Executive Summary

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

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

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as halons. Other fluorine containing halogenated substances include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

There are also several gases that do not have a direct global warming effect but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone. These gases—referred to as ozone precursors—include carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane volatile organic compounds (NMVOCs).[2] Aerosols—extremely small particles or liquid droplets often produced by emissions of sulfur dioxide (SO_2)—can also affect the absorptive characteristics of the atmosphere.

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

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

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

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

Recent Trends in U.S. Greenhouse Gas Emissions

Total U.S. greenhouse gas emissions rose in 1997 to 1,813.6 million metric tons of carbon equivalents (MMTCE)[3] (11.1 percent above 1990 baseline levels). The single year increase in emissions from 1996 to 1997 was 1.3 percent (23.1 MMTCE), down from the previous year's increase of 3.3 percent. Figure ES-1 through Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute change since 1990. Table ES-1 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 1997.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 1997. The primary greenhouse gas emitted by human activities was CO_2. The largest source of CO_2 and of overall greenhouse gas emissions in the United States was fossil fuel combustion. Methane emissions resulted primarily from decomposition of wastes in landfills, manure and enteric fermentation associated with domestic livestock, natural gas systems, and coal mining. Emissions of N_2O were dominated by agricultural soil management and mobile source fossil fuel combustion. The substitution of ozone depleting substances and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate HFC emissions. PFC emissions came mainly from primary aluminum production, while electrical transmission and distribution systems emitted the majority of SF_6.

As the largest source of U.S. GHG emissions, CO_2 from fossil fuel combustion accounted for 81 percent of emissions in 1997 when each gas is weighted by its Glo-

Figure ES-1

U.S. GHG Emissions by Gas

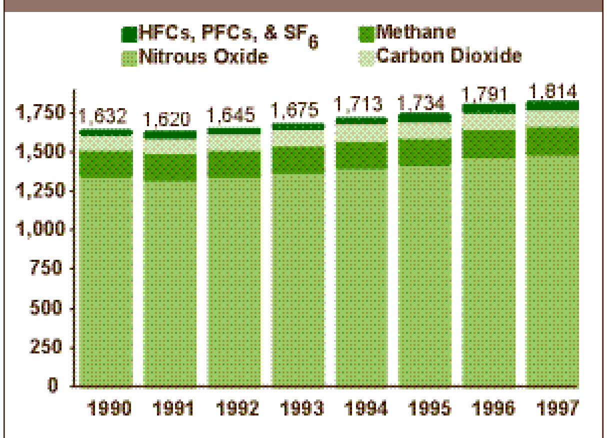


Figure ES-2

Annual Percent Change in U.S. GHG Emissions

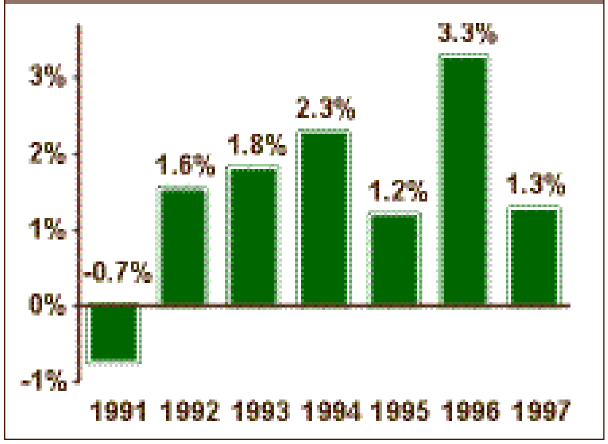
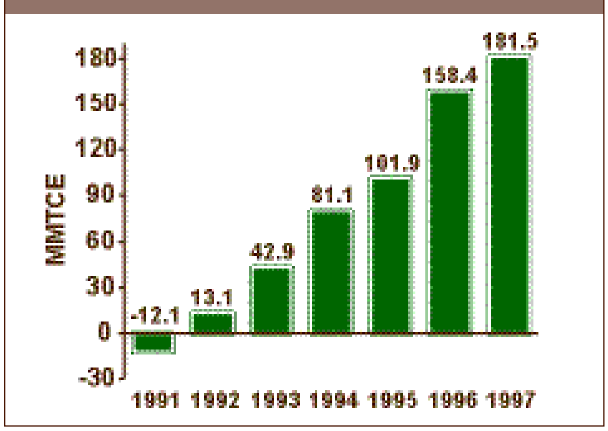


Figure ES-3

Absolute Change in U.S. GHG Emissions Since 1990



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

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

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997
CO_2	**1,344.3**	**1,329.8**	**1,349.6**	**1,379.2**	**1,403.5**	**1,419.2**	**1,469.3**	**1,487.9**
Fossil Fuel Combustion	1,327.2	1,312.6	1,332.4	1,360.6	1,383.9	1,397.8	1,447.7	1,466.0
Natural Gas Flaring	2.3	2.6	2.6	3.5	3.6	4.5	4.3	4.2
Cement Manufacture	8.9	8.7	8.8	9.3	9.6	9.9	9.9	10.2
Lime Manufacture	3.3	3.2	3.3	3.4	3.5	3.7	3.8	3.9
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.9	2.0	2.1
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2
Carbon Dioxide Consumption	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Land-Use Change and Forestry (Sink)[a]	(311.5)	(311.5)	(311.5)	(208.6)	(208.6)	(208.6)	(208.6)	(208.6)
International Bunker Fuels[b]	27.1	27.8	29.0	29.9	27.4	25.4	25.4	26.6
CH_4	**169.9**	**171.0**	**172.5**	**172.0**	**175.5**	**178.6**	**178.3**	**179.6**
Stationary Sources	2.3	2.4	2.4	2.4	2.4	2.5	2.5	2.2
Mobile Sources	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Coal Mining	24.0	22.8	22.0	19.2	19.4	20.3	18.9	18.8
Natural Gas Systems	32.9	33.3	33.9	34.1	33.5	33.2	33.7	33.5
Petroleum Systems	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.6
Petrochemical Production	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Silicon Carbide Production	+	+	+	+	+	+	+	+
Enteric Fermentation	32.7	32.8	33.2	33.6	34.5	34.9	34.5	34.1
Manure Management	14.9	15.4	16.0	16.1	16.7	16.9	16.6	17.0
Rice Cultivation	2.5	2.5	2.8	2.5	3.0	2.8	2.5	2.7
Agricultural Residue Burning	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Landfills	56.2	57.6	57.8	59.7	61.6	63.6	65.1	66.7
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
International Bunker Fuels[b]	+	+	+	+	+	+	+	+
N_2O	**95.7**	**97.6**	**100.1**	**100.4**	**108.3**	**105.4**	**108.2**	**109.0**
Stationary Sources	3.8	3.8	3.9	3.9	4.0	4.0	4.1	4.1
Mobile Sources	13.6	14.2	15.2	15.9	16.7	17.0	17.4	17.5
Adipic Acid Production	4.7	4.9	4.6	4.9	5.2	5.2	5.4	3.9
Nitric Acid Production	3.3	3.3	3.4	3.5	3.7	3.7	3.9	3.8
Manure Management	2.6	2.8	2.8	2.9	2.9	2.9	3.0	3.0
Agricultural Soil Management	65.3	66.2	68.0	67.0	73.4	70.2	72.0	74.1
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Human Sewage	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[b]	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2
HFCs, PFCs, and SF_6	**22.2**	**21.6**	**23.0**	**23.4**	**25.9**	**30.8**	**34.7**	**37.1**
Substitution of Ozone Depleting Substances	0.3	0.2	0.4	1.4	4.0	9.5	11.9	14.7
Aluminum Production	4.9	4.7	4.1	3.5	2.8	2.7	2.9	2.9
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2
Semiconductor Manufacture	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.3
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	3.0	3.0
Total Emissions	**1,632.1**	**1,620.0**	**1,645.2**	**1,675.0**	**1,713.2**	**1,733.9**	**1,790.5**	**1,813.6**
Net Emissions (Sources and Sinks)	**1,320.6**	**1,308.5**	**1,333.7**	**1,466.5**	**1,504.7**	**1,525.4**	**1,582.0**	**1,605.0**

