production statistics for the nitrogen-fixing crops that are forage legumes are highly uncertain because statistics are not compiled for any of these crops except alfalfa, and the alfalfa statistics include alfalfa mixtures. Conversion factors for the nitrogen-fixing crops were based on a limited number of studies, and may not be representative of all conditions in the United States. Data on crop residues left on the field are not available, so expert judgment was used to estimate the amount of residues left on soils. And finally, the estimates of cultivated histosol areas are uncertain because they are from a natural resource inventory that was not explicitly designed as a soil survey, and this natural resource inventory contains data for only three years (1982, 1992, and 1997). Annual histosol areas were estimated by linear interpolation and extrapolation.

Field Burning of Agricultural Residues

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 left on or 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 fuel, animal bedding material, or supplemental animal feed. Field burning of crop residues is not considered a net source of 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 CH_4, N_2O, CO, and 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. Of these residues, less than 5 percent is burned each year, except for rice.[12] Annual emissions from this source over the period 1990 through 2001 averaged approximately 0.7 Tg CO_2 Eq. (35 Gg) of CH_4, 0.4 Tg CO_2 Eq. (1 Gg) of N_2O, 728 Gg of CO, and 32 Gg of NO_x (see Table 5-15 and Table 5-16).

Table 5-15: Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**0.7**	**0.7**	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.3
Barley	+	+	+	+	+	+	+	+
Soybeans	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Peanuts	+	+	+	+	+	+	+	+
N_2O	**0.4**	**0.4**	**0.4**	**0.4**	**0.5**	**0.4**	**0.5**	**0.5**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+	+
Soybeans	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Peanuts	+	+	+	+	+	+	+	+
Total	**1.1**	**1.0**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

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[12] The fraction of rice straw burned each year is significantly higher than that for other crops (see “Data Sources” discussion below).

Table 5-16: Emissions from Field Burning of Agricultural Residues (Gg)*

Gas/Crop Type	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**33**	**31**	**36**	**36**	**37**	**36**	**37**	**36**
Wheat	7	5	5	6	6	5	5	5
Rice	4	4	4	3	3	3	3	3
Sugarcane	1	1	1	1	1	1	1	1
Corn	13	13	16	16	17	16	17	16
Barley	1	1	1	1	1	+	1	+
Soybeans	7	8	9	10	10	10	10	11
Peanuts	+	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+
CO	**685**	**656**	**747**	**761**	**781**	**760**	**784**	**762**
Wheat	137	109	114	124	128	115	112	98
Rice	81	80	85	66	58	69	69	69
Sugarcane	18	20	19	21	22	23	24	23
Corn	282	263	328	328	347	336	353	338
Barley	16	13	15	13	13	10	12	9
Soybeans	148	167	183	207	211	204	212	222
Peanuts	2	2	2	2	2	2	2	3
NO_x	**28**	**29**	**32**	**34**	**35**	**34**	**35**	**35**
Wheat	4	3	3	3	3	3	3	3
Rice	3	3	3	2	2	2	2	2
Sugarcane	+	+	+	+	+	+	+	+
Corn	7	6	8	8	8	8	8	8
Barley	1	+	+	+	+	+	+	+
Soybeans	14	16	17	20	20	19	20	21
Peanuts	+	+	+	+	+	+	+	+

* Full molecular weight basis.
\+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.

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:[13]

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)[14]

Nitrogen Released = (Annual Crop Production) ×
(Residue/Crop Product Ratio) ×
(Fraction of Residues Burned *in situ*) ×
(Dry Matter Content of the Residue) ×
(Burning Efficiency) × (Nitrogen Content
of the Residue) × (Combustion Efficiency)

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[13] Note: As is explained under Data Sources, the fraction of rice residues burned varies among states, so these equations were applied at the state level for rice. These equations were applied at the national level for all other crop types.

[14] 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.

Table 5-17: Agricultural Crop Production (Thousand Metric Tons of Product)

Crop	1990	1995	1996	1997	1998	1999	2000	2001
Wheat	74,292	59,404	61,980	67,534	69,327	62,569	60,758	53,278
Rice	7,105	7,935	7,828	8,339	8,570	9,381	8,697	9,686
Sugarcane	25,525	27,922	26,729	28,766	30,896	32,023	32,762	31,571
Corn*	201,534	187,970	234,518	233,864	247,882	239,549	251,854	241,485
Barley	9,192	7,824	8,544	7,835	7,667	6,103	6,939	5,434
Soybeans	52,416	59,174	64,780	73,176	74,598	72,223	75,055	78,668
Peanuts	1,635	1,570	1,661	1,605	1,798	1,737	1,481	1,923

*Corn for grain (i.e., excludes corn for silage).

Table 5-18: Percentage of Rice Area Burned by State

State	Percent Burned 1990-1998	Percent Burned 1999	Percent Burned 2000	Percent Burned 2001
Arkansas	10	10	10	10
California	variable[a]	27	27	23
Florida[b]	0	0	0	0
Louisiana	6	0	5	4
Mississippi	10	40	40	40
Missouri	5	5	8	5
Texas	1	2	0	0

[a] Values provided in Table 5-19.

[b] Burning of crop residues is illegal in Florida.

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 for all crops except rice in Florida were taken from the USDA's *Field Crops, Final Estimates 1987-1992, 1992-1997* (USDA 1994, 1998), *Crop Production 2000 Summary* (USDA 2001), and *Crop Production 2001 Summary* (USDA 2002). Rice production data for Florida, which are not collected by USDA, were estimated by applying average primary and ratoon crop yields for Florida (Smith 1999) to Florida acreages (Schueneman 1999b, 2001; Deren 2002). The production data for the crop types whose residues are burned are presented in Table 5-17.

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 residue burned were derived from state-level estimates of the percentage of rice area burned each year, which were multiplied by state-level, annual rice production statistics. The annual percentages of rice area burned in each state were obtained from the agricultural extension agents in each of the seven rice-producing states and reports of the California Air Resources Board (CARB) (Bollich 2000; Deren 2002; Guethle 1999, 2000, 2001, 2002; Fife 1999; California Air Resources Board 1999, 2001; Klosterboer 1999a, 1999b, 2000, 2001, 2002; Lindberg 2002; Linscombe 1999a, 1999b, 2001, 2002; Mutters 2002, Najita 2000, 2001; Schueneman 1999a, 1999b, 2001; Slaton 1999a, 1999b, 2000; Street 1999a, 1999b, 2000, 2001, 2002; Wilson 2001, 2002) (see Table 5-18 and Table 5-19). The estimates provided for Arkansas and Florida remained constant over the entire 1990 through 2001 period, while the estimates for all other states varied over the time series. For California, it was assumed that the annual percents of rice area burned in the Sacramento Valley are representative of burning in the entire state, because the Sacramento Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). These percents declined between 1990 and 2001 because of a legislated reduction in rice straw burning (Lindberg 2002) (see Table 5-19).

Table 5-19: Percentage of Rice Area Burned in California

Year	California
1990	75
1995	59
1996	63
1997	34
1998	33
1999	27
2000	27
2001	23

Table 5-20: Key Assumptions for Estimating Emissions from Agricultural Residue Burning*

Crop	Residue/Crop Ratio	Fraction of Residue Burned	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction
Wheat	1.3	0.03	0.93	0.4428	0.0062
Rice	1.4	variable	0.91	0.3806	0.0072
Sugarcane	0.8	0.03	0.62	0.4235	0.0040
Corn	1.0	0.03	0.91	0.4478	0.0058
Barley	1.2	0.03	0.93	0.4485	0.0077
Soybeans	2.1	0.03	0.87	0.4500	0.0230
Peanuts	1.0	0.03	0.86	0.4500	0.0106

* The burning efficiency and combustion efficiency for all crops were assumed to be 0.93 and 0.88, respectively.

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The datum for sugarcane is from University of California (1977). Residue dry matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry matter content was obtained from Strehler and Stützle (1987). Peanut dry matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System. The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue carbon content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The nitrogen content of soybeans is from Barnard and Kristoferson (1985). The nitrogen content of peanuts is from Ketzis (1999). These data are listed in Table 5-20. 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 5-21) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 5-21: 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).

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 published 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[1] caused by 1) changes in forest carbon stocks, 2) changes in carbon stocks in urban trees, 3) changes in agricultural soil carbon stocks, and 4) changes in carbon stocks in landfilled yard trimmings. Seven components of forest carbon stocks are analyzed: trees, understory vegetation, forest floor, down dead wood, soils, wood products in use, and landfilled wood products. The estimated CO_2 flux from each of these forest components was derived from U.S. forest inventory data, using methodologies that are consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Changes in carbon stocks in urban trees were estimated based on field measurements in ten U.S. cities and data on national urban tree cover, using a methodology consistent with the *Revised 1996 IPCC Guidelines*. Changes in agricultural soil carbon stocks include mineral and organic soil carbon stock changes due to use and management of cropland and grazing land, and emissions of CO_2 due to the application of crushed limestone and dolomite to agricultural soils (i.e., soil liming). The methods used to estimate all three components of changes in agricultural soil carbon stocks are consistent with the *Revised 1996 IPCC Guidelines*. Changes in yard trimming carbon stocks in landfills were estimated using analysis of life-cycle greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). Note that the chapter title "Land-Use Change and Forestry" has been used here to maintain consistency with the IPCC reporting structure for national greenhouse gas inventories; however, the chapter covers land-use activities, in addition to land-use change and forestry activities. Therefore, except in table titles, the term "land use, land-use change, and forestry" will be used in the remainder of this chapter.

Unlike the assessments in other chapters, which are based on annual activity data, the flux estimates in this chapter, with the exception of those from wood products, urban trees, and liming, are based on periodic activity data in the form of forest, land-use, and municipal solid waste surveys. Carbon dioxide fluxes from forest carbon stocks (except the wood product components) and from agricultural soils (except the liming component) 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 from forest carbon stocks (except the wood product components) and from agricultural soils (except the liming component) are constant over multi-year intervals, with large discontinuities between intervals. For the landfilled yard trimmings, periodic solid waste survey data were interpolated so that annual storage estimates could be derived. In addition, because the most recent national forest, land-use, and municipal solid waste surveys were completed for the year 1997, the estimates of CO_2 flux from forests, agricultural soils, and landfilled yard trimmings are based in part on modeled projections. Carbon dioxide flux from urban trees is based on neither annual data nor periodic survey data, but instead on data collected over the period 1990 through 1999. This flux has been applied to the entire time series.

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[1] The term "flux" is used here to encompass both emissions of greenhouse gases to the atmosphere, and removal of carbon from the atmosphere. Removal of carbon from the atmosphere is also referred to as "carbon sequestration."

Table 6-1: Net CO_2 Flux from Land-Use Change and Forestry (Tg CO_2 Eq.)

Sink Category	1990	1995	1996	1997	1998	1999	2000	2001
Forests	(982.7)	(979.0)	(979.0)	(759.0)	(751.7)	(762.7)	(755.3)	(759.0)
Urban Trees	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)
Agricultural Soils	(13.3)	(14.9)	(13.6)	(13.9)	(11.5)	(11.9)	(13.8)	(15.2)
Landfilled Yard Trimmings	(18.2)	(11.6)	(9.7)	(9.0)	(8.7)	(7.8)	(6.9)	(5.3)
Total	**(1,072.8)**	**(1,064.2)**	**(1,061.0)**	**(840.6)**	**(830.5)**	**(841.1)**	**(834.6)**	**(838.1)**

Note: Parentheses indicate net 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.

Table 6-2: Net CO_2 Flux from Land-Use Change and Forestry (Tg C)

Sink Category	1990	1995	1996	1997	1998	1999	2000	2001
Forests	(268)	(267)	(267)	(207)	(205)	(208)	(206)	(207)
Urban Trees	(16)	(16)	(16)	(16)	(16)	(16)	(16)	(16)
Agricultural Soils	(4)	(4)	(4)	(4)	(3)	(3)	(4)	(4)
Landfilled Yard Trimmings	(5)	(3)	(3)	(3)	(2)	(2)	(2)	(1)
Total	**(293)**	**(290)**	**(289)**	**(229)**	**(226)**	**(229)**	**(228)**	**(229)**

Note: 1 Tg C = 1 teragram carbon = 1 million metric tons carbon. Parentheses indicate net 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.

Land use, land-use change, and forestry activities in 2001 resulted in a net sequestration of 838 Tg CO_2 Eq. (229 Tg C) (Table 6-1 and Table 6-2). This represents an offset of approximately 14 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net sequestration declined by approximately 22 percent between 1990 and 2001. This decline was primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks. Annual carbon accumulation in landfilled yard trimmings also slowed over this period, while annual carbon accumulation in agricultural soils increased. As described above, the constant rate of carbon accumulation in urban trees is a reflection of limited underlying data (i.e., this rate represents an average for 1990 through 1999).

Changes in Forest Carbon Stocks

For estimating carbon flux, carbon in forest ecosystems can be divided into the following five storage pools.

