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

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

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2000. To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC signatory countries, the estimates presented here were calculated using methodologies consistent with those recommended in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). For most source categories, the IPCC default methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

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

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

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

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

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 nonmethane 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, their atmospheric concentrations have been affected by human activities. Since pre-industrial time (i.e., about 1750), concentrations of these greenhouse gases have increased by 31, 150, and 16 percent, respectively (IPCC 2001). According to the IPCC, the current concentration of CO_2 and CH_4 in the atmosphere has not been exceeded in the last 420,000 years. Additionally, the rate of increase of CO_2 in the atmosphere in the past century has been unprecedented in the last 20,000 years. This build-up has altered the chemical composition of the earth's atmosphere, and therefore effected the global climate system.

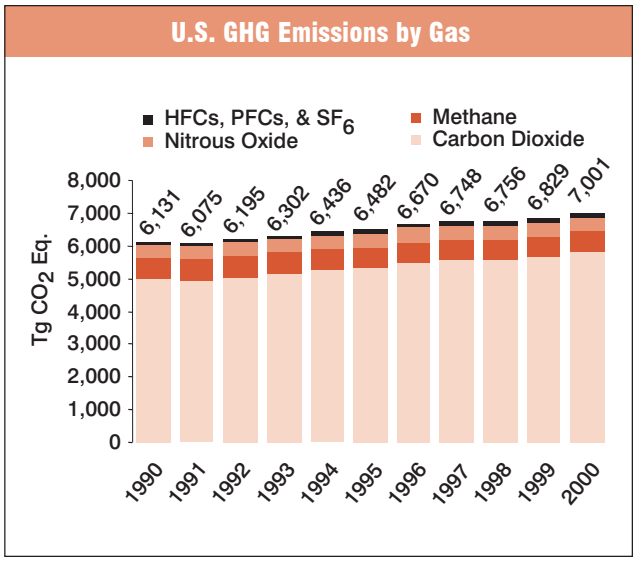
Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODSs) increased by nearly 10 percent per year until the mid-1980s, when international concern about ozone depletion led to the signing of the *Montreal Protocol*. Since then, the production of ODSs is being phased 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 2000, total U.S. greenhouse gas emissions rose to 7,001.2 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.)[5] (14.2 percent above 1990 emissions). The single year increase in emissions from 1999 to 2000 was 2.5 percent (171.7 Tg CO_2 Eq.), which was greater than the average annual rate of increase for 1990 through 2000 (1.3 percent). The higher than average increase in emissions in 2000 was, in part, attributable to the following factors: 1) robust economic growth in 2000, leading to increased demand for electricity and transportation fuels, 2) cooler winter conditions compared to the previous two years, and 3) decreased output from hydroelectric dams. (See 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 2000.

Figure ES-1



[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 the following section on Global Warming Potentials, in Executive Summary or 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
CO_2	**4,998.5**	**5,305.9**	**5,483.7**	**5,568.0**	**5,575.1**	**5,665.5**	**5,840.0**
Fossil Fuel Combustion	4,779.8	5,085.0	5,266.6	5,339.6	5,356.2	5,448.6	5,623.3
Iron and Steel Production	85.4	74.4	68.3	76.1	67.4	64.4	65.7
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.1
Indirect CO_2 from CH_4 Oxidation	30.9	29.5	28.9	28.4	28.2	27.0	26.3
Waste Combustion	14.1	18.6	19.6	21.3	20.3	21.8	22.5
Ammonia Manufacture	18.5	18.9	19.5	19.5	20.1	18.9	18.0
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3
Limestone and Dolomite Use	5.2	7.0	7.4	8.4	8.2	9.1	9.2
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	6.1
Aluminum Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2
Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	2.0
Ferroalloys	2.0	1.9	2.0	2.0	2.0	2.0	1.7
Carbon Dioxide Consumption	0.8	1.0	1.1	1.3	1.4	1.6	1.4
Land-Use Change and Forestry (Sink)[a]	(1,097.7)	(1,110.0)	(1,108.1)	(887.5)	(885.9)	(896.4)	(902.5)
International Bunker Fuels[b]	113.9	101.0	102.3	109.9	112.9	105.3	100.2
CH_4	**651.3**	**657.6**	**643.7**	**633.3**	**627.1**	**620.5**	**614.5**
Landfills	213.4	216.6	211.5	206.4	201.0	203.1	203.5
Enteric Fermentation	127.9	133.2	129.6	126.8	124.9	124.5	123.9
Natural Gas Systems	121.2	125.7	126.6	122.7	122.2	118.6	116.4
Coal Mining	87.1	73.5	68.4	68.1	67.9	63.7	61.0
Manure Management	29.2	34.8	34.2	35.8	38.0	37.6	37.5
Wastewater Treatment	24.3	26.8	27.0	27.5	27.8	28.3	28.7
Petroleum Systems	26.4	24.2	24.0	24.0	23.4	22.3	21.9
Stationary Sources	7.9	8.2	8.4	7.5	7.0	7.3	7.5
Rice Cultivation	7.1	7.6	7.0	7.5	7.9	8.3	7.5
Mobile Sources	4.9	4.8	4.7	4.6	4.5	4.4	4.4
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7	1.7
Agricultural Residue Burning	0.7	0.7	0.7	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
N_2O	**387.3**	**419.8**	**430.5**	**429.8**	**426.3**	**423.5**	**425.3**
Agricultural Soil Management	267.1	283.4	292.6	297.5	298.4	296.3	297.6
Mobile Sources	50.9	60.4	60.1	59.7	59.1	58.7	58.3
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.1	19.8
Manure Management	16.0	16.4	16.8	17.1	17.1	17.1	17.5
Stationary Sources	12.8	13.5	14.1	14.2	14.3	14.6	14.9
Human Sewage	7.0	7.7	7.8	7.9	8.1	8.4	8.5
Adipic Acid	14.9	17.9	17.8	11.5	7.7	7.7	8.1
Agricultural Residue Burning	0.4	0.4	0.4	0.4	0.5	0.4	0.5
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2	0.2
International Bunker Fuels[b]	1.0	0.9	0.9	1.0	1.0	0.9	0.9
HFCs, PFCs, and SF_6	**93.6**	**98.5**	**111.9**	**116.9**	**127.7**	**120.0**	**121.3**
Substitution of Ozone Depleting Substances	0.9	21.8	30.6	38.0	44.9	51.3	57.8
HCFC-22 Production	35.0	27.0	31.1	30.0	40.2	30.4	29.8
Electrical Transmission and Distribution	31.2	26.5	26.8	24.5	20.1	15.5	14.4
Aluminum Production	18.1	11.8	12.5	11.0	9.0	8.9	7.9
Semiconductor Manufacture	2.9	5.9	5.4	6.5	7.3	7.7	7.4
Magnesium Production and Processing	5.5	5.5	5.5	6.9	6.2	6.1	4.0
Total	**6,130.7**	**6,481.8**	**6,669.8**	**6,748.1**	**6,756.2**	**6,829.5**	**7,001.2**
Net Emissions (Sources and Sinks)	**5,033.0**	**5,371.8**	**5,561.7**	**5,860.5**	**5,870.3**	**5,933.1**	**6,098.7**

+ 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.