+ Does not exceed 0.05 MMTCE

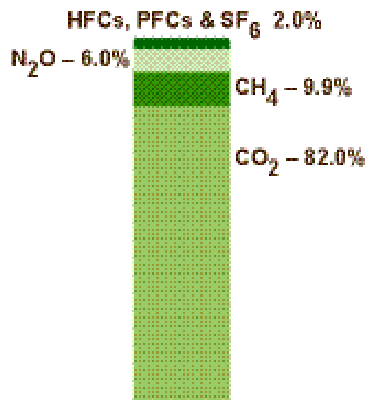
[a] Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

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

Note: Totals may not sum due to independent rounding.

Figure ES-4

1997 Greenhouse Gas Emissions by Gas



bal Warming Potential.[4] Emissions from this source grew by 11 percent (138.8 MMTCE) from 1990 to 1997 and were responsible for over three-quarters of the increase in national emissions during this period. The annual increase in CO_2 emissions from this source was 1.3 percent in 1997, down from the previous year when emissions increased by 3.6 percent.

The dramatic increase in fossil fuel combustion-related CO_2 emissions in 1996 was primarily a function of two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as gas prices rose sharply due to weather conditions, which drove up residential consumption of natural gas for heating; and 2) higher petroleum consumption for transportation. In 1997, by comparison, electric utility natural gas consumption rose to regain much of the previous year's decline as the supply available rose due to lower residential consumption. Despite this increase in natural gas consumption by utilities and relatively stagnant U.S. electricity consumption, coal consumption rose in 1997 to offset the temporary shut-down of several nuclear power plants. Petroleum consumption for transportation activities in 1997 also grew by less than one percent, compared to over three percent the previous year (see Table ES-2). The annual increase in CO_2 emissions from petroleum in 1997 is based on motor gasoline sales data from the U.S. Energy Information Administration; it is expected to be revised upward with the publication of future energy statistics.

[4] See section below entitled Global Warming Potential.

Overall, from 1990 to 1997, total emissions of CO_2, CH_4, and N_2O increased by 143.5 (11 percent), 9.7 (6 percent), and 13.4 MMTCE (14 percent), respectively. During the same period, weighted emissions of HFCs, PFCs, and SF_6 rose by 14.9 MMTCE (67 percent). Despite being emitted in smaller quantities relative to the other principle greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because of their extremely high Global Warming Potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests, which was estimated to be 11 percent of total emissions in 1997.

Other significant trends in emissions from additional source categories over the eight year period from 1990 through 1997 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased dramatically (by 14.4 MMTCE). This increase was partly offset, however, by reductions in PFC emissions from aluminum production (41 percent) and HFC emissions from HCFC-22 production (14 percent), both as a result of voluntary industry emission reduction efforts and, in the former case, from falling domestic aluminum production.
- Combined N_2O and CH_4 emissions from mobile source fossil fuel combustion rose by 3.9 MMTCE (26 percent), primarily due to increased rates of N_2O generation in highway vehicles.

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

Sector	Fuel Type	1995 to 1996	1996 to 1997
Electric Utility	Coal	5.7%	2.9%
Electric Utility	Natural Gas	-14.6%	8.7%
Residential	Natural Gas	8.1%	-4.4%
Transportation*	Petroleum	3.4%	0.3%

* Excludes emissions from International Bunker Fuels.

- Methane emissions from the decomposition of waste in municipal and industrial landfills rose by 10.5 MMTCE (19 percent) as the amount of organic matter in landfills steadily accumulated.
- Emissions from coal mining dropped by 5.2 MMTCE (21 percent) as the use of methane from degasification systems increased significantly.
- Nitrous oxide emissions from agricultural soil management increased by 8.8 MMTCE (13 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.
- An additional domestic adipic acid plant installed emission control systems in 1997; this was estimated to have resulted in a 1.4 MMTCE (27 percent) decline in emissions from 1996 to 1997 despite an increase in production.

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

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

There are several ways to assess a nation's greenhouse gas emitting intensity. These measures of intensity could be based on aggregate energy consumption because energy-related activities are the largest sources of emissions, on fossil fuel consumption only because almost all energy-related emissions involve the combustion of fossil fuels, on electricity consumption because electric utilities were the largest sources of U.S. greenhouse gas emissions in 1997, on total gross domestic product as a measure of national economic activity, or on a per capita basis. Depending upon which of these measures was used, the United States could appear to have reduced or increased its national greenhouse gas intensity. Table ES-3 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.5 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption—thereby indicating an improved or lower greenhouse gas emitting intensity—and much slower than that for either electricity consumption or overall gross domestic product. Emissions, however, are growing faster than national population, thereby indicating a worsening or higher greenhouse gas emitting intensity on a per capita basis (see Figure ES-5). Overall, atmospheric CO_2 concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

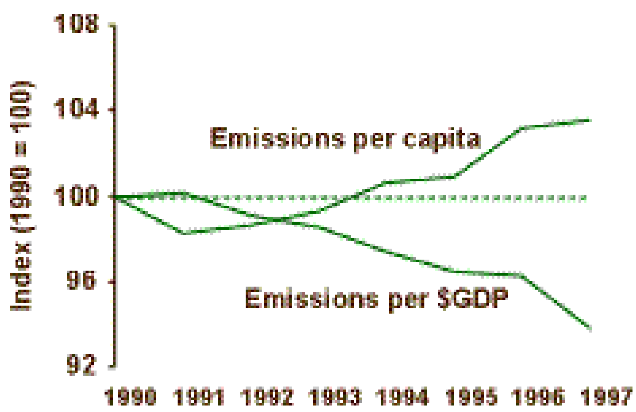
Table ES-3: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	1991	1992	1993	1994	1995	1996	1997	Growth Rate[g]
GHG Emissions[a]	100	99	101	103	105	106	110	111	1.5%
Energy Consumption[b]	100	100	101	104	106	108	112	112	1.6%
Fossil Fuel Consumption[c]	100	99	101	104	106	107	110	112	1.6%
Electricity Consumption[c]	100	102	102	105	108	111	114	115	2.0%
GDP[d]	100	99	102	104	108	110	114	118	2.5%
Population[e]	100	101	102	103	104	105	106	107	1.0%
Atmospheric CO_2 Concentration[f]	100	100	101	101	101	102	102	103	0.4%