- Trees, including the roots, stems, branches, and foliage of living and standing dead trees.
- Understory vegetation, including shrubs and bushes, including the roots, stems, branches, and foliage.
- Forest floor, including fine woody debris, tree litter, and humus.
- Down dead wood, including logging residue and other coarse dead wood on the ground, and stumps and roots of stumps.
- Soil, including all organic material in soil.

Carbon is continuously cycled through and among these storage pools, and between forest ecosystems and the atmosphere as a result of biological processes in forests such as growth and mortality and anthropogenic activities such as harvesting, thinning, clearing, and replanting. As trees grow, carbon is removed from the atmosphere and stored in living tree 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 add carbon to the soil.

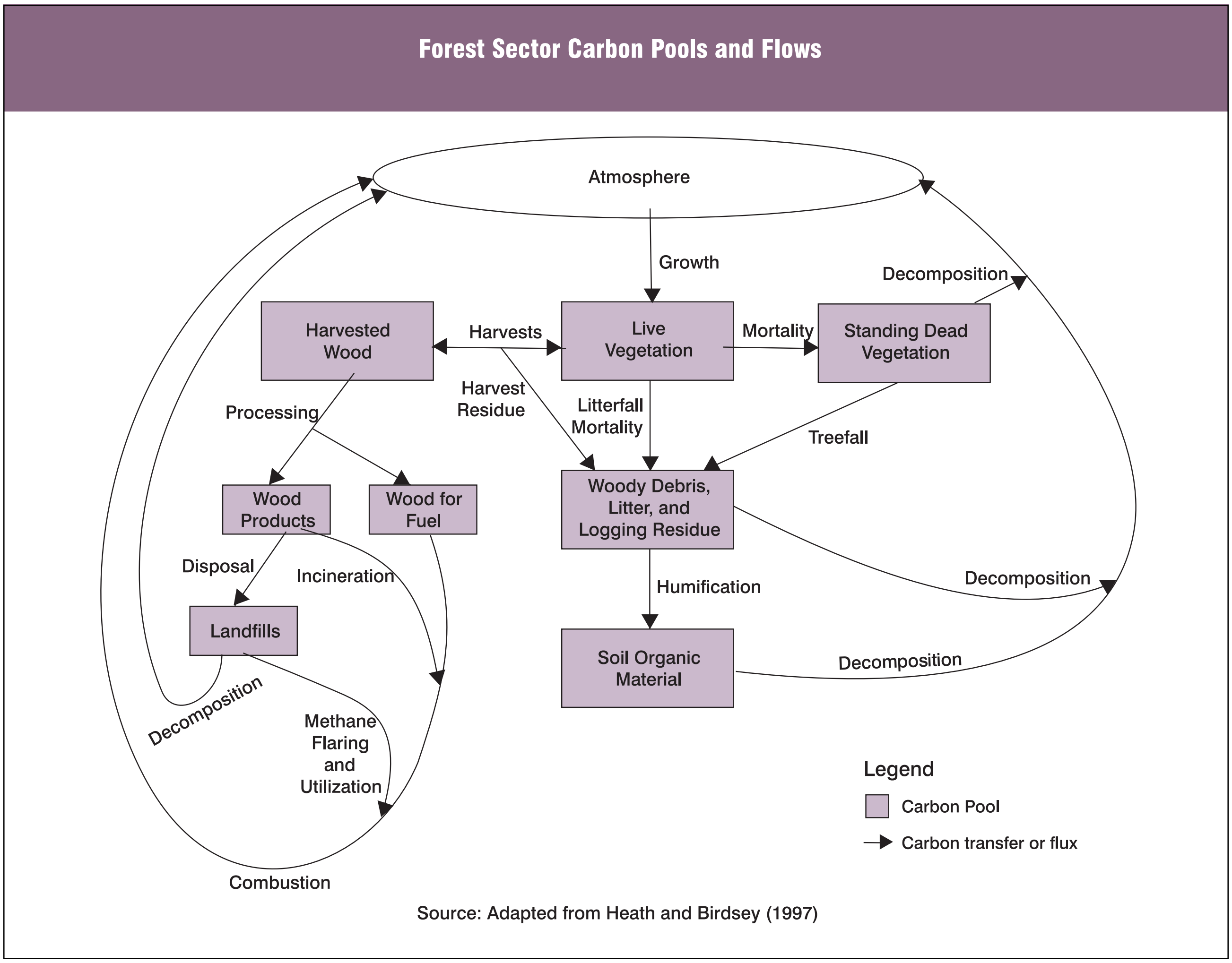
However, the net change in forest carbon is not equivalent to the net flux between forests and the atmosphere because timber harvests may not always result in an immediate flux of carbon to the atmosphere. Harvesting transfers carbon from one of the forest carbon storage pools to a "product pool." Once 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 be stored permanently in the landfill.

This section of the Land-Use Change and Forestry chapter quantifies the net changes in carbon stocks in five forest carbon pools and two harvested wood pools. The net change in stocks for each pool is estimated, and then the changes in stocks are summed over all pools to estimate total net flux.

Forest carbon storage pools, and the flows between them via emissions, sequestration, and transfers, are shown in Figure 6-1. In this figure, forest carbon storage pools are represented by boxes, while flows between storage pools, and between storage pools and the atmosphere, are represented by arrows. Note that the boxes are not identical to the storage pools identified in this chapter. The storage pools identified in this chapter have been altered in this graphic to better illustrate the processes that result in transfers of carbon from one pool to another, and that result in emissions to the atmosphere.

Approximately 33 percent (747 million acres) of the U.S. land area is forested (Smith et al. 2001). Between 1977 and 1987, forest land declined by approximately 5.9 million acres, and between 1987 and 1997, the area increased by about 9.2 million acres. These changes in forest area represent average annual fluctuations of only about 0.1 percent. 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 the ongoing

Figure 6-1



Source: Adapted from Heath and Birdsey (1997) 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[2] of the forest, thereby increasing the uptake of carbon. Harvesting forests removes much of the aboveground carbon, but trees can grow on this area again and sequester carbon. The reversion of cropland to forest land through natural regeneration will cause increased carbon storage in biomass and soils. The net effect of both forest management and land-use change involving forests is captured in these estimates.

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., net sequestration) of carbon during the period from 1990 through 2001. Due to improvements in U.S. agricultural productivity, the rate of forest 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 taken out of crop production, primarily between 1920 and 1950, and were allowed to revert to forests 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, carbon fluxes from Eastern forests have been affected by a trend toward managed growth on private land. Collectively, these changes have produced 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 forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, 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.

Changes in carbon stocks in U.S. forests and harvested wood were estimated to account for an average annual net sequestration of 887 Tg CO_2 Eq. (242 Tg C) over the period 1990 through 2001 (Table 6-3 and Table 6-4).[3] The net sequestration is a reflection of net forest growth and increasing forest area over this period, particularly from 1987 to 1997, as well as net accumulation of carbon in harvested wood pools. The rate of annual sequestration, however, declined by 23 percent between 1990 and 2001. This was due to a greater increase in forest area between 1987 and 1997 than between 1997 and 2001. Most of the decline in annual sequestration occurred in the forest soil carbon pool. This result is due to the method used to account for changes in soil carbon after the conversion of land from forest to non-forest. Specifically, soil carbon stocks for each forest type are assumed to depend on land use and soil type and not to vary over time within forests. Therefore, as lands are converted from non-forest to forest, there is a substantial immediate increase in soil carbon stocks.

Table 6-5 presents the carbon stock estimates for forest and harvested wood storage pools. Together, the tree and forest soil pools account for over 80 percent of total carbon stocks. Carbon stocks in all pools, except forest floor, increased over time, indicating that during these periods, all storage pools, except forest floor, accumulated carbon (e.g., carbon sequestration by trees was greater than carbon removed from the tree pool through respiration, decay, litterfall, and harvest). Figure 6-2 shows 1997 forest carbon stocks, excluding harvested wood stocks, by the regions that were used in the forest carbon analysis. Figure 6-3 shows 1997 forest carbon stocks per hectare, by county, excluding harvested wood stocks, for all counties in the conterminous United States that have at least 5 percent of the county area in forest.

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[2] The term “biomass density” refers to the weight of vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is about 50 percent carbon by weight.

[3] This average annual net sequestration is based on the entire time series (1990 through 2001), rather than the abbreviated time series presented in Table 6-3 and Table 6-4. Results for the entire time series are presented in Annex O.

Table 6-3: Net Changes in Carbon Stocks in Forest and Harvested Wood Pools, and Total Net Forest Carbon Flux (Tg CO2 Eq.)

Carbon Pool	1990	1995	1996	1997	1998	1999	2000	2001
Forest	**(773.7)**	**(773.7)**	**(773.7)**	**(546.3)**	**(546.3)**	**(546.3)**	**(546.3)**	**(546.3)**
Trees	(469.3)	(469.3)	(469.3)	(447.3)	(447.3)	(447.3)	(447.3)	(447.3)
Understory	(11.0)	(11.0)	(11.0)	(14.7)	(14.7)	(14.7)	(14.7)	(14.7)
Forest Floor	(25.7)	(25.7)	(25.7)	29.3	29.3	29.3	29.3	29.3
Down Dead Wood	(55.0)	(55.0)	(55.0)	(58.7)	(58.7)	(58.7)	(58.7)	(58.7)
Forest Soils	(212.7)	(212.7)	(212.7)	(55.0)	(55.0)	(55.0)	(55.0)	(55.0)
Harvested Wood	**(209.0)**	**(205.3)**	**(205.3)**	**(212.7)**	**(205.3)**	**(216.3)**	**(209.0)**	**(212.7)**
Wood Products	(47.7)	(55.0)	(55.0)	(58.7)	(51.3)	(62.3)	(58.7)	(58.7)
Landfilled Wood	(161.3)	(150.3)	(150.3)	(154.0)	(154.0)	(154.0)	(150.3)	(154.0)
Total Net Flux	**(982.7)**	**(979.0)**	**(979.0)**	**(759.0)**	**(751.7)**	**(762.7)**	**(755.3)**	**(759.0)**

Note: Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or stock removal from the carbon pool). The sum of the net stock changes in this table (i.e., total net flux) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys.
Totals may not sum due to independent rounding.

Table 6-4: Net Changes in Carbon Stocks in Forest and Harvested Wood Pools, and Total Net Forest Carbon Flux (Tg C)

Carbon Pool	1990	1995	1996	1997	1998	1999	2000	2001
Forest	**(211)**	**(211)**	**(211)**	**(149)**	**(149)**	**(149)**	**(149)**	**(149)**
Trees	(128)	(128)	(128)	(122)	(122)	(122)	(122)	(122)
Understory	(3)	(3)	(3)	(4)	(4)	(4)	(4)	(4)
Forest Floor	(7)	(7)	(7)	8	8	8	8	8
Down Dead Wood	(15)	(15)	(15)	(16)	(16)	(16)	(16)	(16)
Forest Soils	(58)	(58)	(58)	(15)	(15)	(15)	(15)	(15)
Harvested Wood	**(57)**	**(56)**	**(56)**	**(58)**	**(56)**	**(59)**	**(57)**	**(58)**
Wood Products	(13)	(15)	(15)	(16)	(14)	(17)	(16)	(16)
Landfilled Wood	(44)	(41)	(41)	(42)	(42)	(42)	(41)	(42)
Total Net Flux	**(268)**	**(267)**	**(267)**	**(207)**	**(205)**	**(208)**	**(206)**	**(207)**

Note: 1 Tg C = 1 Tg carbon = 1 million metric tons carbon. This table has been included to facilitate comparison with previous U.S. Inventories. Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or harvest from the carbon pool). The sum of the net stock changes in this table (i.e., total net flux) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys.
Totals may not sum due to independent rounding.

Table 6-5: U.S. Forest Carbon Stock Estimates (Tg C)

Carbon Pool	1987	1997	2002
Forest	**47,595**	**49,695**	**50,440**
Trees	15,168	16,449	17,059
Understory	448	473	493
Forest Floor	4,240	4,306	4,266
Down Dead Wood	2,058	2,205	2,285
Forest Soils	25,681	26,262	26,337
Harvested Wood	**1,920**	**2,478**	**2,767**
Wood Products	1,185	1,319	1,398
Landfilled Wood	735	1,159	1,369
Total Forest Carbon Stocks	**49,515**	**52,173**	**53,207**

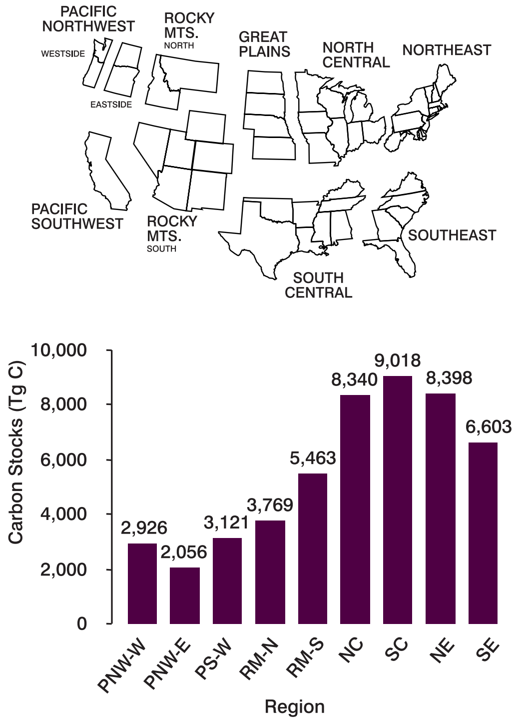
Note: Forest carbon stocks do not include forest stocks in Alaska, Hawaii, or U.S. territories, or trees on non-forest land (e.g., urban trees); wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Shaded areas indicate values based on a combination of historical data and projections. All other estimates are based on historical data only. Totals may not sum due to independent rounding. Note that the stock is listed for 2002 because stocks are defined as of January 1 of the listed year.