Figure ES-2

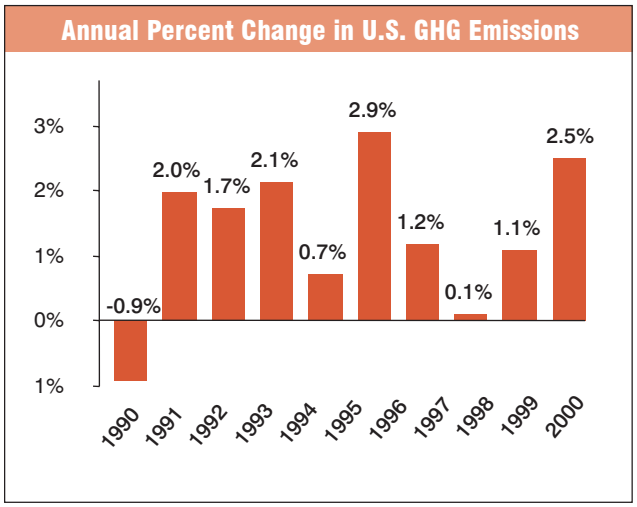


Figure ES-4

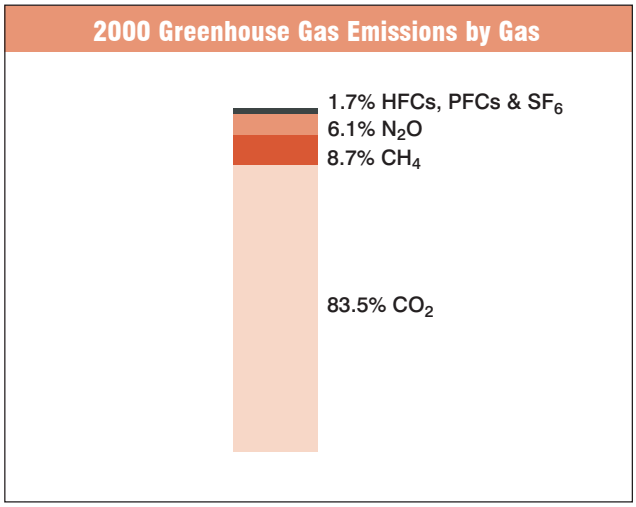


Figure ES-3

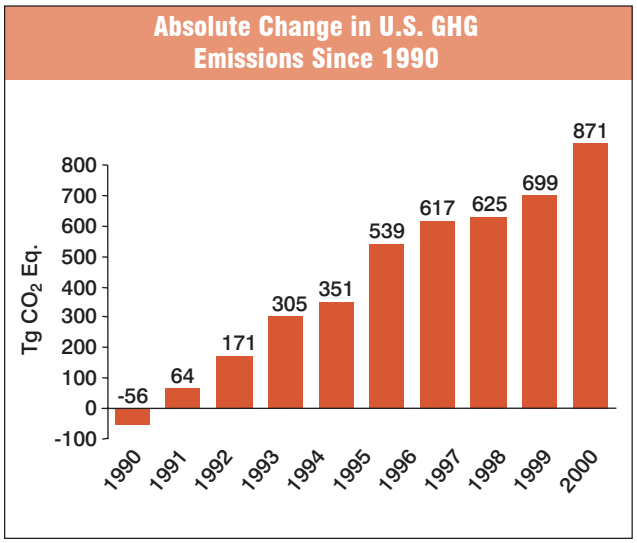


Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2000. The primary greenhouse gas emitted by human activities in the United States was CO_2. The largest source of CO_2, and of overall greenhouse gas emissions, was fossil fuel combustion. Methane emissions resulted primarily from decomposition of wastes in landfills, enteric fermentation associated with domestic livestock, and natural gas systems. Emissions of N_2O were dominated by agricultural soil management and mobile source fossil fuel combustion. 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 were 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 79 percent of global warming potential (GWP) weighted emissions from 1990 to 2000.[6] Emissions from this source category grew by 18 percent (843.4 Tg CO_2 Eq.) from 1990 to 2000 and were responsible for most of the increase in national emissions during this period. The annual increase in CO_2 emissions from fossil fuel combustion was 3.2 percent in 2000, double the source's average annual rate of 1.6 percent from 1990 through 2000. 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 and other countries generally fluctuates in response to changes in economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, 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 would be expected to have proportionally greater fossil fuel

[6] If a full accounting of emissions from fossil fuel combustion is made by including emissions from the combustion of international bunker fuels and CH_4 and N_2O emissions associated with fuel combustion, then this percentage increases to a nearly constant 80 percent during the 1990s.

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 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 are also a function of the type fuel or energy consumed and its carbon intensity. Producing heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 emissions associated with energy consumption because of the lower carbon content of natural gas per unit of useful energy produced. Table ES-2 shows annual changes in emissions during the last few years of the 1990s for selected fuel types and sectors.

Carbon dioxide emissions from fossil fuel combustion grew rapidly in 1996, due primarily to two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as colder winter conditions and the associated rise in demand for natural gas from residential and commercial customers for heating caused gas prices to rise sharply; and 2) higher consumption of petroleum fuels for transportation. Milder weather conditions in summer and winter moderated the growth in emissions in 1997; however, the shut-down of several nuclear power plants lead electric utilities to increase their consumption of coal and other fuels to offset the lost nuclear capacity.

In 1998, weather conditions were again a dominant factor in slowing the growth in emissions. Warm winter temperatures resulted in 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.[7] 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 to record levels, 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

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	1995 to 1996		1996 to 1997		1997 to 1998		1998 to 1999		1999 to 2000	
Electricity Generation	Coal	91.2	5.5%	49.9	2.9%	28.0	1.6%	11.1	0.6%	87.3	4.8%
Electricity Generation	Natural Gas	(24.3)	-8.8%	17.9	7.1%	32.4	12.0%	7.5	2.5%	31.5	10.2%
Electricity Generation	Petroleum	5.0	7.8%	8.9	12.9%	28.1	35.8%	1.2	1.2%	(12.5)	-11.6%
Transportation[a]	Petroleum	38.7	2.5%	7.6	0.5%	32.7	2.1%	68.0	4.2%	59.6	3.5%
Residential	Natural Gas	21.4	8.1%	(14.0)	-4.9%	(24.0)	-8.9%	10.0	4.0%	11.8	4.6%
Commercial	Natural Gas	7.0	4.3%	3.1	1.8%	(11.1)	-6.4%	1.7	1.0%	15.6	9.4%
Industrial	Coal	(5.7)	-4.4%	1.4	1.1%	(5.6)	-4.4%	(4.4)	-3.6%	(14.1)	-12.1%
Industrial	Natural Gas	16.3	4.1%	(5.2)	-1.3%	(31.6)	-7.7%	(5.0)	-1.3%	(1.6)	-0.4%
All Sectors[b]	**All Fuels[b]**	**181.6**	**3.6%**	**72.9**	**1.4%**	**16.6**	**0.3%**	**92.4**	**1.7%**	**174.7**	**3.2%**

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

[7] Normal is calculated as the average of the years 1961 through 1990.

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 sum, emissions from fossil fuel combustion exhibited the second highest annual increase since 1990.

Overall, from 1990 to 2000, total emissions of CO_2 and N_2O increased by 841.5 (17 percent) and 38.0 Tg CO_2 Eq. (10 percent), respectively, while CH_4 emissions decreased by 36.8 Tg CO_2 Eq. (6 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 27.7 Tg CO_2 Eq. (30 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 and in landfilled carbon, which were estimated to be 13 percent of total emissions in 2000.

Other significant trends in emissions from additional source categories over the eleven year period from 1990 through 2000 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 56.8 Tg CO_2 Eq. This increase was significantly offset, however, by reductions in PFC emissions from aluminum production (10.2 Tg CO_2 Eq. or 56 percent), reductions in emissions of HFC-23 from the production of HCFC-22 (5.2 Tg CO_2 Eq. or 15 percent), and reductions of SF_6 from electric power transmission and distribution systems (16.8 Tg CO_2 Eq. or 54 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 due to a reduction in the intensity of emissions from that source, despite 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 26.2 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 from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 30.5 Tg CO_2 Eq. (11 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.
- By 1998, all of the three major adipic acid producing plants had implemented N_2O abatement technology, and as a result, emissions fell by 6.8 Tg CO_2 Eq. (46 percent). The majority of this decline occurred from 1997 to 1998, despite increased production.
- Carbon dioxide emissions from feedstock uses of coal coke for iron and steel production decreased by 19.7 Tg CO_2 Eq. (23 percent), as imports of steel have increased.
- Methane emissions from U.S. landfills decreased 5 percent, as the amount of landfill gas collected and combusted by landfill operators has increased.
- Emissions of N_2O from mobile combustion rose by 7.4 Tg CO_2 Eq. (14 percent), primarily due to an increased average N_2O generation rate for the U.S. highway vehicle fleet.