[a] GWP weighted values
[b] Energy content weighted values. Source: DOE/EIA
[c] Source: DOE/EIA
[d] Gross Domestic Product in chained 1992 dollars (BEA 1998)
[e] (U.S. Census Bureau 1998)
[f] Mauna Loa Observatory, Hawaii (Keeling and Whorf 1998)
[g] Average annual growth rate

Figure ES-5

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



Box ES-2: Greenhouse Gas Emissions from Transportation Activities

Motor vehicle usage is increasing all over the world, including in the United States. Since the 1970s, the number of highway vehicles registered in the United States has increased faster than the overall population, according to the Federal Highway Administration. Likewise, the number of miles driven—up 18 percent from 1990 to 1997—and gallons of gasoline consumed each year in the United States have increased relatively steadily since the 1980s, according to the Energy Information Administration. These increases in motor vehicle usage are the result of a confluence of factors including population growth, economic growth, increasing urban sprawl, and low fuel prices.

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

This report reflects new data on the role that automotive catalytic converters play in emissions of N_2O, a powerful greenhouse gas. The EPA's Office of Mobile Sources has conducted a series of tests in order to measure the magnitude of N_2O emissions from gasoline-fueled passenger cars and light-duty trucks equipped with catalytic converters. Results show that N_2O emissions are lower than the IPCC default factors, and the United States has shared this data with the IPCC. In this report, new emission factors developed from these measurements and from previously published literature were used to calculate emissions from mobile sources in the United States (see Annex C).

Table ES-4 summarizes greenhouse gas emissions from all transportation-related activities. Overall, transportation activities—excluding international bunker fuels—accounted for an almost constant 26 percent of total U.S. greenhouse gas emissions from 1990 to 1997. These emissions were primarily CO_2 from fuel combustion, which increased by 10 percent from 1990 to 1997. However, because of larger increases in N_2O and HFC emissions during this period, overall emissions from transportation activities actually increased by 12 percent.

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

Gas/Vehicle Type	1990	1991	1992	1993	1994	1995	1996	1997
CO_2	**405.0**	**396.7**	**402.4**	**406.8**	**422.1**	**430.7**	**445.3**	**446.5**
Passenger Cars[a]	169.3	167.8	172.0	173.5	172.5	175.6	160.8	162.6
Light-Duty Trucks[a]	77.5	77.2	77.2	80.5	87.2	89.2	109.9	111.1
Other Trucks	57.3	55.1	56.7	59.9	62.7	64.2	68.3	69.5
Buses	2.7	2.9	2.9	3.1	3.3	3.5	3.0	3.0
Aircraft	50.5	48.4	47.4	47.6	49.6	48.3	50.5	50.1
Boats and Vessels	16.4	15.9	16.4	11.7	13.9	16.8	18.5	15.4
Locomotives	7.5	6.9	7.4	6.8	8.0	8.1	8.8	9.0
Other[b]	23.8	22.5	22.4	23.8	24.9	24.9	25.5	25.8
International Bunker Fuels[c]	27.1	27.8	29.0	29.9	27.4	25.4	25.4	26.6
CH_4	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**
Passenger Cars	0.8	0.7	0.7	0.7	0.7	0.7	0.6	0.6
Light-Duty Trucks	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5
Other Trucks and Buses	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Aircraft	+	+	+	+	+	+	+	+
Boats and Vessels	+	+	+	+	+	+	+	+
Locomotives	+	+	+	+	+	+	+	+
Other[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[c]	+	+	+	+	+	+	+	+
N_2O	**13.6**	**14.2**	**15.2**	**15.9**	**16.7**	**17.0**	**17.4**	**17.5**
Passenger Cars	8.7	9.1	9.7	10.1	10.0	10.1	8.9	9.1
Light-Duty Trucks	3.4	3.7	3.9	4.2	5.1	5.2	6.8	6.8
Other Trucks and Buses	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.9
Aircraft[d]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Boats and Vessels	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other[d]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
International Bunker Fuels[c]	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2
HFCs	**+**	**+**	**0.2**	**0.7**	**1.3**	**2.5**	**3.6**	**4.5**
Mobile Air Conditioners[e]	+	+	0.2	0.7	1.3	2.5	3.6	4.5
Total[c]	**420.0**	**412.3**	**419.1**	**424.8**	**441.5**	**451.6**	**467.7**	**469.9**

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

[a] In 1996, the U.S. Federal Highway Administration modified the definition of light-duty trucks to include minivans and sport utility vehicles. Previously, these vehicles were included under the passenger cars category. Hence the sharp drop in CO_2 emissions for passenger cars from 1995 to 1996 was observed. This gap, however, was offset by an equivalent rise in CO_2 emissions from light-duty trucks.

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

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

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

[e] Includes primarily HFC-134a

Box ES-3: Electric Utility-Related Greenhouse Gas Emissions

Like transportation, activities related to the generation, transmission, and distribution of electricity in the United States result in greenhouse gas emissions. Table ES-5 presents greenhouse gas emissions from electric utility-related activities. Aggregate emissions from electric utilities of all greenhouse gases increased by 11.8 percent from 1990 to 1997, and accounted for just under 30 percent of total U.S. greenhouse emissions during the same period. The majority of these emissions resulted from the combustion of coal in boilers to produce steam that is passed through a turbine to generate electricity. Overall, the generation of electricity results in a larger portion of total U.S. greenhouse gas emissions than any other activity.

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

Gas/Fuel Type or Source	1990	1991	1992	1993	1994	1995	1996	1997
CO_2	**476.8**	**473.4**	**472.5**	**490.7**	**494.8**	**494.1**	**513.2**	**532.3**
Coal	409.0	407.2	411.8	428.7	430.2	433.0	457.5	470.9
Natural Gas	41.2	41.1	40.7	39.5	44.0	47.2	40.3	43.8
Petroleum	26.6	25.1	19.9	22.5	20.6	14.0	15.4	17.6
Geothermal	0.1	0.1	0.1	0.1	+	+	+	+
CH_4	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Stationary Sources (Utilities)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**	**2.1**	**2.2**	**2.3**
Stationary Sources (Utilities)	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.3
SF_6	**5.6**	**5.9**	**6.2**	**6.4**	**6.7**	**7.0**	**7.0**	**7.0**
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0
Total	**484.6**	**481.4**	**480.8**	**499.3**	**503.7**	**503.3**	**522.5**	**541.7**