Methodology

The methodology described herein is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The IPCC identifies two approaches for developing estimates of net carbon flux or stock change from Land-Use Change and Forestry: 1) using average annual statistics on land use, 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

Figure 6-2

Forest Carbon Stocks by Region, 1997



This graphic shows total forest carbon stocks in 1997, by region. Harvested wood carbon stocks are not included.

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.[4] The use of direct measurements from forest surveys to estimate the forest pools, and the use of data on wood products and landfilled wood to estimate the harvested wood pool is likely to result in more accurate flux estimates than the alternative IPCC methodologies. Due to differences in data sources, different methods were used to calculate the carbon flux in forests and in harvested wood products. Therefore these methods are described separately below.

Forest Carbon Stock Change

The overall approach was to sample the forest carbon at one time, sample the forest carbon again several years later, and then subtract the two estimates to calculate the net change in carbon stocks. Three periodic inventories (sampling times) were used: 1987, 1997, and 2002.[5] For each periodic inventory, each carbon pool was estimated using coefficients from the FORCARB model, as described below. The carbon pools included live and dead standing trees, understory vegetation, forest floor, and soil. These estimates were summed to calculate total carbon stocks at each time period. Data sources and methods for estimating each carbon pool are described briefly below and more fully in Annex O.

The starting point for estimating forest carbon stock change was to obtain data on the area and growing stock volume for forest lands. For 1987 and 1997, such data were available from periodic inventories conducted by the USDA Forest Service Forest Inventory and Analysis program (Smith et al. 2001, Frayer and Furnival 1999). In the past, the Forest Inventory and Analysis program did not conduct detailed surveys of all forest land, but instead focused on timber producing land, which is called timberland. In addition, some reserved forest land and some other forest land were surveyed.[6] With the introduction of the new annualized inventory design (Gillespie 1999), all forest lands will feature the same type of detailed information. In order to include all forest lands, estimates were made for timberlands and then were extrapolated for non-timberland forests.

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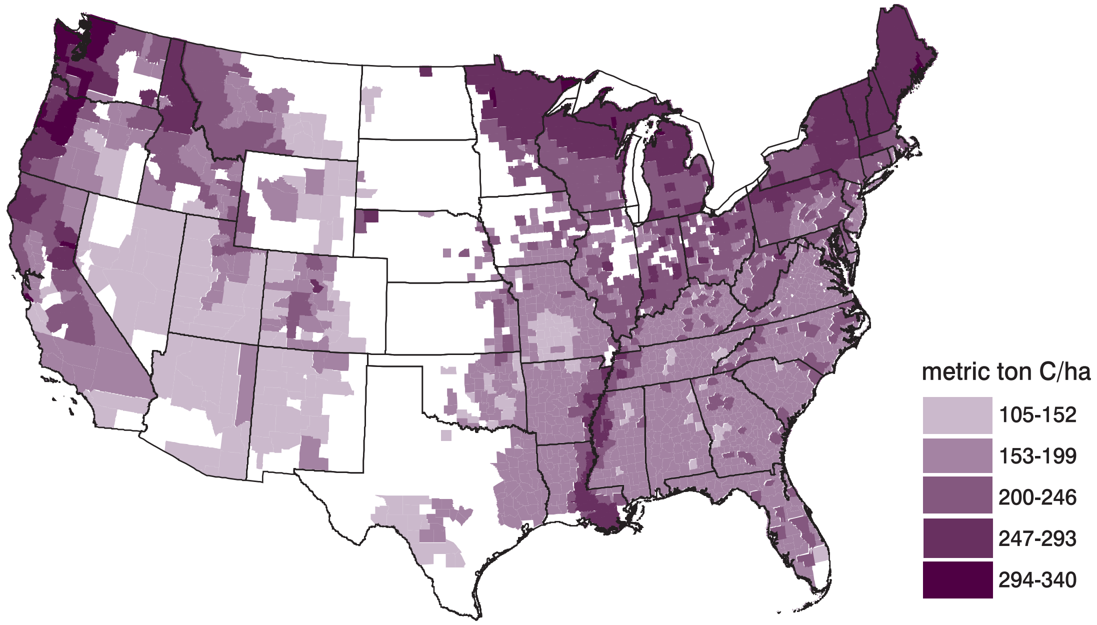
[4] The product estimates in this study do not account for carbon stored in imported wood products. However, they do include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

[5] As explained in the paragraphs below, the 1987 and 1997 "inventories" referred to here are actual forest inventories (i.e., datasets based on field surveys), while the 2002 "inventory" is a projection derived from the historical field data and a linked system of forest sector models. A national (field-based) forest inventory has not been completed for 2002.

[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 1997, there were about 503 million acres of timberlands, which represented 67 percent of all forest lands (Smith and Sheffield 2000). Forest land classified as timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 33 percent of forest land is classified as reserved forest land, which is forest land withdrawn from timber use by statute or regulation, or other forest land, which includes forests on which timber is growing at a rate less than 20 cubic feet per acre per year.

Figure 6-3

Forest Carbon Stocks, per Hectare, by County, 1997



This figure shows total, per hectare, forest carbon stocks in 1997, by county. Only counties in the conterminous United States that have at least 5 percent of the county area in forest are shown. Harvested wood carbon stocks are not included.

The Forest Inventory and Analysis program has conducted consistent forest surveys based on extensive statistically based sampling of much of the forest land in the United States since 1952. Historically, these were conducted periodically, state-by-state within a region. One state within a region would be surveyed, and when finished, another state was surveyed. Eventually (every 5 to 14 years, depending on the state), all states within a region would be surveyed, and then states would be resurveyed. The Forest Inventory and Analysis program has adopted a new annualized design, so that a portion of each state will be surveyed each year (Gillespie 1999); however, data are not yet available for all states. The annualized survey also includes a plan to measure attributes that are needed to estimate carbon in various pools, such as soil carbon and forest floor carbon. Currently, some of these pools must be estimated based on other measured characteristics. Characteristics that were measured in the 1987 and 1997 surveys include individual tree diameter and species, and forest type and age of the plot. For more information about forest inventory data and carbon stock change, see Birdsey and Heath (2001).

Historically, the main purpose of the Forest Inventory and Analysis program has been to estimate areas, volume of growing stock, and timber products output and utilization factors. Growing stock is a classification of timber inventory that includes live trees of commercial species meeting specified standards of quality (Smith et al. 2001). Timber products output refers to the production of industrial roundwood products such as logs and other round timber generated from harvesting trees, and the production of bark and other residue at processing mills. Utilization factors relate inventory volume to the volume cut or destroyed when producing roundwood (May 1998). Growth, harvests, land-use change, and other estimates of change are derived from repeated surveys.

For the 2002 periodic inventory, data were not available from the Forest Inventory and Analysis program. Therefore, areas, volumes, growth, land-use changes, and other forest characteristics were projected with a system of models representing the U.S. forest sector (see Haynes 2002, also see Annex O).

Based on the measured or projected periodic survey data, estimates were made of the total biomass and carbon in trees on timberlands and other forest lands. For timberlands, total biomass and carbon in standing trees were calculated from the growing stock volume. Calculations were made using biomass conversion factors for each forest type and region presented in Smith et al. (in press). For non-timberlands, biomass and carbon in standing trees were estimated based on average carbon estimates derived from similar timberlands. Reserved forests were assumed to contain the same average carbon densities as timberlands of the same forest type, region, and owner group. These averages were multiplied by the areas of non-timberland forests and then aggregated for a national total. Average carbon stocks were derived for other forest land by using average carbon stocks for Timberlands, which were multiplied by 50 percent to simulate the effects of lower productivity.

Understory carbon was estimated from inventory data using equations presented in Birdsey (1992). Forest floor carbon was estimated from inventory data using the equations presented in Smith and Heath (2002). Down dead wood was estimated using a procedure similar to that used for estimating carbon in understory vegetation, as described in Annex O. Data on the carbon content of soils were obtained from the national STATSGO spatial database. These data were combined with spatial data from the Forest Inventory and Analysis program on the location of U.S. forest lands to estimate soil carbon in all forest lands.

Once carbon pools were estimated as described above for each periodic inventory (1987, 1997, and 2002), the pools were summed together to create total forest carbon stock estimates. Average annual carbon stock changes were then calculated by subtracting carbon stocks at the end of a time period from those at the beginning of the time period, and then dividing by the number of years in the time period.

Harvested Wood Products Carbon Stock Change

Estimates of carbon stock changes in wood products and wood discarded in landfills were based on the methods described in Skog and Nicholson (1998). These methods utilize two harvested wood carbon storage pools: wood products in use, and wood discarded in landfills. Annual historical estimates and projections of detailed product production were used to divide consumed roundwood into product, wood mill residue, and pulp mill residue. Rates of decay for wood products and for wood in landfills were estimated and applied to the respective pools. The results were aggregated to produce national estimates. To account for imports and exports, the production approach was used, meaning that carbon in exported wood was included using the same disposal rates as in the United States, while carbon in imported wood was not included. Over the period 1990 through 2001, carbon in exported wood accounted for an average of 22 Tg CO_2 Eq. storage per year, with little variation from year to year. For comparison, imports (which were not included in the harvested wood net flux estimates) increased from 26 Tg CO_2 Eq. per year in 1990 to 47 Tg CO_2 Eq. per year in 2001.

Data Sources

The estimates of forest carbon stocks used in this Inventory to calculate forest carbon fluxes are based largely on areas, volumes, growth, harvests, and utilization factors derived from the forest inventory data collected by the USDA Forest Service Forest Inventory and Analysis program. Compilations of these data for 1987 and 1997 are given in Waddell et al. (1989) and Smith et al. (2001), with trends discussed in the latter citation. The timber volume data used here include timber volumes on forest land classified as timberland, as well as on some reserved forest land and other forest land. Timber volumes on forest land in Alaska, Hawaii, and the U.S. territories are not sufficiently detailed to be used here. Also, timber volumes on non-forest land (e.g., urban trees, rangeland) are not included. The timber volume data include estimates by tree species, size class, and other categories. The forest inventory data are used to derive estimates of carbon stocks as described above in the methodology section and in Annex O. Estimates of soil carbon are based on data from the STATSGO database (USDA 1991). Carbon stocks in wood products in use and wood products stored in landfills are based on historical data from the USDA Forest Service (USDA 1964, Ulrich

1989, Howard 2001), and historical data as implemented in the framework underlying the NAPAP (Ince 1994) and TAMM/ATLAS (Haynes 2002, Mills and Kincaid 1992) models. The carbon conversion factors and decay rates for harvested carbon removed from the forest are taken from Skog and Nicholson (1998).

Uncertainty

This section discusses uncertainties in the carbon sequestration estimates, given the methods and data used. There are sampling and measurement errors associated with the forest survey data that underlie the forest carbon estimates. These surveys are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. Although newer inventories are being conducted annually in every state, many of the data currently used were collected over more than one year in a state, and data associated with a particular year may actually have been collected over several previous years. Thus, there is uncertainty in the year associated with the forest inventory data. In addition, the forest survey data that are currently available generally exclude timber stocks on most forest land in Alaska, Hawaii, and U.S. territories. However, net carbon fluxes from these stocks are believed to be minor. The assumptions that were used to calculate carbon stocks in reserved forests and other forests in the conterminous United States also contribute to the uncertainty. Although the potential for uncertainty is large, the sample design for the forest surveys contributes to limiting the error in carbon flux. Estimates from sampling at different times on permanent plots are correlated, and such correlation reduces the uncertainty in estimates of carbon flux. For example, in a study on the uncertainty of the forest carbon budget of private Timberlands of the United States, Smith and Heath (2000) estimated that the uncertainty of the flux decreased more than three-fold when the correlation coefficient increased from 0.5 to 0.95.