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

There are several ways to assess a nation's greenhouse gas emitting intensity. The basis for measures of intensity can be 1) per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; 2) per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; 3) per unit of electricity consumption, because the electric power industry has been the largest source of U.S. greenhouse gas emissions in the United States; 4) per unit of total gross domestic product as a measure of national economic activity; or 5) on a per capita basis. Depending upon the measure used, the United States could appear to have reduced or increased its national greenhouse gas intensity during the 1990s.

Table ES-3 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.3 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption—thereby indicating an improved or lower greenhouse gas emitting intensity—and much slower than that for either electricity consumption or overall gross domestic product. 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-5). Overall, global atmospheric CO_2 concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

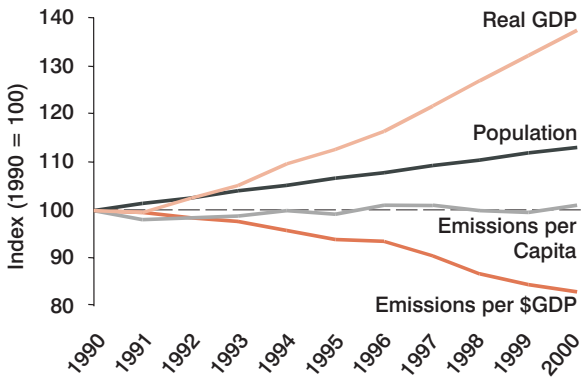
Table ES-3: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	Growth Rate[f]
GHG Emissions[a]	99	101	103	105	106	109	110	110	111	114	1.3%
Energy Consumption[b]	100	101	104	106	108	111	112	112	115	117	1.6%
Fossil Fuel Consumption[b]	99	101	103	106	107	110	112	112	114	116	1.5%
Electricity Consumption[b]	102	102	105	108	111	114	116	120	122	125	2.3%
GDP[c]	100	103	105	110	112	116	122	127	132	138	3.2%
Population[d]	101	103	104	105	107	108	109	110	112	113	1.2%
Global Atmospheric CO_2 Concentration[e]	100	101	101	101	102	102	103	104	104	104	0.4%

[a] GWP weighted values
[b] Energy content weighted values (EIA 2001)
[c] Gross Domestic Product in chained 1996 dollars (BEA 2000)
[d] (U.S. Census Bureau 2000)
[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 2000)
[f] Average annual growth rate

Figure ES-5

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



Source: BEA (2001), U.S. Census Bureau (2000), and emission estimates in this report.

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 methodological reasons, it is also useful to allocate emissions into sectoral categories that are more intuitive. This section reports emissions by the following economic sectors: Residential, Commercial, Industry, Transportation, Electricity Generation, and Agriculture, and U.S. Territories. Table ES-4 summarizes emissions from each of these sectors. Figure ES-6 shows the trend in emissions by sector from 1990 to 2000.

Using this categorization scheme, emissions from electricity generation accounted for the largest portion (34 percent) of U.S. greenhouse gas emissions. The 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 2000. 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 remaining 20 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, commercial, and U.S. territory economic sectors combined. Residences accounted for about 8 percent, and primarily consisted of carbon dioxide (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 nitrous oxide (N_2O) emissions from agricultural soils instead of CO_2 from fossil fuel combustion. The commercial sector accounted for about 5 percent of emissions, while U.S. territories accounted for less than 1 percent of total emissions.

Carbon dioxide was also emitted and sequestered by a variety of activities related to land-use change and forestry.

Figure ES-6

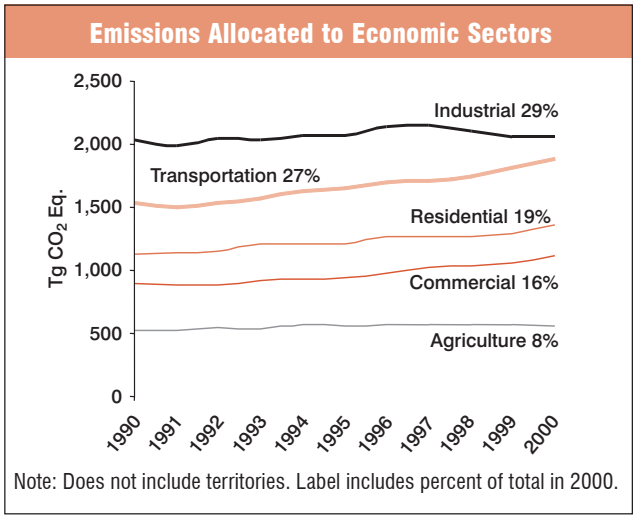


Table ES-4: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2000)

Sector	1990	1995	1996	1997	1998	1999	2000	Percent[a]
Electricity Generation	1,898.2	2,024.3	2,096.9	2,171.6	2,256.1	2,271.2	2,376.9	33.9%
Transportation	1,527.7	1,652.4	1,695.2	1,708.5	1,737.4	1,813.3	1,877.0	26.8%
Industry	1,393.9	1,400.9	1,447.6	1,442.7	1,385.9	1,341.1	1,314.6	18.8%
Agriculture	494.7	533.3	533.3	544.2	545.1	544.9	535.5	7.6%
Residential	484.6	522.7	549.0	531.1	494.3	516.0	531.6	7.6%
Commercial	303.5	313.0	320.8	320.9	302.9	307.1	327.6	4.7%
U.S. Territories	28.1	35.3	27.0	29.1	34.4	35.8	38.0	0.5%
Total	**6,130.7**	**6,481.8**	**6,669.8**	**6,748.1**	**6,756.2**	**6,829.5**	**7,001.2**	**100.0%**
Sinks	**(1,097.7)**	**(1,110.0)**	**(1,108.1)**	**(887.5)**	**(885.9)**	**(896.4)**	**(902.5)**	**--**
Net Emissions (Sources and Sinks)	**5,033.0**	**5,371.8**	**5,561.7**	**5,860.5**	**5,870.3**	**5,933.1**	**6,098.7**	**--**

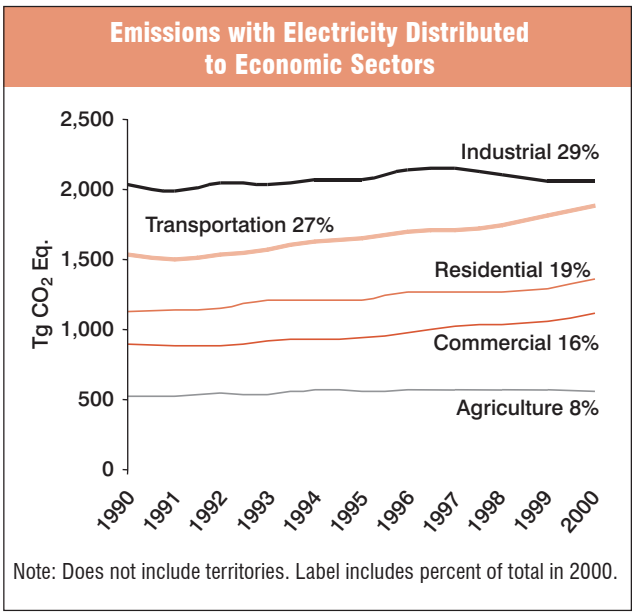
Note: Totals may not sum due to independent rounding. Includes all emissions of CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6.
See Table 1-11 for more detailed data.
[a] Percent of total in 2000.

Table ES-5 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 electric generation were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity.[8] 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.[9]

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (29 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. Figure ES-7 shows the trend in these emissions by sector from 1990 to 2000.

The following sections describe the concept of Global Warming Potentials (GWPs), present the anthropogenic sources and sinks of greenhouse gas emissions in the United States, briefly discuss emission pathways, further summarize the emission estimates, and explain the relative importance of emissions from each source category.

Figure ES-7



Note: Does not include territories. Label includes percent of total in 2000.