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

Global Warming Potentials

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

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

All gases in this executive summary are presented in units of million metric tons of carbon equivalents (MMTCE). Carbon comprises $12/44^{ths}$ of carbon dioxide by weight. In order to convert emissions reported in teragrams (Tg) of greenhouse gas to MMTCE, the following equation was used:

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

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

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

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

Carbon Dioxide Emissions

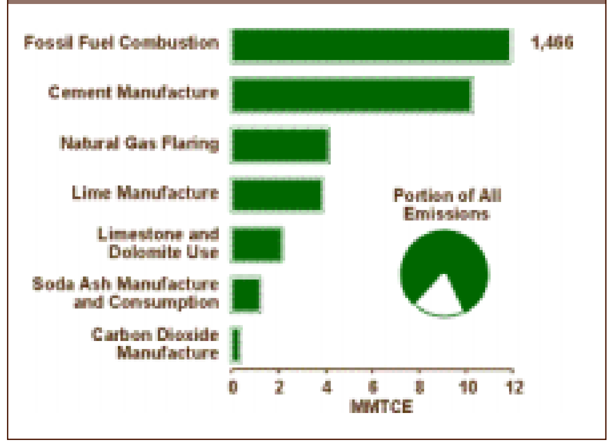
The global carbon cycle is made up of large carbon flows and reservoirs. Hundreds of billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (sinks) and are emitted to the atmosphere annually through natural processes (sources). When in equilibrium, carbon fluxes among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

Since the Industrial Revolution, this equilibrium of atmospheric carbon has been altered. Atmospheric concentrations of CO_2 have risen about 28 percent (IPCC 1996), principally because of fossil fuel combustion, which accounted for almost 99 percent of total U.S. CO_2 emissions in 1997. 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-6 and Table ES-7 summarize U.S. sources and sinks of CO_2, while the remainder of this section discusses CO_2 emission trends in greater detail.

Figure ES-6

1997 Sources of CO_2



Energy

Energy-related activities accounted for almost all U.S. CO_2 emissions for the period of 1990 through 1997. Carbon dioxide from fossil fuel combustion was the main contributor, although CH_4 and N_2O were also emitted. In 1997, 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 renewable or other energy sources such as hydropower, biomass, and nuclear energy (see Figure ES-7 and Figure ES-8). Energy-related activities other than fuel combustion, such as those associated with the production, transmission, storage, and distribution of fossil fuels, also emit GHGs (primarily CH_4). A discussion of specific trends related to CO_2 emissions from energy consumption is presented below.

Fossil Fuel Combustion

As fossil fuels are combusted, the carbon stored in them is almost entirely emitted as CO_2. The amount of carbon in fuels per unit of energy content varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of energy, while petroleum has about 25 percent less carbon than coal, and natural gas has about 45 percent less. From 1990 through 1997, petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent

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

Source	1990	1991	1992	1993	1994	1995	1996	1997
Fossil Fuel Combustion	1,327.2	1,312.6	1,332.4	1,360.6	1,383.9	1,397.8	1,447.7	1,466.0
Cement Manufacture	8.9	8.7	8.8	9.3	9.6	9.9	9.9	10.2
Natural Gas Flaring	2.3	2.6	2.6	3.5	3.6	4.5	4.3	4.2
Lime Manufacture	3.3	3.2	3.3	3.4	3.5	3.7	3.8	3.9
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.9	2.0	2.1
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2
Carbon Dioxide Consumption	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Land-Use Change and Forestry (Sink)[a]	(311.5)	(311.5)	(311.5)	(208.6)	(208.6)	(208.6)	(208.6)	(208.6)
International Bunker Fuels[b]	27.1	27.8	29.0	29.9	27.4	25.4	25.4	26.6
Total Emissions	**1,344.3**	**1,329.8**	**1,349.6**	**1,379.2**	**1,403.5**	**1,419.2**	**1,469.3**	**1,487.9**
Net Emissions (Sources and Sinks)	**1,032.8**	**1,018.3**	**1,038.1**	**1,170.6**	**1,194.9**	**1,210.6**	**1,260.7**	**1,279.3**

[a] Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.
[b] Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.

Figure ES-7

1997 U.S. Energy Consumption by Energy Source

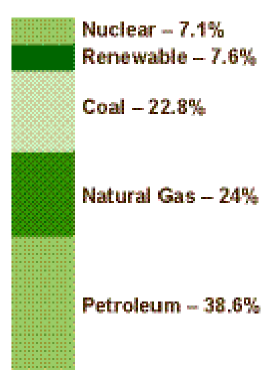
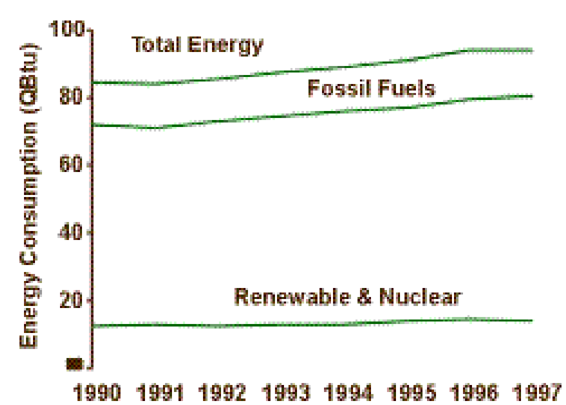


Figure ES-8

U.S. Energy Consumption (Quadrillion Btu)



of total energy consumption. Natural gas and coal followed in order of importance, accounting for an average of 24 and 22 percent of total energy consumption, respectively. Most petroleum was consumed in the transportation sector, while the vast majority of coal was used by electric utilities, and natural gas was consumed largely in the industrial and residential sectors.

Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.5 percent from 1990 to 1997. The fundamental factors behind this trend include (1) a robust domestic economy, (2) relatively low energy prices, and (3) fuel switching by electric utilities. After 1990, when CO_2 emissions from fossil fuel combustion were 1,327.2 MMTCE, there was a slight decline in emissions in 1991, followed by a relatively steady increase to 1,466.0 MMTCE in 1997. Overall, CO_2 emissions from fossil fuel combustion increased by 11 percent over the eight year period and rose by 1.3 percent in the final year.

Of all emissions related to fossil fuel combustion from 1996 to 1997, emissions from coal grew the most (an increase of 12.1 MMTCE or 2.3 percent). Alone, emissions from coal combustion by electric utilities increased by 2.9 percent from 1996 to 1997. Emissions from natural gas remained almost unchanged as increased consumption by electric utilities and the commercial sector were offset by decreases in the residential and industrial sectors.

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

End-Use Sector	1990	1991	1992	1993	1994	1995	1996	1997
Residential	253.0	257.1	255.7	271.6	268.6	269.8	285.4	286.1
Commercial	206.8	206.4	205.3	212.1	214.1	218.4	225.9	237.1
Industrial	453.3	441.8	459.3	459.5	467.8	466.8	478.8	483.7
Transportation	405.0	396.7	402.4	406.8	422.1	430.7	445.3	446.5
U.S. Territories	9.1	10.6	9.7	10.5	11.3	12.0	12.2	12.6
Total	**1,327.2**	**1,312.6**	**1,332.4**	**1,360.6**	**1,383.9**	**1,397.8**	**1,447.7**	**1,466.0**

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

Emissions from the combustion of petroleum products in 1997 increased 1.5 percent from the previous year, accounting for about 33 percent of the increase in CO_2 emissions from fossil fuel combustion.