Additional sources of uncertainty come from the models used to estimate carbon storage in specific ecosystem components, such as forest floor, understory vegetation, and soil. Extrapolation of the results of site-specific ecosystem studies to all forest lands introduces uncertainty because such studies may not adequately represent regional or national averages. Uncertainty also arises due to (1) modeling errors, for example relying on coefficients or relationships that are not well known, and (2) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). An important source of uncertainty is that the impacts of forest management activities, including harvest, on soil carbon are not well understood. For example, while Johnson and Curtis (2001) found little or no net change in soil carbon following harvest on average across a number of studies, many of the individual studies did exhibit differences. Heath and Smith (2000b) noted that the experimental design in a number of soil studies was such that the usefulness of the studies may be limited in determining harvesting effects on soil carbon. Soil carbon impact estimates need to be very precise because even small changes in soil carbon may sum to large differences over large areas. This analysis assumes that soil carbon density for each forest type stays constant over time. As more information becomes available, the effects of changes in land use will be better accounted for in estimates of soil carbon.

Recent studies have begun to quantify the uncertainty in national-level carbon budgets based on the methods adopted here. Smith and Heath (2000) and Heath and Smith (2000a) report on an uncertainty analysis they conducted on carbon sequestration in private timberlands. These studies are not strictly comparable to the estimates in this chapter because they used an older version of the FORCARB model, which was based on older data and produced decadal estimates. However, the magnitudes of the uncertainties should be instructive. Their results indicate that the carbon flux of private timberlands, not including harvested wood, was approximately the average carbon flux (271 Tg CO_2 Eq. per year) ±15 percent at the 80 percent confidence level for the period 1990 through 1999. The flux estimate included the tree, soil, understory vegetation, and forest floor components only. The uncertainty in the carbon inventory of private timberlands for 2000 was approximately 5 percent at the 80 percent confidence level. These estimates did not include all uncertainties, such as the ones associated with public timberlands, and reserved and other forest land, but they did include many of the types of uncertainties listed previously. Because of these additional factors, uncertainty is expected to be greater in estimates for all forest lands.

Changes in Carbon Stocks in Urban Trees

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). It is estimated that urban areas (cities, towns, and villages), which cover 3.5 percent of the continental United States, contain about 3.8 billion trees. With an average tree canopy cover of 27.1 percent, urban areas account for approximately 3 percent of total tree cover in the continental United States.

Trees in urban areas of the continental United States were estimated by Nowak and Crane (2001) to account for an average annual net sequestration of 59 Tg CO_2 Eq. (16 Tg C). This estimate is representative of the period from 1990 through 2001, as it is based on data collected during the 1990s. Annual estimates of CO_2 flux have not been developed (Table 6-6).

Table 6-6: Net CO_2 Flux From Urban Trees (Tg CO_2 Eq.)

Year	Tg CO_2 Eq.
1990	(58.7)
1995	(58.7)
1996	(58.7)
1997	(58.7)
1998	(58.7)
1999	(58.7)
2000	(58.7)
2001	(58.7)

Note: Parentheses indicate net sequestration.

Methodology

The methodology used by Nowak and Crane (2001) is based on average annual estimates of urban tree growth and decomposition, which were derived from field measurements and data from the scientific literature, urban area estimates from U.S. Census data, and urban tree cover estimates from remote sensing data. This approach is consistent with, but more robust than, the default IPCC methodology in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).[7]

Nowak and Crane (2001) developed estimates of annual gross carbon sequestration from tree growth and annual gross carbon emissions from decomposition for ten U.S. cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL; Jersey City, NJ; New York, NY; Oakland, CA; Philadelphia, PA, Sacramento, CA; and Syracuse, NY. The gross carbon sequestration estimates were derived from field data that were collected in these ten cities during the period from 1989 through 1999, including tree measurements of stem diameter, tree height, crown height, and crown width, and information on location, species, and canopy condition. The field data were converted to annual gross carbon sequestration rates for each species (or genus), diameter class, and land-use condition (forested, park-like, and open growth) by applying allometric equations, a root-to-shoot ratio, moisture contents, a carbon content of 50 percent (dry weight basis), an adjustment factor to account for smaller aboveground biomass volumes (given a particular diameter) in urban conditions compared to forests, an adjustment factor to account for tree condition (fair to excellent, poor, critical, dying, or dead), and annual diameter and height growth rates. The annual gross carbon sequestration rates for each species (or genus), diameter class, and land-use condition were then scaled up to city estimates using tree population information.

The annual gross carbon emission estimates were derived by applying to carbon stock estimates, which were derived as an intermediate step in the gross sequestration calculations, estimates of annual mortality by tree diameter and condition class, assumptions about whether dead trees would be removed from the site—since removed trees were assumed to decay faster than those left on the site—and assumed decomposition rates for dead trees left standing and dead trees that are removed. The annual gross carbon emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information.

Annual net carbon sequestration estimates were derived for seven of the ten cities by subtracting the annual gross emission estimates from the annual gross sequestration estimates.[8] See Table 6-7.

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[7] It is more robust in that both growth and decomposition are accounted for, and data from individual trees are scaled up to state and then national estimates based on data on urban area and urban tree canopy cover.

[8] Three cities did not have net estimates.

Table 6-7: Carbon Stocks (Metric Tons C), Annual Carbon Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual Carbon Sequestration per Area of Tree Cover (kg C/m^2 cover-yr) for Ten U.S. Cities

City	Carbon Stocks	Gross Annual Sequestration	Net Annual Sequestration	Tree cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover
New York, NY	1,225,200	38,400	20,800	20.9	0.23	0.12
Atlanta, GA	1,220,200	42,100	32,200	36.7	0.34	0.26
Sacramento, CA	1,107,300	20,200	NA	13.0	0.66	NA
Chicago, IL	854,800	40,100	NA	11.0	0.61	NA
Baltimore, MD	528,700	14,800	10,800	25.2	0.28	0.20
Philadelphia, PA	481,000	14,600	10,700	15.7	0.27	0.20
Boston, MA	289,800	9,500	6,900	22.3	0.30	0.22
Syracuse, NY	148,300	4,700	3,500	24.4	0.30	0.22
Oakland, CA	145,800	NA	NA	21.0	NA	NA
Jersey City, NJ	19,300	800	600	11.5	0.18	0.13

NA = not analyzed

National annual net carbon sequestration by urban trees was estimated from the city estimates of gross and net sequestration, and urban area and urban tree cover data for the contiguous United States. Note that the urban areas are based on U.S. Census data, which define "urban" as having a population density greater than 1,000 people per square mile or population total greater than 2,500. Therefore, urban encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). The gross and net carbon sequestration values for each city were divided by each city's area of tree cover to determine the average annual sequestration rates per unit of tree area for each city. The median value for gross sequestration (0.30 kg C/m^2-year) was then multiplied by an estimate of national urban tree cover area (76,151 km^2) to estimate national annual gross sequestration. To estimate national annual net sequestration, the estimate of national annual gross sequestration was multiplied by the average of the ratios of net to gross sequestration for those cities that had both estimates. The average of these ratios is 0.70.

Data Sources

The field data from the 10 cities, some of which are unpublished, are described in Nowak and Crane (2001) and references cited therein. The allometric equations were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), and the adjustments to account for smaller volumes in urban conditions were based on information in Nowak (1994). A root-to-shoot ratio of 0.26 was taken from Cairns et al. (1997), and species- or genus-specific moisture contents were taken from various literature sources (see Nowak 1994). Adjustment factors to account for tree condition were based on percent crown dieback (Nowak and Crane 2001). Tree growth rates were also taken from existing literature. Average diameter growth was based on the following sources: estimates for trees in forest stands came from Smith and Shifley (1984); estimates for trees on land uses with a park-like structure came from deVries (1987); and estimates for more open-grown trees came from Nowak (1994). Formulas from Fleming (1988) formed the basis for average height growth calculations. Estimates of annual mortality rates by diameter class and condition class were derived from a study of street-tree mortality (Nowak 1986). Assumptions about whether dead trees would be removed from the site were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak and Crane 2001). Urban tree cover area estimates for each of the 10 cities and the contiguous United States were obtained from Dwyer et al. (2000) and Nowak et al. (2001).

Uncertainty

The estimates are based on limited field data collected in ten U.S. cities, and the uncertainty in these estimates increases as they are scaled up to the national level. There is also uncertainty associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate carbon sequestration and emission estimates (Nowak et al. 2002), as well as with the tree cover area estimates for urban areas, as these are based on interpretation of Advanced Very High Resolution Radiometer data. In addition, these results do not include changes in soil carbon stocks, and there may be some overlap between the urban tree carbon estimates and the forest tree carbon estimates. However, both the omission of urban soil carbon flux, and the potential overlap with forest carbon, are believed to be relatively minor (Nowak 2002).

Changes in Agricultural Soil Carbon Stocks

The amount of organic carbon contained in soils depends on the balance between inputs of organic material (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and loss of carbon through decomposition. The quantity and quality of organic matter inputs, and their rate of decomposition, are determined by the combined interaction of climate, soil properties, and land use. Agricultural practices such as clearing, drainage, tillage, planting, grazing, 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 estimation of net CO_2 flux from agricultural soils (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; 2) agricultural land-use and land-management activities on organic soils; and 3) liming of soils. Mineral soils and organic soils are treated separately because each responds differently to land-use practices.

Mineral soils contain comparatively low amounts of organic matter (usually less than 20 percent by weight), much of which is concentrated near the soil surface. Typical well-drained mineral surface soils contain from 1 to 6 percent organic matter (by weight); mineral subsoils contain even lower amounts of organic matter (Brady and Weil 1999). 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 to 60 percent of the carbon loss generally occurs within the first 10 years following conversion; after that, carbon stocks continue to decline 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 organic inputs or decreased oxidation of organic matter (e.g., improved 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.

Organic soils, which are also referred to as histosols, include all soils with more than 20 to 30 percent organic matter by weight, depending on clay content (Brady and Weil 1999). The organic matter layer of these soils is also typically extremely deep. Organic soils form under water-logged conditions, in which decomposition of plant residues is retarded. When organic soils are cultivated, they are first drained which, together with tilling or mixing of the soil, aerates the soil, and thereby accelerates 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. 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 (i.e., decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for annual crops results in greater carbon loss than conversion to pasture or forests, due to deeper drainage and more intensive management practices (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997).

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 applied limestone and dolomite to degrade completely.

Of the three activities, use and management of mineral soils was the most important component of total flux during the 1990 through 2001 period. Carbon sequestration in

Table 6-8: Net CO_2 Flux From Agricultural Soils (Tg CO_2 Eq.)

Soil Type/Management Activity	1990	1995	1996	1997	1998	1999	2000	2001
Mineral Soils	(57.1)	(58.6)	(57.3)	(57.4)	(55.8)	(55.7)	(57.3)	(59.1)
Organic Soils	34.3	34.8	34.8	34.8	34.8	34.8	34.8	34.8
Liming of Soils	9.5	8.9	8.9	8.7	9.6	9.1	8.8	9.1
Total	**(13.3)**	**(14.9)**	**(13.6)**	**(13.9)**	**(11.5)**	**(11.9)**	**(13.8)**	**(15.2)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

mineral soils in 2001 was estimated at approximately 59 Tg CO_2 Eq. (16 Tg C), while emissions from organic soils were estimated at 35 Tg CO_2 Eq. (9 Tg C) and emissions from liming were estimated at 9 Tg CO_2 Eq. (2.5 Tg C). Together, the three activities accounted for net sequestration of approximately 15 Tg CO_2 Eq. (4 Tg C) in 2001. Total annual net CO_2 flux was negative (i.e., net sequestration) each year over the 1990 to 2001 period. Between 1990 and 2001, total net carbon sequestration in agricultural soils increased by close to 14 percent. The increase is largely due to additional acreage of annual cropland converted to permanent pastures and hay production, a reduction in the frequency of summer-fallow use in semi-arid areas and some increase in the adoption of conservation tillage (i.e., reduced and no-till) practices. The relatively large shift in annual net sequestration from 1990 to 1995 is the result of calculating average annual mineral and organic soil fluxes from periodic, rather than annual, activity data.[9]

The spatial variability in annual, per hectare CO_2 flux for mineral and organic soils is displayed in Figure 6-4 through Figure 6-7. The greatest mineral soil sequestration rates are in the south and east central United States and in a small area of the Pacific Northwest, while the greatest organic soil emission rates are along the southeast coast, in the northeast central United States, and along the central west coast.

The flux estimates presented here are restricted to CO_2 fluxes associated with the use and management of agricultural soils. Agricultural soils are also important sources of other greenhouse gases, particularly nitrous oxide (N_2O) from application of fertilizers, manure, and crop residues and from cultivation of legumes, as well as methane (CH_4) from flooded rice cultivation. These emissions are accounted for in the Agriculture chapter.[10] It should be noted that other land-use and land-use change activities result in fluxes of non-CO_2 greenhouse gases to and from soils that are not currently accounted for. These include emissions of CH_4 and N_2O from managed forest soils (above what would occur if the forest soils were undisturbed), as well as CH_4 emissions from artificially flooded lands, resulting from activities such as dam construction. Aerobic (i.e., non-flooded) soils are a sink for CH_4, so soil drainage can result in soils changing from a CH_4 source to a CH_4 sink, but if the drained soils are used for agriculture, fertilization and tillage, disturbance can reduce the ability of soils to oxidize CH_4. The non-CO_2 emissions and sinks from these other land use and land-use change activities were not assessed due to scientific uncertainties about the greenhouse gas fluxes that result from these activities.