Global Warming Potentials

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations of the original gas produce 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).[10] The concept of a Global Warming Potential (GWP) has been developed to compare the ability of each

Table ES-5: 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
Industry	2,029.7	2,071.6	2,136.2	2,151.5	2,104.0	2,059.7	2,054.7
Transportation	1,530.5	1,655.1	1,697.9	1,711.2	1,740.2	1,816.0	1,879.7
Residential	1,131.2	1,213.1	1,270.1	1,265.6	1,266.3	1,293.5	1,357.4
Commercial	890.7	944.9	974.3	1,022.4	1,040.0	1,057.5	1,113.8
Agriculture	520.5	561.8	564.3	568.2	571.4	567.0	557.7
U.S. Territories	28.1	35.3	27.0	29.1	34.4	35.8	38.0
Total	**6,130.7**	**6,481.8**	**6,669.8**	**6,748.1**	**6,756.2**	**6,829.5**	**7,001.2**

Note: Totals may not sum due to independent rounding. Includes all emissions of CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6.
See Table 1-12 for more detailed data.

[8] Emissions were not distributed to U.S. territories, since they do not consume electricity produced by the electricity generation sector.

[9] 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.

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

Box ES-2: 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 global warming potentials (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 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 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 have been 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, which were not presented in the Second Assessment Report. Table ES-6 presents the new Global Warming Potentials, relative to those presented in the Second Assessment Report.

Table ES-6: Comparison of 100 Year GWPs

Gas	SAR	TAR	Change	
			Absolute	Percent
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 Inventory will continue to use the GWPs from the Second Assessment Report. The guidelines under which this Inventory is developed, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the UNFCCC reporting guidelines for national inventories[11] were 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 (see Annex Q).

greenhouse gas to trap heat in the atmosphere relative to another gas. Carbon dioxide (CO_2) was chosen as the reference gas to be consistent with IPCC guidelines.

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).

[11] See FCCC/CP/1999/7 at <www.unfccc.de>.

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. Indirect radiative forcing occurs when chemical transformations involving the original gas produces a gas or gases that are greenhouse gases, or when a gas influences 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.)[12] 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, the 100 year GWPs recommended by the IPCC and employed by the United States for policy making and reporting purposes were used in this report (IPCC 1996). GWP values are listed below in Table ES-7.

Table ES-7: Global Warming Potentials (100 Year Time Horizon)

Gas	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)*	21
Nitrous oxide (N_2O)	310
HFC-23	11,700
HFC-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 (sinks) and are emitted to the atmosphere annually through natural processes (sources). When in equilibrium, carbon fluxes among these various reservoirs are roughly balanced. Since the Industrial Revolution, this equilibrium of atmospheric carbon has been altered. Atmospheric concentrations of CO_2 have risen about 31 percent (IPCC 2001), principally because of fossil fuel combustion, which accounted for 96 percent of total U.S. CO_2 emissions in 2000. 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).[13] Changes in land use and forestry practices can also emit CO_2 (e.g., through conversion of forest land to agricultural or urban use) or can act as a sink for CO_2 (e.g., through net additions to forest biomass).

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

Energy

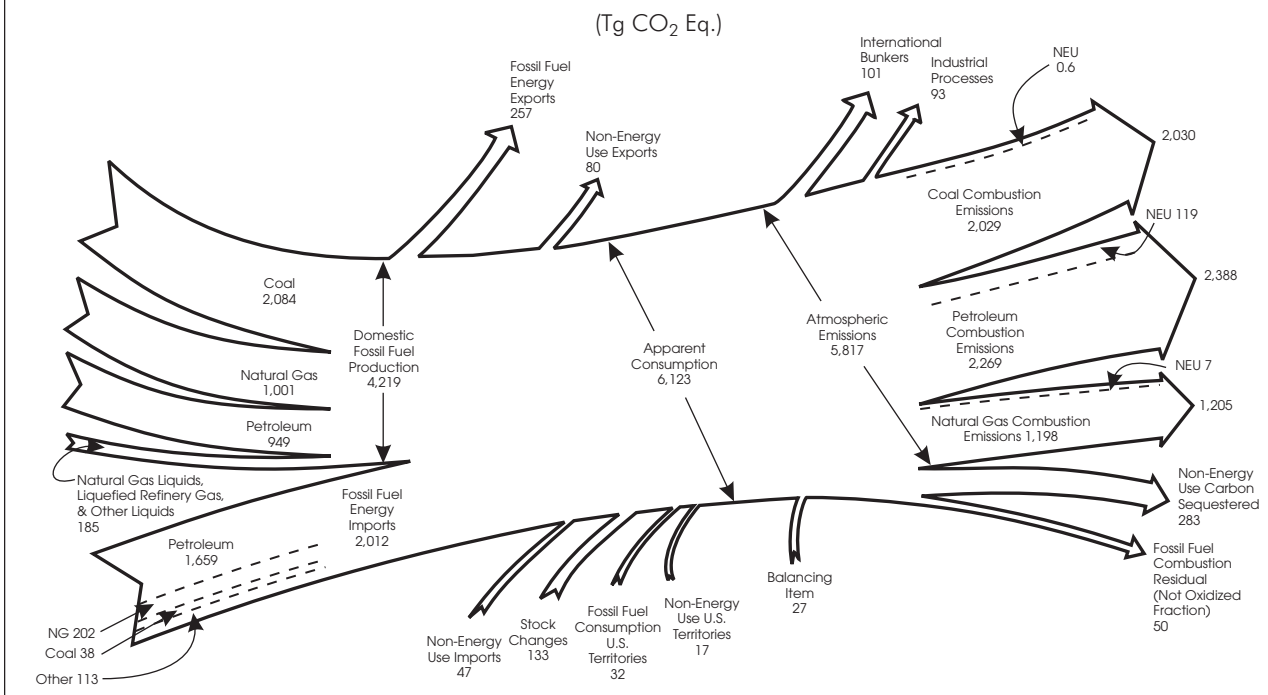
Energy-related activities accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2000. Carbon dioxide from fossil fuel combustion was the dominant contributor. In 2000, approximately 85 percent of the energy consumed in the United States was produced through the combustion of fossil fuels. The remaining 15 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar 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.

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

[13] Global CO_2 emissions from fossil fuel combustion were taken from Marland et al. (2001). <http://cdiac.esd.ornl.gov/trends/emis/meth_reg.htm>

Figure ES-8

U.S. Carbon Flows for 2000



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

2000 Sources of CO_2

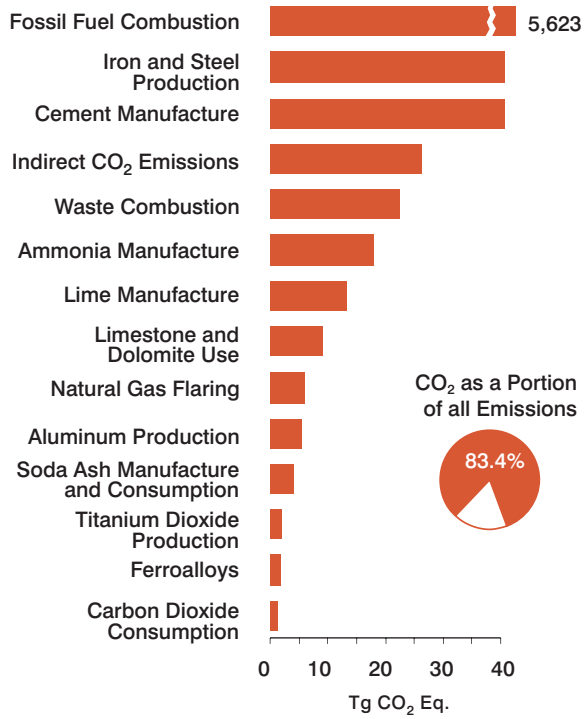
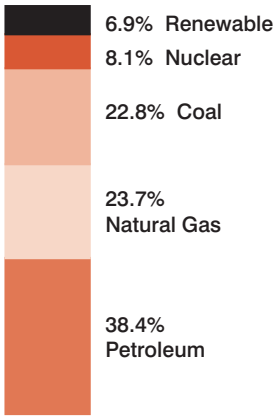