The four end-use sectors contributing to CO_2 emissions from fossil fuel combustion include: industrial, transportation, residential, and commercial. Electric utilities also emit CO_2, although these emissions are produced as they consume fossil fuel to provide electricity to one of the four end-use sectors. For the discussion below, utility emissions have been distributed to each end-use sector based upon their aggregate electricity consumption. Emissions from utilities are addressed separately after the end-use sectors have been discussed. Emissions from U.S. territories are also calculated separately due to a lack of end-use-specific consumption data. Table ES-8, Figure ES-9, and Figure ES-10 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

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

Transportation End-Use Sector. Transportation activities—excluding international bunker fuels—accounted for 30 percent of CO_2 emissions from fossil fuel combustion in 1997. Virtually all of the energy consumed in this end-use sector came from petroleum products. Two thirds of the emissions resulted from gasoline consumption in motor vehicles. The remaining emissions came from other transportation activities, including the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircraft.

Figure ES-9

1997 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

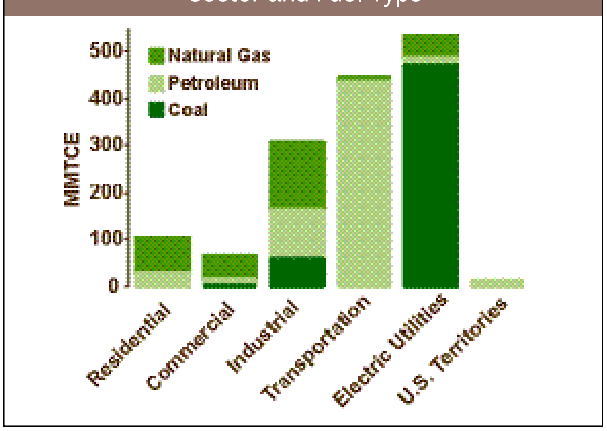
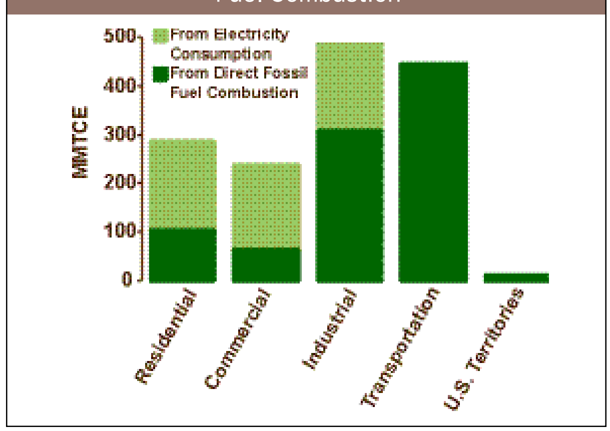


Figure ES-10

1997 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Residential and Commercial End-Use Sectors. The residential and commercial sectors accounted for 19 and 16 percent, respectively, of CO_2 emissions from fossil fuel consumption in 1997. Both sectors relied heavily on electricity for meeting energy needs, with 64 and 73 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were largely due to the consumption of natural gas and petroleum, primarily for meeting heating and cooking needs.

Electric Utilities. The United States relies on electricity to meet a significant portion of its energy demands, especially for lighting, electric motors, heating, and air conditioning. Electric utilities are responsible for consuming 28 percent of overall U.S. energy and emitted 36 percent of CO_2 from fossil fuel consumption in 1997. The type of fuel combusted by utilities has a significant effect on their emissions. For example, some electricity is generated with low CO_2 emitting energy technologies, particularly non-fossil options such as nuclear, hydroelectric, or geothermal energy. However, electric utilities rely on coal for over half of their total energy requirements and accounted for 88 percent of all coal consumed in the United States in 1997. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Natural Gas Flaring

Carbon dioxide is produced when methane 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 1997, flaring activities emitted approximately 4.2 MMTCE, or about 0.3 percent of U.S. CO_2 emissions.

Biomass Combustion

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

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

Gross CO_2 emissions from biomass combustion were 59.1 MMTCE, with the industrial sector accounting for 79 percent of the emissions, and the residential sector, 18 percent. Ethanol consumption by the transportation sector accounted for only 3 percent of CO_2 emissions from biomass combustion.

Industrial Processes

Emissions are often produced as a by-product of various non-energy-related activities. For example, industrial processes can chemically transform raw materials. This transformation often releases greenhouse gases such as CO_2. The production processes that emit CO_2 include cement manufacture, lime manufacture, limestone and dolomite use (e.g., in iron and steel making), soda ash manufacture and consumption, and CO_2 consumption. Total CO_2 emissions from these sources were approximately 17.8 MMTCE in 1997, accounting for about 1 percent of total CO_2 emissions. Since 1990, emissions from each of these sources increased, except for emissions from soda ash manufacture and consumption, which remained relatively constant.

Cement Manufacture (10.2 MMTCE)

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

Lime Manufacture (3.9 MMTCE)

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

Limestone and Dolomite Use (2.1 MMTCE)

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

Soda Ash Manufacture and Consumption (1.2 MMTCE)

Commercial soda ash (sodium carbonate, Na_2CO_3) is used in many consumer products, such as glass, soap and detergents, paper, textiles, and food. During the manufacturing of soda ash, some natural sources of sodium carbonate are heated and transformed into a crude soda ash, in which CO_2 is generated as a by-product. In addition, CO_2 is often released when the soda ash is consumed.

Carbon Dioxide Consumption (0.3 MMTCE)

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

Land-Use Change and Forestry

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

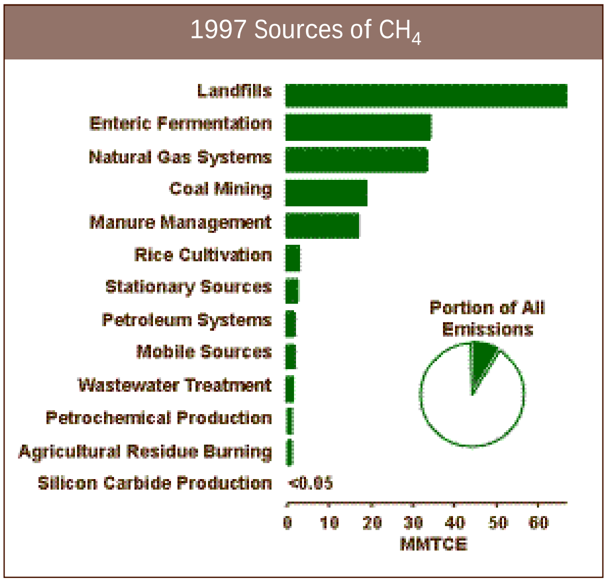
Since the early 1950s, the managed growth of private forest land in the East has nearly doubled the biomass density there. The 1970s and 1980s saw a resurgence of federally sponsored tree-planting programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve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

In 1997, the CO_2 flux from land-use change and forestry activities was estimated to have been a net uptake of 208.6 MMTCE. This carbon was sequestered in trees, understory, litter, and soils in forests, U.S. wood product pools, and wood in landfills. This net carbon uptake represents an offset of about 14 percent of the CO_2 emissions from fossil fuel combustion in 1997. The amount of carbon sequestered through U.S. forestry and land-use practices is estimated to have declined by about a third between 1990 and 1997 largely due to the maturation of existing U.S. forests and the slowed expansion of Eastern forest cover.