Methodology and Data Sources

The methodologies used to calculate net CO_2 flux from use and management of mineral and organic soils and from liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997, Ogle et al. 2002, Ogle et al. in review), except where noted below. (Additional details on the methodology and data used to estimate flux from mineral and organic soils are described in Annex P). Mineral soil organic carbon stocks were estimated for 1982, 1992, and 1997 for the conterminous United States and Hawaii using U.S. data on climate, soil types, land use and land management activity data, reference carbon stocks (for agricultural soils rather than native soils) and field studies

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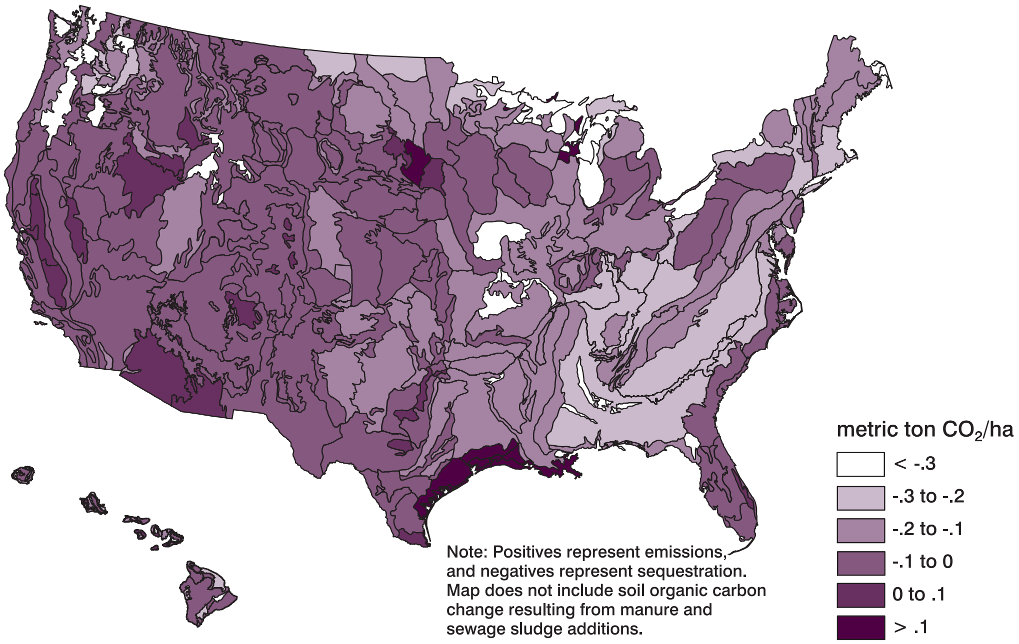
[9] Mineral and organic soil results for the entire time series are presented in Annex P.

[10] Nitrous oxide emissions from agricultural soils and methane emissions from rice fields are addressed under the Agricultural Soil Management and Rice Cultivation sections, respectively, of the Agriculture chapter.

Figure 6-4

Net Annual CO_2 Flux, per Hectare, From Mineral Soils Under Agriculture Management, 1990–1992

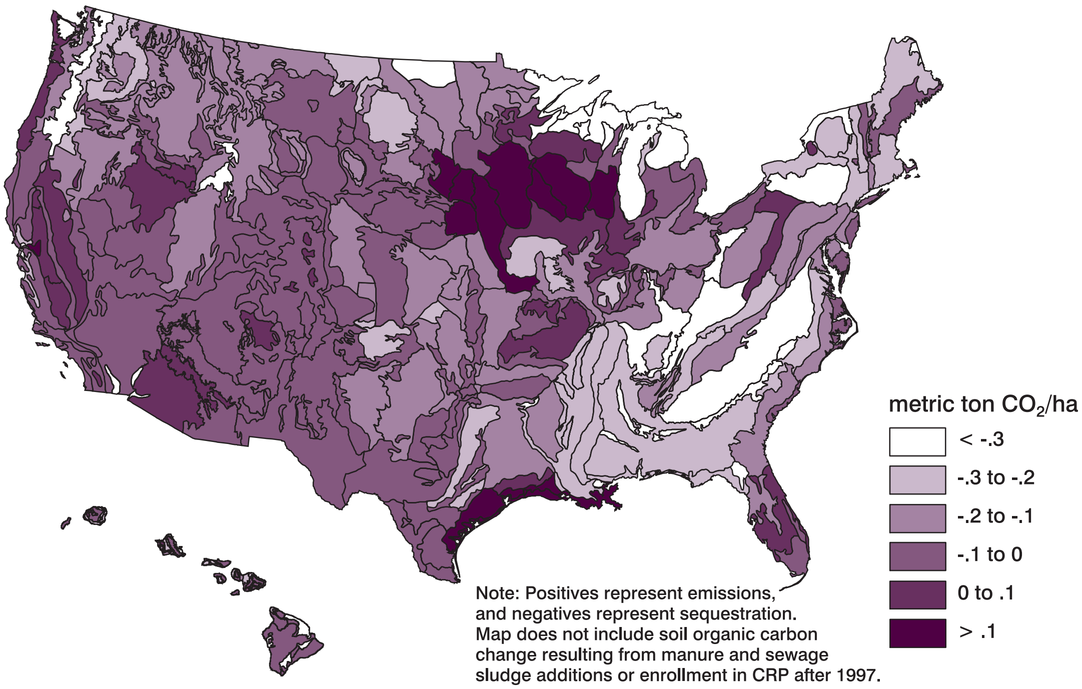


Note: Positives represent emissions, and negatives represent sequestration. Map does not include soil organic carbon change resulting from manure and sewage sludge additions.

This map shows the spatial variability in net annual carbon dioxide flux from mineral soils for the year 1990 through 1992. The color assigned to each polygon represents the average annual flux per hectare for the area of managed mineral soils in that polygon.

Figure 6-5

Net Annual CO_2 Flux, per Hectare, From Mineral Soils Under Agriculture Management, 1993–2001

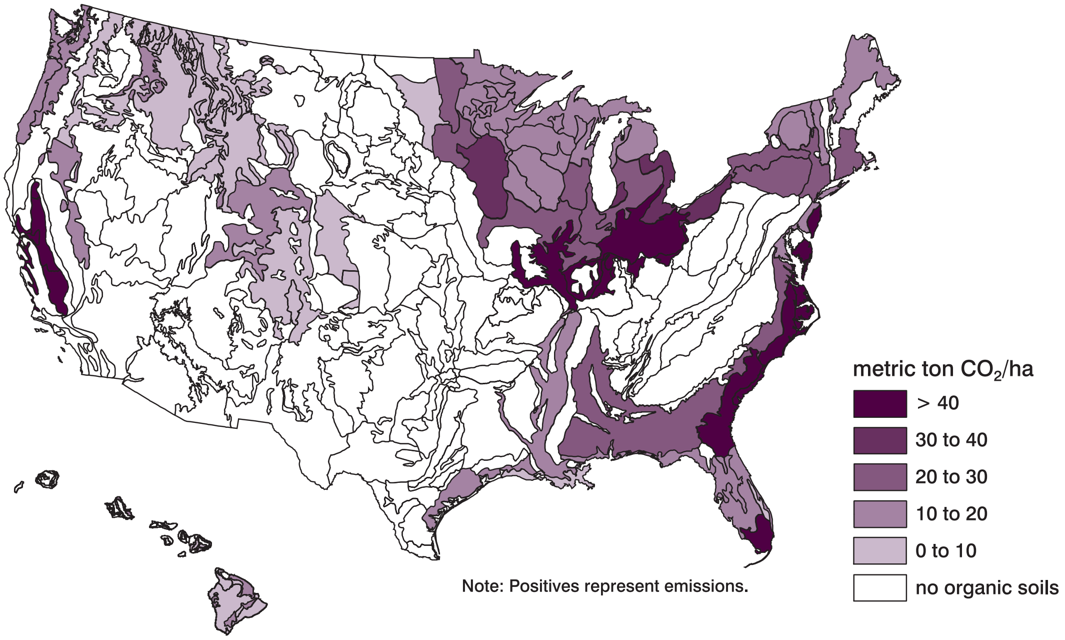


Note: Positives represent emissions, and negatives represent sequestration. Map does not include soil organic carbon change resulting from manure and sewage sludge additions or enrollment in CRP after 1997.

This map shows the spatial variability in net annual carbon dioxide flux from mineral soils for the year 1993 through 2001. The color assigned to each polygon represents the average annual flux per hectare for the area of managed mineral soils in that polygon.

Figure 6-6

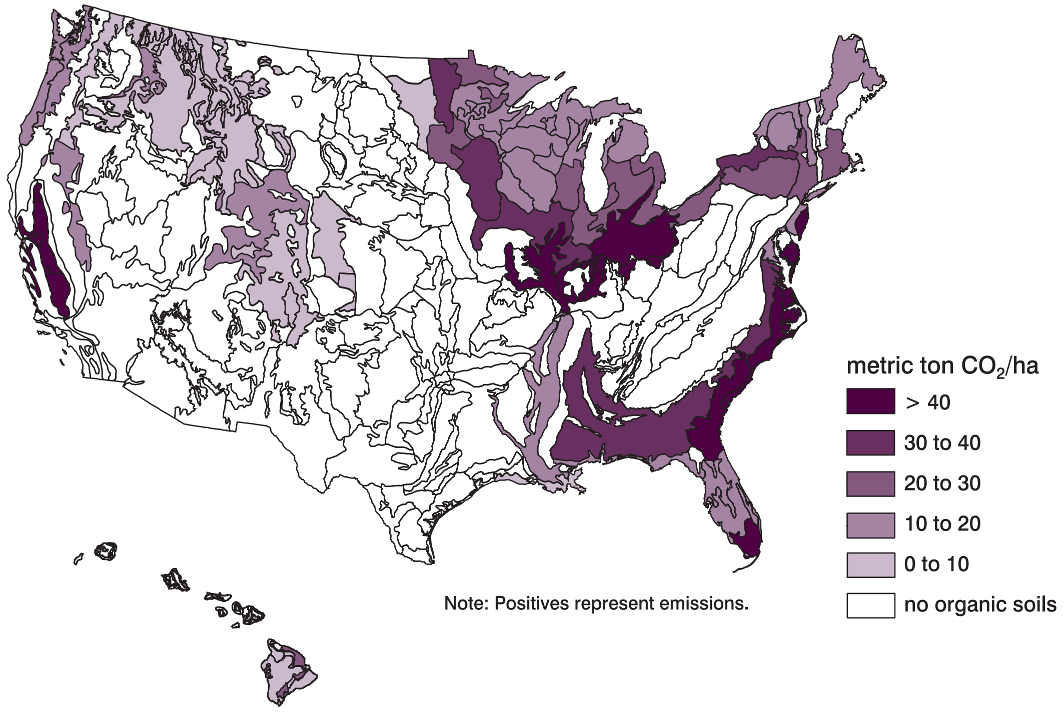
Net Annual CO_2 Flux, per Hectare, From Organic Soils Under Agriculture Management, 1990–1992



This map shows the spatial variability in net annual carbon dioxide flux from organic soils for the year 1990 through 1992.
The color assigned to each polygon represents the average annual flux per hectare for the area of managed organic soils in that polygon.

Figure 6-7

Net Annual CO_2 Flux, per Hectare, From Organic Soils Under Agriculture Management, 1993–2001



This map shows the spatial variability in net annual carbon dioxide flux from organic soils for the year 1993 through 2001.
The color assigned to each polygon represents the average annual flux per hectare for the area of managed organic soils in that polygon.

Table 6-9: Net Annual CO_2 Flux from U.S. Agricultural Soils Based on Monte Carlo Simulation (Tg CO_2 Eq.)