Figure ES-10

2000 U.S. Energy Consumption by Energy Source



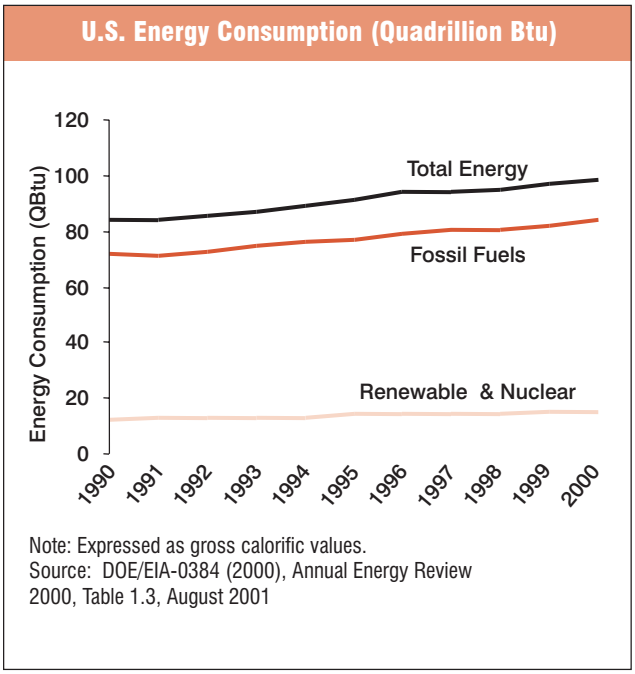
Source: DOE/EIA-0384(2000), Annual Energy Review 2000, Table 1.3, August 2001

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
Fossil Fuel Combustion	4,779.8	5,085.0	5,266.6	5,339.6	5,356.2	5,448.6	5,623.3
Electricity Generation	1,858.9	1,989.3	2,061.2	2,137.9	2,226.4	2,246.2	2,352.5
Transportation	1,471.8	1,579.4	1,618.7	1,628.8	1,655.0	1,728.2	1,789.5
Industrial	871.6	894.9	936.5	935.2	881.1	858.1	829.2
Residential	332.1	362.3	390.4	374.9	341.8	360.5	374.8
Commercial	217.3	223.9	232.8	233.7	217.5	219.8	239.3
U.S. Territories	28.1	35.3	27.0	29.1	34.4	35.8	38.0
Iron and Steel Production	85.4	74.4	68.3	76.1	67.4	64.4	65.7
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.1
Indirect CO_2 From CH_4 Oxidation	30.9	29.5	28.9	28.4	28.2	27.0	26.3
Waste Combustion	14.1	18.6	19.6	21.3	20.3	21.8	22.5
Ammonia Manufacture	18.5	18.9	19.5	19.5	20.1	18.9	18.0
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3
Limestone and Dolomite Use	5.2	7.0	7.4	8.4	8.2	9.1	9.2
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	6.1
Aluminum Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2
Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	2.0
Ferroalloys	2.0	1.9	2.0	2.0	2.0	2.0	1.7
Carbon Dioxide Consumption	0.8	1.0	1.1	1.3	1.4	1.6	1.4
Land-Use Change and Forestry (Sink)[a]	(1,097.7)	(1,110.0)	(1,108.1)	(887.5)	(885.9)	(896.4)	(902.5)
International Bunker Fuels[b]	113.9	101.0	102.3	109.9	112.9	105.3	100.2
Total	**4,998.5**	**5,305.9**	**5,483.7**	**5,568.0**	**5,575.1**	**5,665.5**	**5,840.0**
Net Emissions (Sources and Sinks)	**3,900.8**	**4,195.9**	**4,375.6**	**4,680.5**	**4,689.2**	**4,769.1**	**4,937.5**

[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-11



Note: Expressed as gross calorific values.
Source: DOE/EIA-0384 (2000), Annual Energy Review 2000, Table 1.3, August 2001

Fossil Fuel Combustion (5,623.3 Tg CO_2 Eq.)

As fossil fuels are combusted, the carbon stored in them is almost entirely emitted as CO_2. The amount of carbon in fuels per unit of energy content varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of energy, while petroleum has about 25 percent less carbon than coal, and natural gas about 45 percent less. From 1990 through 2000, 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 1.6 percent from 1990 to 2000. The fundamental factors behind this trend include (1) a robust domestic economy, (2) relatively low energy prices

as compared to 1990, (3) significant growth in emissions from transportation activities and electricity generation, and (4) heavier reliance on nuclear energy. Between 1990 and 2000, CO_2 emissions from fossil fuel combustion steadily increased from 4,779.8 Tg CO_2 Eq. to 5,623.3 Tg CO_2 Eq.—an 18 percent total increase over the eleven year period.

As introduced above, the four end-use sectors contributing to CO_2 emissions from fossil fuel combustion include 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 based upon the sector's share of aggregate electricity consumption. This method of distributing emissions assumes that each end-use sector consumes electricity that is generated with the national average mix of fuels according to their carbon intensity. In reality, sources of electricity vary widely in carbon intensity. By 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.

Figure ES-12

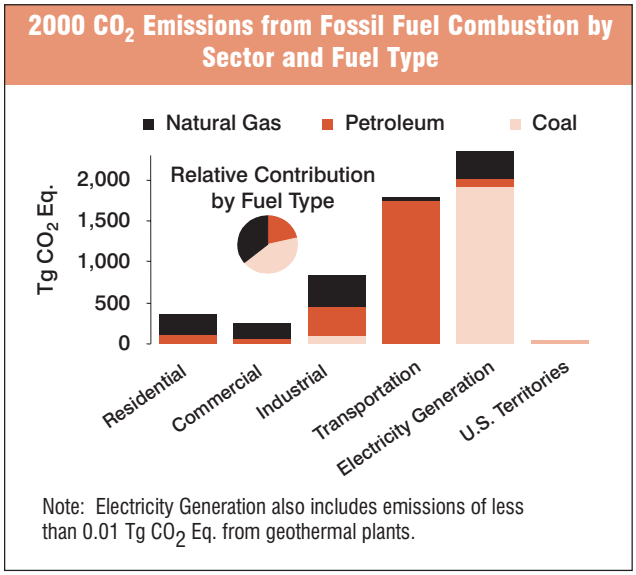
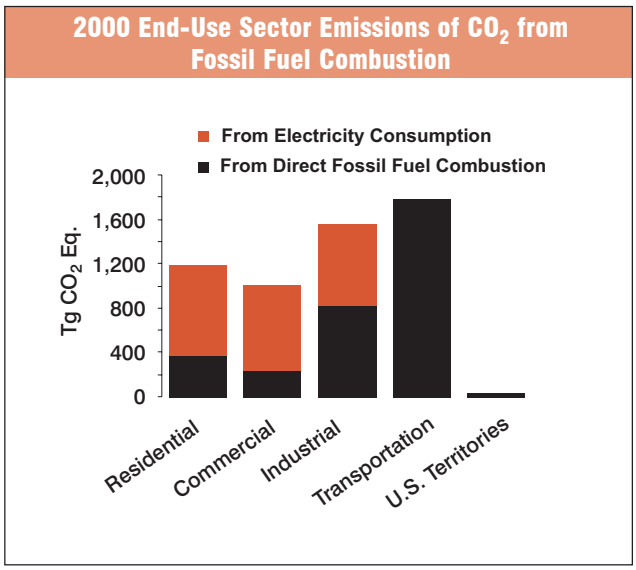


Figure ES-13



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.

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 28 percent of CO_2 from fossil fuel combustion in 2000. 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 2000.[14] 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 in motor vehicles. The remaining emissions came from other transportation activities, including the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircraft.

[14] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 34 percent of U.S. emissions from fossil fuel combustion in 2000.