Methane Emissions

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

Figure ES-11



Landfills

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

Methane emissions from U.S. landfills in 1997 were 66.7 MMTCE, a 19 percent increase since 1990 due to the steady accumulation of wastes in landfills. Emissions from U.S. municipal solid waste landfills, which received about 61 percent of the solid waste generated in the United States, accounted for 93 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 14 percent of the methane generated in U.S. landfills in 1997 was recovered and combusted, often for energy.

A regulation promulgated in March 1996 requires the largest U.S. landfills to begin collecting and combusting their landfill gas to reduce emissions of nonmethane volatile organic compounds (NMVOCs). It

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

Source	1990	1991	1992	1993	1994	1995	1996	1997
Landfills	56.2	57.6	57.8	59.7	61.6	63.6	65.1	66.7
Enteric Fermentation	32.7	32.8	33.2	33.6	34.5	34.9	34.5	34.1
Natural Gas Systems	32.9	33.3	33.9	34.1	33.5	33.2	33.7	33.5
Coal Mining	24.0	22.8	22.0	19.2	19.4	20.3	18.9	18.8
Manure Management	14.9	15.4	16.0	16.1	16.7	16.9	16.6	17.0
Rice Cultivation	2.5	2.5	2.8	2.5	3.0	2.8	2.5	2.7
Stationary Sources	2.3	2.4	2.4	2.4	2.4	2.5	2.5	2.2
Petroleum Systems	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.6
Mobile Sources	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Petrochemical Production	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Agricultural Residue Burning	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Silicon Carbide Production	+	+	+	+	+	+	+	+
International Bunker Fuels*	+	+	+	+	+	+	+	+
Total	**169.9**	**171.0**	**172.5**	**172.0**	**175.5**	**178.6**	**178.3**	**179.6**

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

is estimated that by the year 2000, this regulation will have reduced landfill methane emissions by more than 50 percent. Furthermore, the EPA is currently reviewing site-specific information on landfill gas recovery and anticipates that this new information will lead to a higher estimate of the national recovery total, and thus, lower net methane emissions. This new information will be available in future inventories.

Natural Gas and Petroleum Systems

Methane is the major component of natural gas. During the production, processing, transmission, and distribution of natural gas, fugitive emissions of methane often occur. Because natural gas is often found in conjunction with petroleum deposits, leakage from petroleum systems is also a source of emissions. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment conditions. In 1997, emissions from U.S. natural gas systems were estimated to be 33.5 MMTCE, accounting for approximately 19 percent of U.S. methane emissions.

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 1997, emissions from petroleum systems were estimated to be 1.6 MMTCE, or 1 percent of U.S. methane emissions. EPA is reviewing new information on methane emissions from petroleum systems and anticipates that future emission estimates will be higher for this source.

From 1990 to 1997, combined methane emissions from natural gas and petroleum systems increased by about 2 percent as the number of gas producing wells and miles of distribution pipeline rose.

Coal Mining

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

Methane from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed. Because methane in underground mines is explosive at concentrations of 5 to 15 percent in air, most active underground mines are required to vent this methane, typically to the atmosphere. At some mines, methane-recovery systems may supplement these ventilation systems. U.S. recovery of methane has been increasing in recent years. During 1997, coal mining activities emitted 18.8 MMTCE of methane, or 10 percent of U.S. methane emissions. From 1990 to 1997, emissions from this source decreased by 22 percent due to increased use of the methane collected by mine degasification systems.

Agriculture

Agriculture accounted for 30 percent of U.S. methane emissions in 1997, with enteric fermentation in domestic livestock and manure management accounting for the majority. Other agricultural activities contributing directly to methane emissions included rice cultivation and agricultural waste burning.

Enteric Fermentation (34.1 MMTCE)

During animal digestion, methane is produced through the process of enteric fermentation, in which microbes residing in animal digestive systems break down the feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest methane emissions among all animal types because they have a rumen, or large fore-stomach, in which methane-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have much lower methane emissions. In 1997, enteric fermentation was the source of about 19 percent of U.S. methane emissions, and more than half of the methane emissions from agriculture. From 1990 to 1997, emissions from this source increased by 5 percent due mainly to increased livestock populations.

Manure Management (17.0 MMTCE)

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

Emissions from manure management were about 9 percent of U.S. methane emissions in 1997, and about a third of the methane emissions from agriculture. From 1990 to 1997, emissions from this source increased by 14 percent because of larger farm animal populations and expanded use of liquid manure management systems.

Rice Cultivation (2.7 MMTCE)

Most of the world's rice, and all of the rice in the United States, is grown on flooded fields. When fields are flooded, anaerobic conditions develop and the organic matter in the soil decomposes, releasing methane to the atmosphere, primarily through the rice plants. In 1997, rice cultivation was the source of slightly over 1 percent of total U.S. methane emissions, and about 5 percent of U.S. methane emissions from agriculture. Emissions estimates from this source did not change significantly from 1990 levels.

Agricultural Residue Burning (0.2 MMTCE)

Burning crop residue releases a number of greenhouse gases, including methane. Agricultural residue burning is considered to be a net source of methane emissions because, unlike CO_2, methane released during burning is not reabsorbed by crop regrowth during the next growing season. Because field burning is not common in the United States, it was responsible for only 0.1 percent of U.S. methane emissions in 1997.

Other Sources

Methane is also produced from several other sources in the United States, including fossil fuel combustion, wastewater treatment, and some industrial processes. Fossil fuel combustion by stationary and mobile sources was responsible for methane emissions of 2.2 and 1.4 MMTCE, respectively in 1997. The majority of emissions from stationary sources resulted from the combustion of wood in the residential and industrial sectors. The combustion of gasoline in highway vehicles was responsible for the majority of the methane emitted from mobile sources. Wastewater treatment was a smaller source of methane, emitting 0.9 MMTCE in 1996. Methane emissions from two industrial sources—petrochemical and silicon carbide production—were also estimated, totaling 0.4 MMTCE.