Soil Type	1990-1992	1993-2001
Mineral Soils		
Estimate*	(35.8)	(35.4)
Uncertainties	(13.9) to (58.7)	(20.9) to (50.3)
Organic Soils		
Estimate	34.3	34.8
Uncertainties	23.1 to 48.4	23.5 to 49.1
Total		
Estimate	**(1.5)**	**(0.7)**
Uncertainties	**24.2 to (27.2)**	**19.5 to (19.5)**

Note: Parentheses indicate net sequestration. The uncertainties are based on the Monte Carlo analysis. The range is a 95 percent confidence interval, based on the simulated values at the 2.5 and 97.5 percentiles in the final distribution of 50,000 estimates.
* Does not include the change in carbon storage resulting from the annual application of manure and sewage sludge, or the change in Conservation Reserve Program enrollment after 1997.

addressing management effects on soil organic carbon storage. National-scale data on land-use and management changes over time were obtained from the *1997 National Resources Inventory* (NRCS 2000). The *1997 National Resources Inventory* provides land use/management data and soils information for more than 400,000 locations in U.S. agricultural lands. Two other sources were used to supplement the land-use information from the *1997 National Resources Inventory*. The Conservation Technology Information Center (CTIC 1998) provided data on tillage activity, with adjustments for long-term adoption of no-till agriculture (Towery 2001), and Euliss and Gleason (2002) provided activity data on wetland restoration of Conservation Reserve Program Lands. Major Land Resource Areas (MLRAs, NRCS 1981) were used as the base spatial unit for mapping climate regions in the United States. Each Major Land Resource Area represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981).[11] Major Land Resource Areas were classified into climate zones according to the IPCC categories using the Parameter-Evaluation Regressions on Independent Slopes Model (PRISM) climate-mapping program of Daly et al. (1994). Reference carbon stocks were estimated using the National Soil Survey Characterization Database (NRCS 1997), and the reference condition for the stock estimates was cultivated cropland, rather than native vegetation as used in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Changing the reference condition was necessary because soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997). Management factors were derived from published literature to determine the impact of management practices on soil organic carbon storage, including changes in tillage, cropping rotations and intensification, as well as land-use change between cultivated and uncultivated conditions (Ogle et al. in review). Euliss and Gleason (2002) provided the data for computing the change in soil organic carbon storage resulting from restoration of Conservation Reserve Program Lands (Olness et al. in press, Euliss et al. in prep). Combining information from these data sources, carbon stocks were estimated 50,000 times for 1982, 1992, and 1997, using a Monte Carlo simulation approach and the probability density functions for U.S.-specific management factors, reference carbon stocks, and land-use activity data (Ogle et al. in review, Ogle et al. 2002). The annual carbon flux for 1990 through 1992 was estimated by calculating the annual change in stocks between 1982 and 1992; annual carbon flux for 1993 through 2001 was estimated by calculating the annual change in stocks between 1992 and 1997 (see Table 6-9).

Annual carbon emission estimates from organic soils used for agriculture between 1990-2001 were derived using *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), except that U.S.-specific carbon loss rates were used in the calculations rather than default IPCC rates (Ogle et al. 2002). Similar to mineral soils, the final estimates include a measure of uncertainty as determined from the Monte Carlo simulation. Data from published literature were used to derive probability density functions for carbon loss rates (Ogle et al. in review), which were used to compute emissions based on the 1992 and 1997 land areas in each climate/land-use category defined in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The area estimates were derived from the same climate, soil, and land-use/management databases that were used for mineral soil calculations (Daly et al. 1994, USDA 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2001 (see Table 6-9).

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[11] The polygons displayed in Figure 6-4 through Figure 6-7 are the Major Land Resource Areas.

Table 6-10: Quantities of Applied Minerals (Thousand Metric Tons)

Mineral	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Limestone	19,012	20,312	17,984	15,609	16,686	17,297	17,479	16,539	14,882	16,894	15,863	16,473
Dolomite	2,360	2,618	2,232	1,740	2,264	2,769	2,499	2,989	6,389	3,420	3,812	3,959

Annual carbon flux estimates for mineral soils between 1990 and 2001 were adjusted to account for additional carbon sequestration from manure and sewage sludge applications, as well as gains or losses in carbon sequestration due to changes in Conservation Reserve Program enrollment after 1997. The amount of land receiving manure and sewage sludge was estimated from nitrogen application data from the Agricultural Soil Management section of the Agriculture chapter of this volume, and an assumed application rate derived from Kellogg et al. (2000). The total land area was subdivided between cropland and grazing land based on supplemental information collected by the USDA (ERS 2000, NASS 2002). Carbon storage rate was estimated at 0.10 metric tons C per hectare per year for cropland and 0.33 metric tons C per hectare per year for grazing land. To estimate the carbon impacts of changes in Conservation Reserve Program enrollment after 1997, the changes in Conservation Reserve Program acreage relative to 1997 were derived based on Barbarika (2002), and the mineral soil changes were multiplied by 0.5 metric tons C per hectare per year.

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 6-10) by CO_2 emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite).[12] These emission factors are based on the assumption that all of the carbon in these materials evolves as CO_2 in the same year in which the minerals are applied. The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys* (Tepordei 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002; USGS 2002). To develop these data, USGS (U.S. Bureau of Mines prior to 1997) 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 were 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 "unspecified" and "estimated" 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 in a specific year were equal to the fraction of "specified" production that was applied to agricultural soils in that same year. In addition, data were not available for 1990, 1992, and 2001 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 the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2001 data, the 2000 fractions were applied to a 2001 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2002* (USGS 2002).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the U.S. Geological Survey from 1995 to the present. In 1994, the "Crushed Stone" chapter in *Minerals Yearbook* began rounding (to the nearest thousand) quantities for total crushed stone produced or

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[12] 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.

Box 6-1: Century model estimates of soil carbon stock changes on cropland

Soil carbon stock changes on U.S. cropland were estimated using a dynamic ecosystem simulation model called Century (Metherell et al. 1993, Parton et al. 1994). This method differs from the IPCC approach in that annual changes are computed dynamically as a function of inputs of carbon to soil (e.g., crop residues, manure) and carbon emissions from organic matter decomposition, which are governed by climate and soil factors as well as management practices. The model simulates all major field crops (maize, wheat and other small grains, soybean, sorghum, cotton) as well as hay and pasture (grass, alfalfa, clover). Management variables included tillage, fertilization, irrigation, drainage, and manure addition.

Input data were largely from the same sources as in the IPCC-based method (i.e., climate variables were from the PRISM database; crop rotation, irrigation and soil characteristics were from the National Resources Inventory (NRI); and tillage data were from the Conservation Technology Information Center (CTIC). In addition, the Century analysis used detailed information on crop rotation-specific fertilization and tillage implements obtained from USDA's Economic Research Service. The main difference between the methods is that the climate, soil and management data serve as 'driving variables' in the Century simulation, whereas in the IPCC approach these data are more highly aggregated and are used for classification purposes. In the Century-based analysis, land areas having less than 5 percent of total area in crop production were excluded and several less-dominant crops (e.g., vegetables, sugar beets and sugar cane, potatoes, tobacco, orchards, and vineyards), for which the model has not yet been parameterized, were not included. Thus, the total area included in the Century analysis (149 million hectares) was smaller than the corresponding area of cropland (165 million hectares) included in the IPCC estimates.

Preliminary results using the Century model suggest (as with the IPCC model) that U.S. cropland mineral soils (excluding organic soils) are currently acting as a carbon sink. The Century model estimates are that U.S. cropland soils sequester approximately 77 Tg CO_2 Eq. per year (21 Tg C/year) (average rates for 1992 through 1997). Organic soils (which contribute large C losses) were not simulated by Century.

As with the IPCC method, increases in mineral soil C stocks in the Century analysis are associated with reduced tillage, Conservation Reserve Program lands, reduced bare fallow and some increase in hay area. However, the Century analysis also includes the effect of a long-term trend in increasing residue inputs due to higher productivity on cropland in general, which contributes to the increase in soil carbon stocks. However, further work is needed to refine model input data and to estimate uncertainty for the dynamic model approach. Potential advantages of a dynamic simulation-based approach include the ability to use actual observed weather, observed annual crop yields, and more detailed soils and management information to drive the estimates of soil carbon change. This would facilitate annual estimates of carbon stock changes and CO_2 emissions from soils that would better reflect interannual variability in cropland production and weather influences on carbon cycle processes.

used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Uncertainty

Although the mineral and organic soil estimates have been improved from previous years using a Monte Carlo approach with the incorporation of U.S.-specific reference carbon stocks and management factor values, some limitations do remain in the analysis. First, minimal data exist on where and how much manure and sewage sludge has been applied to U.S. agricultural lands. Consequently, uncertainties have not been estimated for the change in soil organic carbon storage resulting from these applications. Second, due to the IPCC requirement that inventories include all land areas that are potentially subject to land-use change, the *1997 National Resources Inventory* dataset includes some points designated as non-agricultural land-uses if this designation changed during the period from 1992 to 1997. The non-agricultural land uses are urban, water, and miscellaneous non-cropland (e.g., roads and barren areas). The impact on carbon storage resulting from converting cropland to non-agricultural uses is not well understood, and therefore, those points were not included in the calculations. Third, this inventory may underestimate losses of carbon from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, this methodology does not take into account changes in carbon stocks due to pre-1982 land use and land-use change.

A revised inventory approach to better quantify uncertainty and to better represent between-year variability in annual fluxes is being developed and is currently under review. This new annual activity-based inventory, using a dynamic simulation model, would use climate, soil, and land-use/land-management databases to estimate annual variation in fluxes and include the effects of long-term trends in agricultural productivity on soil carbon stocks (see Box 6-1).

Uncertainties in the estimates of emissions from liming result from both the methodology and the activity data. The IPCC method assumes that all the inorganic carbon in the applied minerals evolves to CO_2, and that this degradation occurs in the same year that the minerals are applied. However, recent research has shown that liming can either be a carbon source or a sink, depending upon weathering reactions, which are pH dependent (Hamilton et al. 2002). Moreover, it can take several years for agriculturally applied limestone and dolomite to degrade completely. However, application rates are fairly constant over the entire time series, so this latter assumption may not contribute significantly to overall uncertainty.

There are several sources of uncertainty in the limestone and dolomite activity data. When reporting data to the USGS (or U.S. Bureau of Mines), some producers do not distinguish between limestone and dolomite. In these cases, data are reported as limestone, so this could lead to an overestimation of limestone and an underestimation of dolomite. In addition, the total quantity of crushed stone listed each year in the *Minerals Yearbook* excludes American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands. The *Mineral Industry Surveys* further excludes Alaska and Hawaii from its totals.

Changes in Yard Trimming Carbon Stocks in Landfills

As is the case with carbon in 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, and a large fraction of the collected yard trimmings are discarded in landfills. However, both the amount of yard trimmings collected annually and the fraction that is landfilled have declined over the last decade. In 1990, nearly 32 million metric tons (wet weight) of yard trimmings were collected at landfills and transfer stations (Franklin Associates 1999). Since then, programs banning or discouraging disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 21 percent decrease in the amount of yard trimmings collected. At the same time, a dramatic increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills—from 72 percent in 1990 to 26 percent in 2001. The decrease in the yard trimmings landfill disposal rate has resulted in a decrease in the rate of landfill carbon storage from approximately 18 Tg CO_2 Eq. in 1990 to 5 Tg CO_2 Eq. in 2001 (Table 6-11).

Table 6-11: Net CO_2 Flux from Landfilled Yard Trimmings (Tg CO_2 Eq.)

Year	Tg CO_2 Eq.
1990	(18.2)
1995	(11.6)
1996	(9.7)
1997	(9.0)
1998	(8.7)
1999	(7.8)
2000	(6.9)
2001	(5.3)

Note: Parentheses indicate net storage. Shaded area indicates values based on projections.

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 weight of landfilled yard trimmings and a storage factor. The storage factor, which is the ratio of the weight of the carbon that is stored indefinitely to the wet weight of the landfilled yard trimmings, is based on a series of experiments designed to evaluate CH_4 generation and residual organic material in landfills (Barlaz 1998). These experiments analyzed grass, leaves, branches, and other materials, and were designed to promote biodegradation by providing ample moisture and nutrients.

Barlaz (1998) determined carbon storage factors, on a dry weight basis, for each of the three components of yard trimmings: grass, leaves, and branches (see Table 6-12). For purposes of this analysis, these were converted to wet weight basis using assumed moisture contents of

Table 6-12: Storage Factor (kg C/kg dry yard trimmings), Moisture Content (kg water/kg wet yard trimmings), Yard Trimmings Composition (percent), and Carbon Storage Factor (kg C/kg wet yard trimmings) of Landfilled Yard Trimmings

	Grass	Leaves	Branches
Storage Factor[a]	0.30	0.46	0.43
Moisture Content	0.60	0.20	0.40
Yard Trimmings Composition	50%	25%	25%
Converted Storage Factor[b]	0.12	0.37	0.26

[a] From Barlaz (1998), adjusted using CH_4 yields in Eleazer et al. (1997).

[b] The converted storage factor for each component is the product of the original storage factor and one minus the moisture content; the weighted average storage factor for yard trimmings is obtained by weighting the component storage factors by the yard trimmings composition percents.

0.6, 0.2, and 0.4, respectively. To develop a weighted average carbon storage factor, the composition of yard trimmings was assumed to consist of 50 percent grass clippings, 25 percent leaves, and 25 percent branches on a wet weight basis. The weighted average carbon storage factor is 0.22 (weight of carbon stored indefinitely per unit weight of wet yard trimmings).