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
Industrial	**1,519.6**	**1,563.4**	**1,623.5**	**1,640.8**	**1,598.1**	**1,575.7**	**1,568.5**
Combustion	871.6	894.9	936.5	935.2	881.1	858.1	829.2
Electricity	648.0	668.5	687.0	705.6	717.0	717.7	739.3
Transportation	**1,474.5**	**1,582.0**	**1,621.3**	**1,631.5**	**1,657.7**	**1,731.0**	**1,792.3**
Combustion	1,471.8	1,579.4	1,618.7	1,628.8	1,655.0	1,728.2	1,789.5
Electricity	2.7	2.6	2.7	2.7	2.7	2.7	2.8
Residential	**965.3**	**1,050.6**	**1,109.9**	**1,106.1**	**1,112.6**	**1,136.9**	**1,199.8**
Combustion	332.1	362.3	390.4	374.9	341.8	360.5	374.8
Electricity	633.2	688.2	719.5	731.2	770.8	776.5	825.0
Commercial	**792.3**	**853.8**	**884.8**	**932.0**	**953.4**	**969.2**	**1,024.7**
Combustion	217.3	223.9	232.8	233.7	217.5	219.8	239.3
Electricity	575.0	629.9	652.0	698.4	735.9	749.4	785.4
U.S. Territories	**28.1**	**35.3**	**27.0**	**29.1**	**34.4**	**35.8**	**38.0**
Total	**4,779.8**	**5,085.0**	**5,266.6**	**5,339.6**	**5,356.2**	**5,448.6**	**5,623.3**
Electricity Generation	**1,858.9**	**1,989.3**	**2,061.2**	**2,137.9**	**2,226.4**	**2,246.2**	**2,352.5**

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.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel consumption in 2000. Both sectors relied heavily on electricity for meeting energy needs, with 69 and 77 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were largely due to the consumption of natural gas and petroleum, primarily for meeting heating and cooking needs.

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 generation is responsible for consuming 34 percent of U.S. energy from fossil fuels and emitted 42 percent of the CO_2 from fossil fuel combustion in 2000. 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 94 percent of all coal consumed in the United States in 2000. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Indirect CO_2 from CH_4 Oxidation (26.3 Tg CO_2 Eq.)

Indirect CO_2 emissions are formed in the atmosphere from the oxidation of methane (CH_4). Although this indirect CO_2 is a greenhouse gas, its generation is not accounted for within the global warming potential (GWP) of CH_4. Thus for the sake of completion, it is necessary to account for these indirect emissions whenever anthropogenic sources of CH_4 are calculated. Non-biogenic and non-combustion emissions of CH_4 are considered in this calculation.

Waste Combustion (22.5 Tg CO_2 Eq.)

Waste combustion involves the burning of garbage and non-hazardous solids, referred to as municipal solid waste (MSW), as well as the burning of hazardous waste. Waste combustion, in the United States, is usually performed to recover energy from the waste materials. Carbon dioxide emissions arise from the organic (i.e., carbon) materials found in these 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. However, several components of MSW—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 (6.1 Tg CO_2 Eq.)

Carbon dioxide is produced when natural gas from oil wells is flared (i.e., combusted) to relieve rising pressure or to dispose of small quantities of gas that are not commercially marketable. In 2000, flaring activities emitted less than 0.1 percent of U.S. CO_2 emissions.

Biomass Combustion (184.4 Tg CO_2 Eq.)

Biomass in the form of fuel wood and wood waste was used primarily by the industrial end-use sector, while the transportation end-use sector was the predominant user of biomass-based fuels, such as ethanol from corn and woody crops.

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 under Land-Use Change and Forestry.

The industrial sector accounted for 74 percent of gross CO_2 emissions from biomass combustion, and the residential sector accounted for 19 percent. Ethanol consumption by the transportation sector accounted for only 5 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. This transformation often releases greenhouse 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. Carbon dioxide emissions from these sources were approximately 161.9 Tg CO_2 Eq. in 2000, accounting for about 3 percent of total CO_2 emissions.

Iron and Steel Production (65.7 Tg CO_2 Eq.)

The production of iron and steel generates process-related emissions of CO_2. 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—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 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 (41.1 Tg CO_2 Eq.)

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

Ammonia Manufacturing (18.0 Tg CO_2 Eq.)

Carbon dioxide emissions occur during the production of ammonia. In the United States, roughly 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas, and the remainder is produced using naphtha (i.e., a petroleum fraction) or the electrolysis of brine at chlorine plants (EPA 1997). The former two fossil fuel-based reactions produce carbon monoxide and hydrogen gas. This carbon monoxide is transformed into CO_2 in the presence of a catalyst—usually a metallic oxide—and generally released into the atmosphere.

Lime Manufacture (13.3 Tg CO_2 Eq.)

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

Limestone and Dolomite Use (9.2 Tg CO_2 Eq.)

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)$) are basic raw materials used by a wide variety of industries, including the 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 (5.4 Tg CO_2 Eq.)

Carbon dioxide is emitted during the aluminum smelting process 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 (4.2 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 (2.0 Tg CO_2 Eq.)

Titanium dioxide (TiO_2) is a metal oxide manufactured from titanium ore, and is principally used as a pigment. Titanium dioxide is used as an ingredient in white paint and 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.

Ferroalloy Production (1.7 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 are used to alter the material properties of the steel.

Carbon Dioxide Consumption (1.4 Tg CO_2 Eq.)

Carbon dioxide (CO_2) is used directly in many segments of the economy, including food processing, beverage manufacturing, chemical processing, and a host of industrial and other miscellaneous applications. 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 alter the natural carbon flux between biomass, soils, and the atmosphere. Forest management practices, the management of agricultural soils, management of trees in urban areas, and landfilling of yard trimmings have resulted in a net uptake (sequestration) of carbon in the United States that is equivalent to about 13 percent of total U.S. gross emissions. Forests (including vegetation, soils, and harvested wood) accounted for approximately 85 percent of the total sequestration, agricultural soils (including mineral and organic soils and the application of lime) accounted for over 7 percent, urban trees accounted for more than 6 percent, and landfilled yard trimmings accounted for less than 1 percent of the total sequestration. The net forest sequestration is largely a result of improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting. In agricultural soils, mineral soils account for a net carbon sink that is more than three times larger than the sum of emissions from organic soils and liming. Net sequestration in agricultural mineral soils is largely due to improved cropland and grazing land management practices, especially the adoption of conservation tillage practices and leaving residues on the field after harvest, and to taking erodable lands out of production and planting them with grass or trees through the Conservation Reserve Program. The landfilled yard trimmings net sequestration is due to the long-term accumulation of yard trimming carbon in landfills.

Methane Emissions

Atmospheric methane (CH_4) is an integral component of the greenhouse effect. Methane's overall contribution to global warming is significant because it has been estimated to be more than 20 times as effective at trapping heat in the atmosphere as CO_2. Over the last two hundred and fifty years, methane's concentration in the atmosphere has increased by 150 percent (IPCC 2001). Experts believe

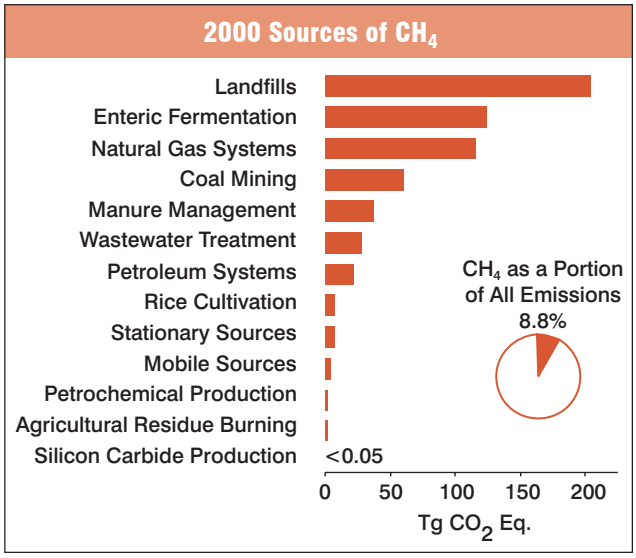
that over half of these atmospheric increases were due to emissions from anthropogenic sources, such as landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes (see Figure ES-14 and Table ES-10).

Landfills (203.5 Tg CO_2 Eq.)

Landfills are the largest source of anthropogenic CH_4 emissions in the United States. In an environment where the oxygen content is low or nonexistent, organic materials, such as yard waste, household waste, food waste, and paper, can be decomposed by bacteria, resulting in the generation of CH_4 and biogenic CO_2. Methane emissions from landfills are affected by site-specific factors such as waste composition, moisture, and landfill size.

Methane emissions from U.S. landfills have decreased by almost 5 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.

Figure ES-14



Natural Gas and Petroleum Systems (138.2 Tg CO_2 Eq.)