Nitrous Oxide Emissions

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

Agricultural Soil Management

Nitrous oxide (N_2O) is produced naturally in soils through microbial processes of nitrification and denitrification. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as N_2O by these microbial processes. Direct additions of nitrogen occur through the application of synthetic and organic

Figure ES-12

1997 Sources of N_2O

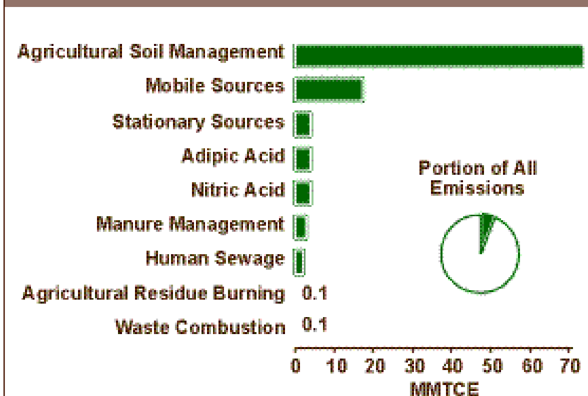


Table ES-10: U.S. Sources of Nitrous Oxide Emissions (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Agricultural Soil Management	65.3	66.2	68.0	67.0	73.4	70.2	72.0	74.1
Mobile Sources	13.6	14.2	15.2	15.9	16.7	17.0	17.4	17.5
Stationary Sources	3.8	3.8	3.9	3.9	4.0	4.0	4.1	4.1
Adipic Acid Production	4.7	4.9	4.6	4.9	5.2	5.2	5.4	3.9
Nitric Acid Production	3.3	3.3	3.4	3.5	3.7	3.7	3.9	3.8
Manure Management	2.6	2.8	2.8	2.9	2.9	2.9	3.0	3.0
Human Sewage	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels*	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2
Total	**95.7**	**97.6**	**100.1**	**100.4**	**108.3**	**105.4**	**108.2**	**109.0**

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

fertilizers, cultivation of nitrogen-fixing crops, cultivation of high-organic-content soils, the application of livestock manure on croplands and pasture, the incorporation of crop residues in soils, and direct excretion by animals onto soil. Indirect emissions result from volatilization and subsequent atmospheric deposition of ammonia (NH_3) and oxides of nitrogen (NO_x) and from leaching and surface run-off. These indirect emissions originate from nitrogen applied to soils as fertilizer and from managed and unmanaged livestock wastes.

In 1997, agricultural soil management accounted for 74.1 MMTCE, or 68 percent of U.S. N_2O emissions. From 1990 to 1997, emissions from this source increased by 13 percent as fertilizer consumption and cultivation of nitrogen fixing crops rose.

Fossil Fuel Combustion

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

In 1997, N_2O emissions from mobile sources totaled 17.5 MMTCE, or 16 percent of U.S. N_2O emissions. Emissions of N_2O from stationary sources were 4.1 MMTCE, or 4 percent of U.S. N_2O emissions. From 1990 to 1997, combined N_2O emissions from stationary and mobile sources increased by 22 percent, primarily due to increased rates of N_2O generation in motor vehicles.

Adipic Acid Production

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

In 1997, U.S. adipic acid production emitted 3.9 MMTCE of N_2O, or 4 percent of U.S. N_2O emissions. By the end of 1997, all but one of the four adipic acid plant in the United States were believed to have installed emission control systems that almost eliminate N_2O emissions. Even though adipic acid production increased from 1990 to 1997, emissions from this source decreased by 17 percent, due to the installation of control systems on additional production plants.

Nitric Acid Production

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

Virtually all of the nitric acid manufactured in the United States is produced by the oxidation of ammonia, during which N_2O is formed and emitted to the atmosphere. In 1997, N_2O emissions from nitric acid production were 3.8 MMTCE, or 4 percent of U.S. N_2O emissions. From 1990 to 1997, emissions from this source increased by 14 percent as nitric acid production grew.

Manure Management

Nitrous oxide is produced as part of microbial nitrification and denitrification processes in managed and unmanaged manure, the latter of which is addressed under agricultural soil management. Total N_2O emissions from managed manure systems in 1997 were 3.0 MMTCE, accounting for 3 percent of U.S. N_2O emissions. Emissions increased by 15 percent from 1990 to 1997.

Other Sources

Other sources of N_2O included agricultural reside burning, waste combustion, and human sewage in wastewater treatment systems. In 1997, agricultural residue burning and municipal solid waste combustion each emitted approximately 0.1 MMTCE of N_2O. Although N_2O emissions from wastewater treatment were not fully estimated because of insufficient data availability, the human sewage component of domestic wastewater resulted in emissions of 2.3 MMTCE in 1997.

HFCs, PFCs and SF_6 Emissions

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

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

In addition to their use as substitutes for ozone depleting substances, the other industrial sources of these gases are aluminum production, HCFC-22 production, semiconductor manufacturing, electrical transmission and distribution, and magnesium production and processing. Figure ES-13 and Table ES-11 present emission estimates for HFCs, PFCs, and SF_6, which totaled 37.1 MMTCE in 1997.

Figure ES-13

1997 Sources of HFCs, PFCs, and SF_6

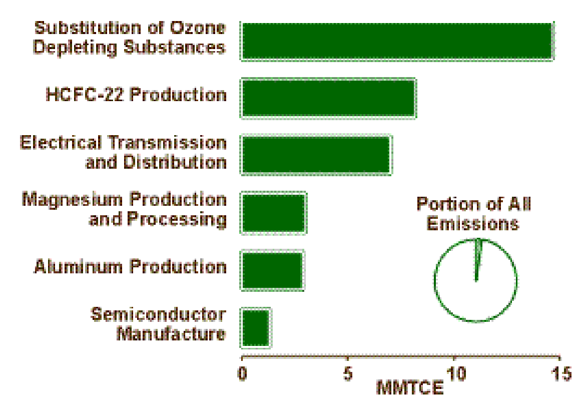


Table ES-11: Emissions of HFCs, PFCs, and SF_6 (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996	1997
Substitution of Ozone Depleting Substances	0.3	0.2	0.4	1.4	4.0	9.5	11.9	14.7
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5	8.2
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	3.0	3.0
Aluminum Production	4.9	4.7	4.1	3.5	2.8	2.7	2.9	2.9
Semiconductor Manufacture	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.3
Total	**22.2**	**21.6**	**23.0**	**23.4**	**25.9**	**30.8**	**34.7**	**37.1**

Note: Totals may not sum due to independent rounding.

Substitution of Ozone Depleting Substances

The use and subsequent emissions of HFCs and PFCs as ODS substitutes increased dramatically from small amounts in 1990 to 14.7 MMTCE in 1997. This increase was the result of efforts to phase-out CFCs and other ODSs in the United States, especially the introduction of HFC-134a as a CFC substitute in refrigeration applications. This trend is expected to continue for many years, and will accelerate in the early part of the next century as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol.*

Other Industrial Sources

HFCs, PFCs, and SF_6 are also emitted from a number of other industrial processes. During the production of primary aluminum, two PFCs (CF_4 and C_2F_6) are emitted as intermittent by-products of the smelting process. Emissions from aluminum production were estimated to have decreased by 41 percent between 1990 and 1997 due to voluntary emission reductions efforts by the industry and falling domestic aluminum production.