Data Sources

The yard trimmings discards data were taken from two reports: *Characterization of Municipal Solid Waste in the United States: 1998 Update* (Franklin Associates 1999) and *Municipal Solid Waste in the United States: 2000 Facts and Figures* (EPA 2002), which provide estimates for 1990 through 2000 (see Table 6-13). Yard trimmings discards for 2001 were projected using a linear regression of the 1990 through 2000 data. These reports do not subdivide discards of individual materials into volumes landfilled and combusted, although they provide an estimate of the overall distribution of solid waste between these two management methods (i.e., ranging from 81 percent and 19 percent respectively in 1990, to 77 percent and 23 percent in 2001) for the waste stream as a whole.[13] Thus, yard trimmings disposal to landfills is the product of the quantity discarded and the proportion of discards managed in landfills. As discussed above, the carbon storage factor was derived from the results of Barlaz (1998) and Eleazer et al. (1977), and assumed moisture contents and component fractions for yard trimmings.

Uncertainty

The principal source of uncertainty for the landfill carbon storage estimates stems 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 values for 2001 disposal from estimates for the period from 1990 through 2000. In addition, the methodology does not include an accounting of changes in carbon stocks in yards.

Table 6-13: Collection and Destination of Yard Trimmings (Million Metric Tons, or Tg, wet weight)

Destination	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Municipal Composting Facilities	3.8	4.4	4.9	6.3	7.3	8.2	9.4	10.4	11.4	12.9	14.3	16.6
Discarded	27.9	27.4	26.9	23.9	21.3	18.8	15.9	14.7	13.8	12.3	10.9	8.6
Landfill	22.8	22.2	21.7	19.2	17.1	14.5	12.1	11.3	10.8	9.8	8.6	6.6
Incineration	5.2	5.2	5.2	4.7	4.2	4.3	3.8	3.4	2.9	2.5	2.3	1.9
Total	**31.8**	**31.8**	**31.8**	**30.2**	**28.6**	**26.9**	**25.3**	**25.2**	**25.2**	**25.2**	**25.2**	**25.2**

Note: Shaded area indicates values based on projections.

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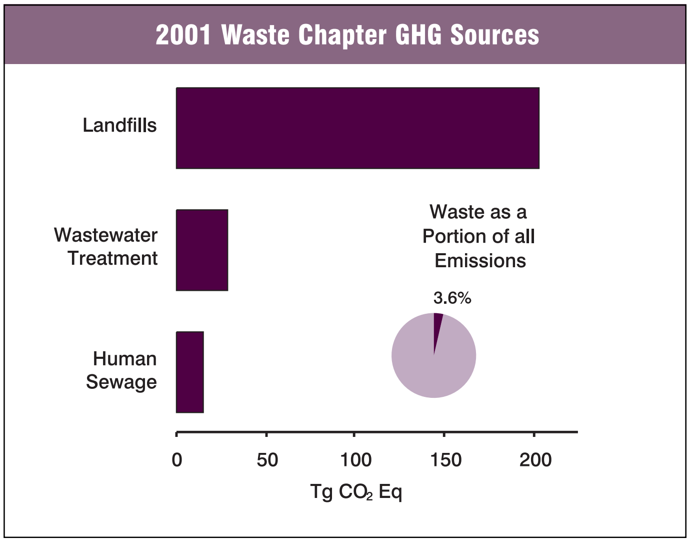
[13] These percents represent the percent of total municipal solid waste (MSW) discards after recovery for recycling or composting.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills were the largest source of anthropogenic methane (CH_4) emissions, accounting for 33 percent of the U.S. total.[1] Smaller amounts of CH_4 are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of nitrous oxide (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 waste activities, 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.

Figure 7-1



Overall, in 2001, waste activities generated emissions of 246.6 Tg CO_2 Eq., or 3.6 percent of total U.S. greenhouse gas emissions.

Landfills

Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2001, landfill CH_4 emissions were approximately 202.9 Tg CO_2 Eq. (9,663 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 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Over 2,100 operational landfills exist in the United States (BioCycle 2001), with the largest landfills receiving most of the waste and generating the majority of the CH_4.

After being placed in a landfill, biogenic waste (such as paper, food scraps, and yard trimmings) is initially digested by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which can 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

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[1] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land-Use Change and Forestry chapter.

Table 7-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**236.2**	**242.7**	**238.9**	**234.8**	**230.1**	**231.9**	**234.1**	**231.3**
Landfills	212.1	216.1	212.1	207.5	202.4	203.7	205.8	202.9
Wastewater Treatment	24.1	26.6	26.8	27.3	27.7	28.2	28.3	28.3
N_2O	**12.7**	**13.9**	**14.1**	**14.4**	**14.6**	**15.1**	**15.1**	**15.3**
Human Sewage	12.7	13.9	14.1	14.4	14.6	15.1	15.1	15.3
Total	**248.9**	**256.6**	**253.1**	**249.2**	**244.7**	**247.0**	**249.2**	**246.6**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**11,245**	**11,557**	**11,378**	**11,182**	**10,957**	**11,042**	**11,146**	**11,013**
Landfills	10,099	10,290	10,100	9,880	9,639	9,701	9,798	9,663
Wastewater Treatment	1,147	1,267	1,278	1,301	1,318	1,341	1,348	1,350
N_2O	**41**	**45**	**46**	**46**	**47**	**49**	**49**	**49**
Human Sewage	41	45	46	46	47	49	49	49

Note: Totals may not sum due to independent rounding.

stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent CH_4, by volume.[2] Significant CH_4 production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

From 1990 to 2001, net CH_4 emissions from landfills decreased by approximately 4 percent (see Table 7-3 and Table 7-4), with small increases occurring in some interim years. This slightly downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted by landfill operators, which has more than offset the additional CH_4 emissions resulting from increases in the amount of MSW landfilled.

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) the characteristics of landfills receiving waste (i.e., composition of waste-in-place; size, climate); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of methane oxidized in landfills instead of being released into the atmosphere. The estimated total quantity of waste-in-place contributing to emissions increased from about 4,926 Tg in 1990 to 6,280 Tg in 2001, an increase of 28 percent (see Annex Q`). During this period, the estimated CH_4 recovered and flared from landfills increased as well. In 1990, for example, approximately 1,190 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills. In 2001, the estimated quantity of CH_4 recovered and combusted increased to 5,263 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 CH_4 that is recovered and either flared or used for energy purposes is expected to increase, as a result of a 1996 regulation that requires large MSW landfills to collect and combust landfill gas (see 40 CFR Part 60, Subparts Cc 2002), and an EPA program that encourages voluntary CH_4 recovery and use at landfills not affected by the regulation.

Methodology

Methane emissions from landfills were estimated to equal the CH_4 produced from municipal landfills, minus the CH_4 recovered and combusted, plus the CH_4 produced by industrial landfills, minus the CH_4 oxidized before being released into the atmosphere.

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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). Additionally, less than 1 percent of landfill gas is composed of non-methane volatile organic compounds (NMVOCs).

Box 7-1: Biogenic Emissions and Sinks of Carbon

For many countries, CO_2 emissions from the combustion or degradation of biogenic materials are 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 paper). The carbon contained in paper was originally stored in trees during photosynthesis. Under natural conditions, this material 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.

Carbon dioxide emissions from biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis 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. However, CH_4 emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills, and are consequently included in this Inventory.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin 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 153 Tg CO_2 Eq. and 5 to 18 Tg CO_2 Eq. per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in the Land-Use Change and Forestry chapter, as recommended in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) regarding the tracking of carbon flows.

Table 7-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
MSW Landfills	243.6	278.0	283.9	289.8	295.0	302.1	307.8	314.0
Industrial Landfills	17.1	19.5	19.9	20.3	20.6	21.1	21.5	22.0
Recovered								
Gas-to-Energy	(15.4)	(22.3)	(25.6)	(30.5)	(36.8)	(42.0)	(45.9)	(50.3)
Flared	(9.6)	(35.0)	(42.5)	(49.1)	(53.9)	(54.8)	(54.8)	(60.2)
Oxidized[1]	(23.6)	(24.0)	(24.2)	(24.2)	(24.1)	(23.7)	(23.2)	(22.6)
Total	**212.1**	**216.1**	**212.1**	**207.5**	**202.4**	**203.7**	**205.8**	**202.9**

Note: Totals may not sum due to independent rounding.

[1] Includes oxidation at both municipal and industrial landfills.

Table 7-4: CH_4 Emissions from Landfills (Gg)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
MSW Landfills	11,559	13,238	13,520	13,802	14,047	14,385	14,659	14,954
Industrial Landfills	812	927	946	966	983	1,007	1,026	1,047
Recovered								
Gas-to-Energy	(732)	(1,064)	(1,220)	(1,452)	(1,752)	(2,002)	(2,187)	(2,396)
Flared	(458)	(1,668)	(2,024)	(2,338)	(2,568)	(2,611)	(2,611)	(2,867)
Oxidized[1]	(1,122)	(1,143)	(1,154)	(1,155)	(1,149)	(1,128)	(1,104)	(1,077)
Total	**10,099**	**10,290**	**10,100**	**9,880**	**9,639**	**9,701**	**9,798**	**9,663**

Note: Totals may not sum due to independent rounding.

[1] Includes oxidation at municipal and 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, as evidenced in an extensive landfill survey by the EPA's Office of Solid Waste in 1986. 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 CH_4 generation was estimated using its year of opening, its waste acceptance rate, year of closure, and design capacity. Data on national municipal waste landfilled each year was apportioned by landfill. Emissions from municipal landfills were then estimated by multiplying the quantity of waste contributing to emissions by emission factors (EPA 1993). For further information see Annex Q.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment and a database of landfill gas-to-energy (LFGTE) projects compiled by EPA's Landfill Methane Outreach Program (LMOP). Based on the information provided by vendors, the CH_4 combusted by 642 flares in operation from 1990 to 2001 was estimated. This quantity likely underestimates flaring, because EPA does not have information on all flares in operation. Additionally, the LFGTE database provided data on landfill gas flow and energy generation for 334 operational LFGTE projects. If both flare data and LFGTE recovery data for a particular landfill were available, then the emissions recovery was based on the LFGTE data, which provides actual landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given flare size. Given that each LFGTE project was likely to also have had a flare, double counting reductions from flares and LFGTE projects was avoided by subtracting emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.[3]

Emissions from industrial landfills were assumed to be equal to seven percent of the total CH_4 emissions from municipal landfills (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (Liptay et al. 1998). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 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 generation and disposal data for 1991 through 2001 were obtained from *BioCycle* (2001). Because *BioCycle* does not account for waste generated in U.S. territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2000) and per capita MSW generation from EPA's *Municipal Solid Waste Disposal in the United States* report (2002a). Documentation on the landfill CH_4 emissions methodology employed is available in EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993). Information on flares was obtained from vendors (ICF 2002), and information on landfill gas-to-energy projects was obtained from the EPA's Landfill Methane Outreach Program database (EPA 2002a).

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is not available for waste in place for every landfill - a fundamental factor that affects CH_4 production. The heterogeneity of waste disposed in landfills is uncertain as well. The approach used here assumes that the landfill set is representative of waste composition and reflects this heterogeneity. Also, the approach used to estimate the contribution of industrial non-hazardous wastes to total CH_4 generation employs introduces uncertainty. Aside from uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of oxidation efficiency. Overall, uncertainty in the landfill CH_4 emission rate is estimated to be roughly ±30 percent.

The N_2O emissions from application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from

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[3] Due to the differences in referencing landfills and incomplete data on the national population of flares, matching flare vendor data with the LFGTE data was problematic and a flare could not be identified for each of the LFGTE projects. Because each LFGTE project likely has a flare, the aggregate estimate of emission reductions through flaring was reduced by the LFGTE projects for which a specific flare could not be identified. This approach eliminated the potential for double counting emissions reductions at landfills with both flares and a LFGTE project.

sewage sludge applied to landfills would be relatively small because the microbial environment in landfills is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. The total nitrogen (N) in sewage sludge increased from 178 to 234 Gg total N between 1990 and 2001. The quantity of sewage sludge applied to landfills decreased from 28 to 11 percent from 1990 to 2001.

Wastewater Treatment

Wastewater from domestic sources (municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur off-site or on-site. For example, in the United States, approximately 25 percent of domestic wastewater is treated in septic systems or other on-site systems. Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. Untreated wastewater may also produce CH_4 if contained under anaerobic conditions.

The organic content, expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD), determines the CH_4 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. COD refers to the amount of oxygen consumed under specified conditions in the oxidation of the organic and oxidizable inorganic matter and is a parameter typically used to characterize industrial wastewater. Under anaerobic conditions and with all other parameters, such as temperature, being the same, wastewater with higher organic content will produce more CH_4 than wastewater with lower BOD or COD.

In 2001, CH_4 emissions from domestic wastewater treatment were 13.9 Tg CO_2 Eq. (660 Gg). Emissions have increased since 1990 in response to the increase in the U.S. human population. Industrial emission sources include wastewater from the following industries: pulp and paper; meat and poultry processing; and vegetables, fruits and juices processing.[4] In 2001, CH_4 emissions from industrial wastewater treatment were 14.5 Tg CO_2 Eq. (690 Gg). Table 7-5 and Table 7-6 provide emission estimates from domestic and industrial wastewater treatment.