Methane is the major component of natural gas. During the production, processing, transmission, and distribution of natural gas, fugitive emissions of methane often occur. Because natural gas is often found in conjunction with petroleum deposits, leakage from petroleum systems is also a source of emissions. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment conditions. In 2000, CH_4 emissions from U.S. natural gas systems were accounted for approximately 19 percent of U.S. CH_4 emissions.

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

Source	1990	1995	1996	1997	1998	1999	2000
Landfills	213.4	216.6	211.5	206.4	201.0	203.1	203.5
Enteric Fermentation	127.9	133.2	129.6	126.8	124.9	124.5	123.9
Natural Gas Systems	121.2	125.7	126.6	122.7	122.2	118.6	116.4
Coal Mining	87.1	73.5	68.4	68.1	67.9	63.7	61.0
Manure Management	29.2	34.8	34.2	35.8	38.0	37.6	37.5
Wastewater Treatment	24.3	26.8	27.0	27.5	27.8	28.3	28.7
Petroleum Systems	26.4	24.2	24.0	24.0	23.4	22.3	21.9
Stationary Sources	7.9	8.2	8.4	7.5	7.0	7.3	7.5
Rice Cultivation	7.1	7.6	7.0	7.5	7.9	8.3	7.5
Mobile Sources	4.9	4.8	4.7	4.6	4.5	4.4	4.4
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7	1.7
Agricultural Residue Burning	0.7	0.7	0.7	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
Total*	**651.3**	**657.6**	**643.7**	**633.3**	**627.1**	**620.5**	**614.5**

+ 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 is found in the same geological structures as natural gas, and the two are often retrieved together. Methane is also saturated in crude oil, and volatilizes as the oil is exposed to the atmosphere at various points along the system. Methane emissions from the components of petroleum systems—including crude oil production, crude oil refining, transportation, and distribution—generally occur as a result of system leaks, disruptions, and routine maintenance. In 2000, emissions from petroleum systems were just under 4 percent of U.S. methane emissions.

Enteric Fermentation (123.9 Tg CO_2 Eq.)

During animal digestion, methane is produced through the process of enteric fermentation, in which microbes residing in animal digestive systems break down the feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest 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 2000, enteric fermentation was the source of about 20 percent of U.S. CH_4 emissions, and more than half of the CH_4 emissions from agriculture. From 1990 to 2000, 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.

Coal Mining (61.0 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 depth and type of the coal that is mined.

Methane from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed. Because 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 2000, coal mining activities emitted 10 percent of U.S. CH_4 emissions. From 1990 to 2000, 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.

Manure Management (37.5 Tg CO_2 Eq.)

The decomposition of organic animal waste in an anaerobic environment produces methane. 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 2000 and 22 percent of the methane emissions from agriculture. From 1990 to 2000, emissions from this source increased by 28 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.

Wastewater Treatment (28.7 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.

Stationary and Mobile Combustion (11.9 Tg CO_2 Eq.)

Stationary and mobile combustion were responsible for methane emissions of 7.5 and 4.4 Tg CO_2 Eq., respectively. The majority of 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.

Rice Cultivation (7.5 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 methane to the atmosphere, primarily through the rice plants. In 2000, rice cultivation was the source of 1 percent of U.S. methane emissions, and about 4 percent of U.S. CH_4 emissions from agriculture. Emission estimates from this source have increased about 5 percent since 1990 due to an increase in the area harvested.

Petrochemical and Silicon Carbide Production (1.7 Tg CO_2 Eq.)

Methane emissions resulted from two industrial sources, petrochemical and silicon carbide production. Small amounts of CH_4 were released during the production of five petrochemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol. These production processes resulted in emissions of 1.7 Tg CO_2 Eq. in 2000. Methane is also emitted from the production of silicon carbide, a material used as an industrial abrasive. In 2000, silicon carbide production resulted in emissions of less than 0.1 Tg CO_2 Eq.

Agricultural Residue Burning (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 1999.

Nitrous Oxide Emissions

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

Agricultural Soil Management (297.6 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

Figure ES-15

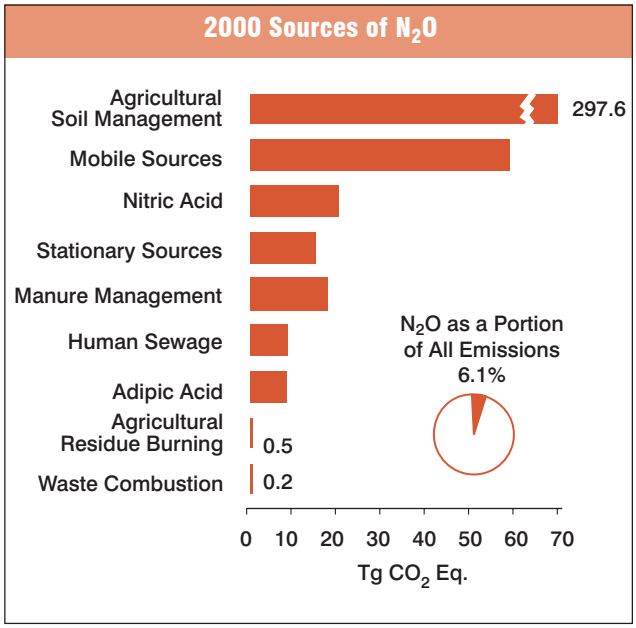


Table ES-11: U.S. Sources of Nitrous Oxide Emissions (Tg CO_2 Eq.)

Source	1990	1995	1996	1997	1998	1999	2000
Agricultural Soil Management	267.1	283.4	292.6	297.5	298.4	296.3	297.6
Mobile Sources	50.9	60.4	60.1	59.7	59.1	58.7	58.3
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.1	19.8
Manure Management	16.0	16.4	16.8	17.1	17.1	17.1	17.5
Stationary Sources	12.8	13.5	14.1	14.2	14.3	14.6	14.9
Human Sewage	7.0	7.7	7.8	7.9	8.1	8.4	8.5
Adipic Acid	14.9	17.9	17.8	11.5	7.7	7.7	8.1
Agricultural Residue Burning	0.4	0.4	0.4	0.4	0.5	0.4	0.5
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2	0.2
International Bunker Fuels*	1.0	0.9	0.9	1.0	1.0	0.9	0.9
Total*	**387.3**	**419.8**	**430.5**	**429.8**	**426.3**	**423.5**	**425.3**

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

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; 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 soils as fertilizer, livestock manure, and sewage sludge.

In 2000, agricultural soil management accounted for 70 percent of U.S. N_2O emissions. From 1990 to 2000, emissions from this source increased by 11 percent as fertilizer consumption, manure production, and crop production rose.

Stationary and Mobile Combustion (73.2 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, catalytic converters installed to reduce motor vehicle pollution can result in the formation of N_2O.

In 2000, N_2O emissions from mobile combustion were 14 percent of U.S. N_2O emissions, while stationary combustion accounted for 4 percent. From 1990 to 2000, combined N_2O emissions from stationary and mobile combustion increased by 15 percent, primarily due to increased rates of N_2O generation in highway vehicles.

Adipic Acid Production (8.1 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 2000, U.S. adipic acid plants emitted 2 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 46 percent since 1990.

Nitric Acid Production (19.8 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 2000, N_2O emissions from nitric acid production accounted for 5 percent of U.S. N_2O emissions. From 1990 to 2000, emissions from this source category increased by 11 percent as nitric acid production grew.

Manure Management (17.5 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 2000 accounted for 4 percent of U.S. N_2O emissions. From 1990 to 2000, emissions from this source category increased by 9 percent, as poultry and swine populations have increased.

Agricultural Residue Burning (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. Field burning is not a common method of agricultural residue disposal in the United States; therefore, emissions from this source are minor.

Human Sewage (8.5 Tg CO_2 Eq.)

Domestic human sewage is usually mixed with other household wastewater and transported by a collection system to either a direct discharge, an on-site or decentralized wastewater system, or a centralized wastewater 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 (N_2O) may be generated during both nitrification and denitrification of the nitrogen that is present in the sewage, usually in the form of urea and proteins. Emissions of N_2O from treated human sewage discharged into aquatic environments were estimated to be 8.5 Tg CO_2 Eq. in 2000.