HFC-23 is a by-product emitted during the production of HCFC-22. Emissions from this source were 8.2 MMTCE in 1997, and have decreased by 14 percent since 1990 due mainly to voluntary efforts by industry.

The semiconductor industry uses combinations of HFCs, PFCs, and SF_6 for plasma etching and chemical vapor deposition processes. For 1997, it was estimated that the U.S. semiconductor industry emitted a total of 1.3 MMTCE. These gases were not widely used in the industry in 1990.

The primary use of SF_6 is as a dielectric in electrical transmission and distribution systems. Fugitive emissions of SF_6 occur from leaks in and servicing of substations and circuit breakers, especially from older equipment. Estimated emissions from this source increased by 25 percent from 1990, to 7.0 MMTCE in 1997.

Lastly, SF_6 is also used as a protective covergas for the casting of molten magnesium. Estimated emissions from primary magnesium production and magnesium casting were 3.0 MMTCE in 1997, an increase of 76 percent since 1990.

Criteria Pollutant Emissions

In the United States, carbon monoxide (CO), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2) are commonly referred to as "criteria pollutants," as termed in the Clean Air Act. 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. NMVOCs—which include such compounds as propane, butane, and ethane—are emitted primarily from transportation, industrial processes, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from the combustion of fossil fuels and by the metals industry.

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

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

[5] NO_x and CO emission estimates from agricultural burning were estimated separately, and therefore not taken from EPA (1998).

Box ES-4: Emissions of Ozone Depleting Substances

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

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

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

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

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

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

Compound	1990	1991	1992	1993	1994	1995	1996	1997
Class I								
CFC-11	53,500	48,300	45,100	45,400	36,600	36,200	26,600	25,100
CFC-12	112,600	103,500	80,500	79,300	57,600	51,800	35,500	23,100
CFC-113	26,350	20,550	17,100	17,100	8,550	8,550	+	+
CFC-114	4,700	3,600	3,000	3,000	1,600	1,600	300	100
CFC-115	4,200	4,000	3,800	3,600	3,300	3,000	3,200	2,900
Carbon Tetrachloride	32,300	31,000	21,700	18,600	15,500	4,700	+	+
Methyl Chloroform	158,300	154,700	108,300	92,850	77,350	46,400	+	+
Halon-1211	1,000	1,100	1,000	1,100	1,000	1,100	1,100	1,100
Halon-1301	1,800	1,800	1,700	1,700	1,400	1,400	1,400	1,300
Class II								
HCFC-22	79,789	79,540	79,545	71,224	71,386	74,229	77,472	79,620
HCFC-123	+	+	285	570	844	1,094	1,335	1,555
HCFC-124	+	+	429	2,575	4,768	5,195	5,558	5,894
HCFC-141b	+	+	+	1,909	6,529	11,608	14,270	12,113
HCFC-142b	+	+	3,526	9,055	14,879	21,058	27,543	28,315
HCFC-225ca/cb	+	+	+	+	+	565	579	593

Source: EPA Office of Air and Radiation estimates
+ Does not exceed 10 Mg

Since 1970, the United States has published estimates of annual emissions of criteria pollutants (EPA 1998).[5] Table ES-13 shows that fuel combustion accounts for the majority of emissions of these gases. In 1997, fossil fuel combustion by mobile sources emitted 49, 81, and 41 percent of U.S. NO_x, CO, and NMVOC emissions, respectively. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—were also significant sources of CO, NO_x, and NMVOCs.

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

Gas/Activity	1990	1991	1992	1993	1994	1995	1996	1997
NO_x	**21,139**	**21,213**	**21,460**	**21,685**	**21,964**	**21,432**	**21,160**	**21,267**
Stationary Fossil Fuel Combustion	9,884	9,779	9,914	10,080	9,993	9,822	9,543	9,729
Mobile Fossil Fuel Combustion	10,231	10,558	10,659	10,749	10,949	10,732	10,636	10,519
Oil and Gas Activities	139	110	134	111	106	100	100	104
Industrial Processes	771	648	629	603	774	656	754	781
Solvent Use	1	2	2	2	2	3	3	3
Agricultural Burning	30	30	34	28	37	30	34	37
Waste	83	86	87	112	103	89	91	94
CO	**83,056**	**84,776**	**81,764**	**81,696**	**85,729**	**76,699**	**78,350**	**75,158**
Stationary Fossil Fuel Combustion	4,999	5,313	5,583	5,068	5,007	5,383	5,424	4,369
Mobile Fossil Fuel Combustion	66,429	70,256	68,503	68,974	70,655	63,846	63,205	60,794
Oil and Gas Activities	302	313	337	337	307	316	316	330
Industrial Processes	9,580	7,166	5,480	5,500	7,787	5,370	7,523	7,689
Solvent Use	4	4	5	4	5	5	5	6
Agricultural Burning	763	712	824	681	858	703	786	843
Waste	979	1,012	1,032	1,133	1,111	1,075	1,091	1,127
NMVOCs	**18,723**	**18,838**	**18,453**	**18,622**	**19,191**	**18,360**	**17,209**	**17,129**
Stationary Fossil Fuel Combustion	912	975	1,011	901	898	973	978	780
Mobile Fossil Fuel Combustion	7,952	8,133	7,774	7,819	8,110	7,354	7,156	6,949
Oil and Gas Activities	555	581	574	588	587	582	469	488
Industrial Processes	3,193	2,997	2,825	2,907	3,057	2,873	2,521	2,622
Solvent Use	5,217	5,245	5,353	5,458	5,590	5,609	5,691	5,882
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
Waste	895	907	916	949	949	968	393	407
SO_2	**21,870**	**21,258**	**21,076**	**20,729**	**20,187**	**17,741**	**17,972**	**18,477**
Stationary Fossil Fuel Combustion	18,407	17,959	17,684	17,459	17,134	14,724	15,253	15,658
Mobile Fossil Fuel Combustion	1,728	1,729	1,791	1,708	1,524	1,525	1,217	1,252
Oil and Gas Activities	390	343	377	347	344	334	334	349
Industrial Processes	1,306	1,187	1,186	1,159	1,135	1,116	1,125	1,175
Solvent Use	+	+	+	1	1	1	1	1
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
Waste	38	39	39	56	48	42	42	44

Source: (EPA 1998) except for estimates from agricultural burning.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

Box ES-5: Sources and Effects of Sulfur Dioxide

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

Sulfur dioxide is also a major contributor to the formation of urban smog, which can cause significant increases in acute and chronic respiratory diseases. Once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to the Earth as the primary source of acid rain. Because of these harmful effects, the United States has regulated SO_2 emissions in the Clean Air Act. Electric utilities are the largest source of SO_2 emissions in the United States, accounting for 64 percent in 1997. Coal combustion contributes nearly all of those emissions (approximately 96 percent). Sulfur dioxide emissions have significantly decreased in recent years, primarily as a result of electric utilities switching from high sulfur to low sulfur coal.