Table 7-5: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Domestic	12.1	12.9	13.0	13.2	13.4	13.5	13.7	13.9
Industrial*	12.0	13.7	13.8	14.2	14.3	14.6	14.6	14.5
Total	**24.1**	**26.6**	**26.8**	**27.3**	**27.7**	**28.2**	**28.3**	**28.3**

* Industrial activity includes the following industries: pulp and paper; meat and poultry; and vegetables, fruits and juices processing.
Note: Totals may not sum due to independent rounding.

Table 7-6: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Domestic	576	613	620	627	637	644	651	660
Industrial*	571	653	658	674	681	697	697	690
Total	**1,147**	**1,267**	**1,278**	**1,301**	**1,318**	**1,341**	**1,348**	**1,350**

* Industrial activity includes the following industries: pulp and paper; meat and poultry; and vegetables, fruits and juices processing.
Note: Totals may not sum due to independent rounding.

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[4] Industrial wastewater emissions from petroleum systems are included in the petroleum systems section in the Energy chapter.

Methodology

Domestic wastewater CH_4 emissions were estimated using the default IPCC methodology (IPCC 2000). 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 0.065 kilograms of wastewater BOD_5[5] was produced per day per capita and that 16.25 percent of wastewater BOD_5 was anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.6 kg CH_4/kg BOD_5.

A top-down approach was used to develop estimates of CH_4 emissions from industrial wastewater according to the methodology described in the IPCC *Good Practice Guidance* (IPCC 2000). Industry categories were identified that are likely to have significant CH_4 emissions from their wastewater treatment. Industries were chosen that typically have both a high volume of wastewater generated and a high organic COD wastewater load. The top three industries that met these criteria were:

- Pulp and paper manufacturing
- Meat and poultry packing
- Vegetables, fruits and juices processing

Methane emissions from these categories were estimated by multiplying the annual product output (metric tons/year) by the average outflow (m^3/ton of output), the organics loading in the outflow (grams of organic COD/m^3), the emission factor (grams CH_4/grams COD), and the percentage of organic COD assumed to degrade anaerobically.

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow 1991). The most important step is lagooning for storage, settling, and biological treatment (secondary treatment). In developing estimates for this category, BOD was used instead of COD, because more accurate BOD numbers were available. In determining the percent that degraded anaerobically, both primary and secondary treatment were considered. Primary treatment lagoons are aerated to reduce anaerobic activity. However, the lagoons are large and zones of anaerobic activity may occur. Approximately 42 percent of the BOD passes on to secondary treatment, which are less likely to be aerated (EPA 1993). It was assumed that 25 percent of the BOD in secondary treatment lagoons degrades anaerobically, while 10 percent passes through to be discharged with the effluent (EPA 1997a). Overall, the percentage of wastewater organics that degrade anaerobically was determined to be 10.3 percent. The emission factor that was used is 0.6 kg CH_4/kg BOD, which is the default emission factor from IPCC (2000).

The meat and poultry processing industry makes extensive use of anaerobic lagoons, and it was estimated that 77 percent of all wastewater organics from this industry degrades anaerobically (EPA 1997b).

Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to the sewer. Therefore, it was assumed that this industry is likely to use lagoons intended for aerobic operation, but that the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used. Consequently, it was estimated that 5 percent of these wastewater organics degrade anaerobically.

Data Sources

National population data for 1990 to 2001 used in the domestic wastewater emissions estimates, were based on data from the U.S. Census Bureau (2001). Per-capita production of BOD_5 for domestic wastewater was obtained from the EPA (1997b). The emission factor (0.6 kg CH_4/kg BOD_5) employed for domestic wastewater treatment was taken from IPCC (2000). The same emission factor was used for pulp and paper wastewater, whereas the emission factor for meat and poultry, and vegetables, fruits and juices category is 0.25 kg CH_4/kg COD (IPCC 2000).

Table 7-7 provides U.S. population and wastewater BOD data.

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[5] The 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1991).

Table 7-7: U.S. Population (Millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD_5
1990	249	5,905
1991	252	5,983
1992	255	6,054
1993	257	6,102
1994	261	6,196
1995	265	6,291
1996	268	6,363
1997	271	6,434
1998	275	6,529
1999	278	6,600
2000	281	6,681
2001	285	6,766

For pulp and paper, a time series of CH_4 emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post Directory 1992 - 2002). The overall wastewater outflow was estimated to be 85 m^3/ton and the average BOD loading entering the secondary treatment lagoons was estimated to be 0.4 gram BOD/liter. Both values are based on information from multiple handbooks.

Production data for the meat and poultry industry were obtained from the U.S. Census (2001). EPA (1997b) provides wastewater outflows of 13 (out of a range of 8 to 18) m^3/ton and an average COD value of 4.1 (out of a range of 2 to 7) g/liter. These parameters are currently undergoing review, based on a recent comprehensive survey conducted by EPA's Office of Water (EPA, 2002).

The USDA National Agricultural Statistics Service (USDA 2001) provided production data for the fruits, vegetables, and juices processing sector. Outflow data for various subsectors (canned fruit, canned vegetables, frozen vegetables, fruit juices, jams, baby food) were obtained from World Bank (1999) and an average wastewater outflow of 5.6 m^3/ton was used. For the organics loading, a COD value of 5 (out of a range of 2 to 10) g/liter was used (EPA 1997b).

Table 7-8 provides U.S. pulp and paper; meat and poultry; and vegetables, fruits, and juices production data.

Table 7-8: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Million Metric Tons)

Year	Pulp and paper	Meat and Poultry	Vegetables Fruits and Juices
1990	128.9	28.2	29.7
1991	129.2	29.0	30.8
1992	134.5	30.0	32.9
1993	134.1	31.0	33.6
1994	139.3	32.0	36.7
1995	140.9	33.6	36.2
1996	140.3	34.2	35.9
1997	145.6	34.6	37.1
1998	144.0	35.7	35.9
1999	145.1	37.0	36.8
2000	142.8	37.4	38.3
2001	134.3	38.6	34.3

Uncertainty

Domestic wastewater emissions estimates are uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, especially incidental occurrences.

Large uncertainties are associated with the industrial wastewater emission estimates. Wastewater outflows and organics loading may vary greatly for different plants and different sub-sectors (e.g. paper vs. board, poultry vs. beef, baby food vs. juices, etc.). Also, the degree to which anaerobic degradation occurs in treatment systems is very difficult to assess. In addition, it is believed that pulp and paper, meat and poultry and vegetables, fruits and juices are the most significant industrial sources, but there may be additional sources that also produce wastewater organics that may degrade under anaerobic conditions (e.g., organic chemicals and plastics production).

Human Sewage (Domestic Wastewater)

Domestic human sewage is usually mixed with other household wastewater, which includes shower drains, sink drains, washing machine effluent, etc., and transported by a collection system to either a direct discharge, an on-site or decentralized wastewater treatment (WWT) system, or a centralized WWT system. Decentralized WWT systems are septic systems and package plants. Centralized WWT systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. Often, centralized WWT systems also treat certain flows of industrial, commercial, and institutional wastewater. After processing, treated effluent may be discharged to a receiving water environment (e.g., river, lake, estuary, etc.), applied to soils, or disposed of below the Earth's surface.

Nitrous oxide may be generated during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. These are converted to nitrate via nitrification, an aerobic process converting ammonia-nitrogen into nitrate (NO_3^-). Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide can be an intermediate product of both processes, but is more often associated with denitrification.

The U.S. quantifies two distinct sources for N_2O emissions from domestic wastewater: emissions from wastewater treatment (WWT) processes, and emissions from effluent that has been discharged into aquatic environments. The 2001 emissions of N_2O from WWT processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (0.9 Gg) and 15.0 Tg CO_2 Eq. (48.5 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 15.3 Tg CO_2 Eq. (49.3 Gg). (See Table 7-9).

Table 7-9: N_2O Emissions from Human Sewage

Year	Tg CO_2 Eq.	Gg
1990	12.7	41
1995	13.9	45
1996	14.1	46
1997	14.4	46
1998	14.6	47
1999	15.1	49
2000	15.1	49
2001	15.3	49

Methodology

Nitrous oxide emissions from human sewage effluent disposal were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) with three modifications (see below). The IPCC method assumes that nitrogen disposal—and thus N_2O emissions associated with land disposal, subsurface disposal, as well as domestic WWT—are negligible and that all nitrogen is discharged directly into aquatic environments.

- In the United States, some nitrogen is removed with the sewage sludge, which is land applied, incinerated or landfilled. The nitrogen disposal into aquatic environments is thus reduced to account for the sewage sludge application.
- Emissions from wastewater treatment plants (WWTPs) are not accounted for in the current IPCC methodology. A new overall emission factor of 4 g N_2O/person.year is used to estimate N_2O emissions from U.S. municipal WWTPs. This emission factor is based on a factor of 3.2 g N_2O/person-year (Czepiel, 1995) multiplied by 1.25 to adjust for co-discharged industrial nitrogen. The nitrogen quantity associated with these emissions is calculated by multiplying the N_2O emitted by $^{(2 \times 14)}/_{44}$.
- The IPCC method uses annual, per capita protein consumption (kg/year). This number is likely to underestimate the amount of protein entering the sewer or septic system. Food (waste) that is not consumed is often washed down the drain, as a result of the use of garbage disposals. Also, bath and laundry water can be expected to contribute to nitrogen loadings. Furthermore, industrial wastewater co-discharged with domestic wastewater is not accounted for in the existing methodology. A factor of 1.75 is applied to protein consumption to account for the extra nitrogen from these sources.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$$N_2O(s) = (US_{POP} \times 0.75 \times EF_1) + \{[(Protein \times 1.75 \times Frac_{NPR} \times US_{POP}) - N_{WWT} - N_{sludge}] \times EF_2 \times {}^{44}/_{28}\}$$

where,

$N_2O(s)$ = N_2O emissions from domestic wastewater (“human sewage”)

US_{POP} = U.S. population

0.75 = Fraction of population using WWTPs (as opposed to septic systems)

EF_1 = Emission factor (4 g N_2O/person.year)

Protein = Annual, per capita protein consumption

1.75 = Fraction of non-consumption protein in domestic wastewater

$Frac_{NPR}$ = Fraction of nitrogen in protein

N_{WWT} = Quantity of wastewater nitrogen removed by WWT processes $[(US_{POP} \times 0.75 \times EF_1) \times {}^{28}/_{44}]$

N_{sludge} = Quantity of sewage sludge N not entering aquatic environments

EF_2 = Emission factor (kg N_2O-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 (2001). The fraction of the US population using WWTPs is from the NEEDS Survey (1996). The emission factor (EF_1) used to estimate emissions from WWT is based on Czepiel, et al. (1995). Data on annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 2001) (See Table 7-10). Because data on protein intake were unavailable for 2001, the value of per capita protein consumption for the previous year was used. The fraction of non-consumption protein in domestic wastewater is based on expert judgment and on Metcalf & Eddy (1991) and Mullick (1987). An emission factor to estimate emissions from effluent (EF_2) 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. The fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 7-10: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year)

Year	Population	Protein
1990	250	39.2
1991	253	39.8
1992	257	40.0
1993	260	40.2
1994	263	41.2
1995	266	40.6
1996	269	40.7
1997	273	41.0
1998	276	41.1
1999	279	41.9
2000	282	41.6
2001	285	41.6

Uncertainty

The U.S. population, per capita protein intake data (Protein), and fraction of nitrogen in protein ($Frac_{NPR}$) are believed to be fairly accurate. Large uncertainty exists, however, in the emission factor for effluent (EF_2). This uncertainty is due to regional differences in the receiving waters that would likely affect N_2O emissions but are not accounted for in the default IPCC factor. Also, the emission factor for emissions from WWT (EF_1) is uncertain. When more plants incorporate nitrification/denitrification in the future, this emission factor is likely to increase. However, emissions from WWT are less significant than emissions from effluent-surface water. Taken together, these uncertainties present significant difficulties in estimating N_2O emissions from domestic wastewater.

Table 7-11: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
NO_x	**+**	**1**	**3**	**3**	**3**	**3**	**3**	**3**
Landfills	+	1	2	2	2	3	3	3
Wastewater Treatment	+	+	+	+	+	+	+	+
Miscellaneous[a]	+	1	1	1	1	+	+	+
CO	**1**	**2**	**5**	**5**	**5**	**14**	**14**	**14**
Landfills	1	2	5	5	5	13	13	13
Wastewater Treatment	+	+	+	+	+	1	1	1
Miscellaneous[a]	+	1	+	+	+	+	+	+
NMVOCs	**673**	**731**	**158**	**157**	**161**	**151**	**153**	**158**
Landfills	58	68	32	32	33	29	29	30
Wastewater Treatment	57	61	61	62	63	64	65	68
Miscellaneous[a]	558	602	65	64	65	58	59	60

[a] 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.
+ Does not exceed 0.5 Gg

Waste Sources of Ambient Air 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 NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2001 are provided in Table 7-11.

Methodology and Data Sources

These emission estimates were taken directly from EPA data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2003). 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.

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