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). However, some components—plastics, synthetic rubber, and synthetic fibers—are of fossil origin, which accounted for emissions of 0.2 Tg CO_2 Eq. in 2000.

HFC, PFC, and SF_6 Emissions

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

These compounds, however, along with sulfur hexafluoride (SF_6), are potent greenhouse gases. In addition to having high global warming potentials, SF_6 and 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 121.3 Tg CO_2 Eq. in 2000.

Figure ES-16

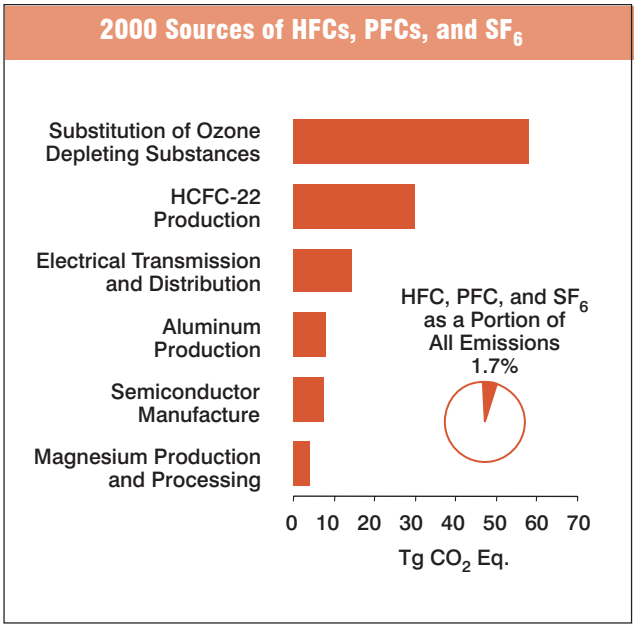


Table ES-12: Emissions of HFCs, PFCs, and SF_6 (Tg CO_2 Eq.)

Source	1990	1995	1996	1997	1998	1999	2000
Substitution of Ozone Depleting Substances	0.9	21.8	30.6	38.0	44.9	51.3	57.8
HCFC-22 Production	35.0	27.0	31.1	30.0	40.2	30.4	29.8
Electrical Transmission and Distribution	31.2	26.5	26.8	24.5	20.1	15.5	14.4
Aluminum Production	18.1	11.8	12.5	11.0	9.0	8.9	7.9
Semiconductor Manufacture	2.9	5.9	5.4	6.5	7.3	7.7	7.4
Magnesium Production and Processing	5.5	5.5	5.5	6.9	6.2	6.1	4.0
Total	**93.6**	**98.5**	**111.9**	**116.9**	**127.7**	**120.0**	**121.3**

Note: Totals may not sum due to independent rounding.

Substitution of Ozone Depleting Substances (57.8 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 48 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. In the short term, this trend is expected to continue, and will likely accelerate in the next decade as hydrochlorofluorcarbons (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 (7.9 Tg CO_2 Eq.)

During the production of primary aluminum, two PFCs—CF_4 and C_2F_6—are emitted as intermittent by-products of the smelting process. These PFCs are primarily formed when fluorine from the croylite bath combines with carbon from the electrolyte anode. Emissions from aluminum production have decreased by 56 percent between 1990 and 2000 due to emission reduction efforts by the industry and falling domestic aluminum production.

HCFC-22 Production (29.8 Tg CO_2 Eq.)

HFC-23 is a by-product emitted during the production of HCFC-22. Emissions from this source have decreased by 15 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 significantly since 1990, although production has been increasing.

Semiconductor Manufacturing (7.4 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 2000. This later reduction is due to the implementation of PFC emission reduction methods, such as process optimization.

Electrical Transmission and Distribution Systems (14.4 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 54 percent since 1990, primarily due to higher SF_6 prices and industrial efforts to reduce emissions.

Magnesium Production (4.0 Tg CO_2 Eq.)

SF_6 is also used as a protective covergas for the casting of molten magnesium. Emissions from primary magnesium production and magnesium casting have decreased by 27 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 been used in 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). However, they are also potent greenhouse gases.

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

The IPCC Guidelines and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased out under the *Montreal Protocol*. The United States believes that a greenhouse gas emissions inventory is incomplete without these emissions; therefore, estimates for several Class I and Class II ODSs are provided in Table ES-13. 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
Class I							
CFC-11	53.5	36.2	26.6	25.1	24.9	24.0	22.8
CFC-12	112.6	51.8	35.5	23.1	21.0	14.0	17.2
CFC-113	52.7	17.1	+	+	+	+	+
CFC-114	4.7	1.6	0.3	0.1	0.1	+	+
CFC-115	4.2	3.0	3.2	2.9	2.7	2.6	2.3
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
Halon-1301	1.8	1.4	1.4	1.3	1.3	1.3	1.3
Class II							
HCFC-22	34.0	39.3	41.0	42.4	43.8	74.1	79.1
HCFC-123	+	0.6	0.7	0.8	0.9	1.0	1.1
HCFC-124	+	5.6	5.9	6.2	6.4	6.5	6.5
HCFC-141b	1.3	9.9	9.9	8.8	9.7	10.9	10.9
HCFC-142b	0.8	3.6	4.0	4.3	4.7	5.0	5.4
HCFC-225ca/cb	+	+	+	+	+	+	+

Source: EPA, Office of Atmospheric Programs
+ Does not exceed 0.5 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 includes 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.

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 2001).[15] 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.

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 63 percent in 2000. Coal combustion contributes nearly all of those emissions (approximately 94 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.

[15] NO_x and CO emission estimates from agricultural residue burning were estimated separately, and therefore not taken from EPA (2001).

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

Gas/Activity	1990	1995	1996	1997	1998	1999	2000
NO_x	**21,873**	**24,126**	**24,999**	**25,508**	**25,470**	**25,224**	**25,038**
Stationary Fossil Fuel Combustion	9,884	9,822	9,522	9,577	9,400	9,022	8,740
Mobile Fossil Fuel Combustion	10,900	13,329	14,338	14,771	14,976	15,087	14,941
Oil and Gas Activities	139	100	126	130	130	130	132
Industrial Processes	921	842	976	991	924	946	1,184
Solvent Use	1	3	3	3	3	3	3
Agricultural Burning	28	29	32	34	35	34	35
Waste	+	1	3	3	3	3	3
CO	**85,016**	**79,726**	**87,109**	**87,567**	**83,379**	**86,354**	**94,033**
Stationary Fossil Fuel Combustion	4,999	5,383	3,936	3,926	3,905	3,928	4,140
Mobile Fossil Fuel Combustion	69,523	68,072	74,927	73,764	72,797	70,565	69,296
Oil and Gas Activities	302	316	321	333	332	332	335
Industrial Processes	9,502	5,291	7,171	8,776	5,557	10,763	19,469
Solvent Use	4	5	1	1	1	1	1
Agricultural Burning	685	656	747	761	781	760	786
Waste	1	2	5	5	5	5	5
NMVOCs	**18,630**	**18,434**	**17,411**	**17,766**	**16,797**	**16,970**	**17,907**
Stationary Fossil Fuel Combustion	912	973	1,020	1,019	1,018	1,025	1,089
Mobile Fossil Fuel Combustion	8,154	7,725	8,485	8,257	8,158	7,962	7,638
Oil and Gas Activities	555	582	433	442	440	385	393
Industrial Processes	3,110	2,805	2,344	2,783	2,341	3,043	4,232
Solvent Use	5,225	5,618	4,973	5,108	4,679	4,390	4,388
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
Waste	673	731	156	157	161	164	168
SO_2	**21,481**	**17,408**	**17,629**	**18,076**	**18,185**	**17,541**	**16,498**
Stationary Fossil Fuel Combustion	18,407	14,724	14,726	15,104	15,192	14,540	13,496
Mobile Fossil Fuel Combustion	1,339	1,189	1,612	1,636	1,655	1,668	1,626
Oil and Gas Activities	390	334	304	312	310	309	314
Industrial Processes	1,306	1,117	958	993	996	992	1,031
Solvent Use	+	1	1	1	1	1	+
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
Waste	39	43	29	30	31	31	32

Source: (EPA 2001) except for estimates from agricultural burning.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.