

## Executive Summary

Central to any study of climate change is the development of an emission inventory that identifies and quantifies a country's primary sources and sinks of greenhouse gases (GHGs). This inventory adheres to both (1) a comprehensive and detailed methodology for estimating sources and sinks of greenhouse gases, and (2) a common, consistent mechanism that enables all signatory countries to the United Nations' Framework Convention on Climate Change (FCCC) to estimate emissions and 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. greenhouse gas emission trends from 1990 through 1996. To ensure that the U.S. emissions inventory is comparable to those of other FCCC signatory countries, the estimates presented here were calculated using methodologies similar to those recommended in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA/UNEP 1997). For emission sources related to energy consumption, land-use change and forestry, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF<sub>6</sub>), and select methane (CH<sub>4</sub>) sources, the IPCC default methodologies were expanded, resulting in a more comprehensive estimate of emissions.

### Recent Trends in U.S. Greenhouse Gas Emissions

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and ozone (O<sub>3</sub>). Several classes of halocarbons that contain fluorine, chlorine, and bromine are also greenhouse gases, but they are, for the most part, emitted solely by human activities. Chlorofluorocarbons (CFCs) and hydrofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as halons. Other fluorine containing halocarbons include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>).

There are also several gases that, although they do not have a direct radiative forcing effect, do influence the formation and destruction of ozone, which does. These gases—referred to as ozone precursors—include carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), and nonmethane volatile organic compounds (NMVOCs). Aerosols—extremely small particles or liquid droplets often produced by emissions of sulfur dioxide (SO<sub>2</sub>)—can affect the absorptive characteristics of the atmosphere.

Although CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O occur naturally in the atmosphere, their recent buildup is largely the result of human activities. Since 1800, atmospheric concentrations of these greenhouse gases have increased by 30, 145, and 15 percent, respectively (IPCC 1996). This buildup has altered the composition of the earth's atmosphere, and may affect global climate system.

Beginning in the 1950's, the use of CFCs and other ozone depleting substance (ODSs) increased by nearly 10 percent a year, until the mid-1980's when international concern about ozone depletion led to the signing of the *Montreal Protocol*. Since then, the consumption of ODSs has rapidly declined as they are phased-out. In contrast, use of ODS substitutes such as HFCs, PFCs, and SF<sub>6</sub> has grown significantly.

Figure ES-1 and Table ES-1 summarize the trends in U.S. greenhouse gas emissions and sinks for 1990 through 1996. 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).

Figure ES-1: Recent Trends in U.S. Greenhouse Gas Emissions

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

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO <sub>2</sub>	1,348.4	1,333.3	1,353.5	1,385.7	1,408.7	1,419.3	1,471.2

Fossil Fuel Combustion	1,331.4	1,316.4	1,336.6	1,367.5	1,389.6	1,398.7	1,450.3
Natural Gas Flaring	2.0	2.2	2.2	3.0	3.0	3.7	3.5
Cement Manufacture	8.9	8.7	8.8	9.3	9.6	9.9	10.1
Lime Manufacture	3.3	3.2	3.3	3.4	3.5	3.7	3.8
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.8	1.8
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2
Carbon Dioxide Manufacture	0.3	0.3	0.4	0.4	0.4	0.4	0.5
Land-Use Change and Forestry (Sink)*	(311.5)	(311.5)	(311.5)	(208.6)	(208.6)	(208.6)	(208.6)
CH <sub>4</sub>	168.2	169.4	170.7	170.4	174.8	177.3	176.7
Stationary Sources	2.4	2.4	2.5	2.4	2.4	2.5	2.6
Mobile Sources	1.5	1.4	1.4	1.4	1.4	1.4	1.4
Coal Mining	24.4	23.3	22.4	20.1	20.8	21.1	19.6
Natural Gas Systems	30.6	31.0	31.5	31.5	31.2	31.0	31.4
Petroleum Systems	1.6	1.6	1.6	1.6	1.6	1.6	1.5
Petrochemical Production	0.3	0.3	0.3	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
Manure Management	14.9	15.4	16.0	16.1	16.7	16.9	16.6
Rice Cultivation	2.5	2.5	2.8	2.5	3.0	2.8	2.5
Agricultural Residue Burning	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
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9
N <sub>2</sub> O	105.8	109.7	113.0	117.7	123.9	126.5	130.2
Stationary Sources	4.3	4.3	4.3	4.4	4.4	4.4	4.6
Mobile Sources	36.7	39.2	42.2	45.0	48.7	52.0	54.7
Adipic Acid	4.7	4.9	4.6	4.9	5.2	5.2	5.4
Nitric Acid	3.4	3.3	3.4	3.5	3.7	3.7	3.8
Manure Management	3.3	3.5	3.5	3.6	3.7	3.6	3.7
Agricultural Soil Management	52.0	52.9	53.5	54.8	56.6	55.9	56.5
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Human Sewage	1.3	1.4	1.4	1.4	1.4	1.4	1.4
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HFCs, PFCs, and SF <sub>6</sub>	22.2	21.9	23.8	24.8	28.0	33.0	36.4
Substitution of Ozone Depleting Substances	0.3	0.3	0.4	1.4	4.0	9.5	11.9
Aluminum Production	4.9	4.9	4.9	4.9	4.9	4.9	4.9
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5
Semiconductor Manufacture	0.2	0.4	0.6	0.8	1.0	1.2	1.4
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	2.7
Total Emissions	1,644.7	1,634.2	1,661.0	1,698.5	1,735.4	1,756.1	1,814.5
Net Emission (Sources and Sinks)	1,333.2	1,322.7	1,349.5	1,490.0	1,526.8	1,547.6	1,606.0

+ Does not exceed 0.05 MMTCE

\* Sinks are only included in net emissions total.

Note: Totals may not sum due to independent rounding.

Figure ES-2: 1996 Greenhouse Gas Emissions by Gas

Figure ES-2 illustrates the relative contribution of the primary greenhouse gases to total U.S. emissions in 1996. The largest source of CO<sub>2</sub> and of overall GHG emissions in the U.S. 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 nitrous oxide 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. PFCs emissions came mainly from primary aluminum production, while electrical transmission and distribution systems emitted the majority of SF<sub>6</sub>.

Total U.S. greenhouse gas emissions rose 10.3 percent in 1996 from 1990 baseline levels, to 1,814.5 MMTCE. The largest single year increase in emissions over this time period was registered in 1996 (58.4 MMTCE or 3.3 percent).

The largest source of U.S. GHG emissions was CO<sub>2</sub> from fossil fuel combustion, which accounted for 80 percent in 1996. Emissions of CO<sub>2</sub> from fossil fuel combustion grew by 9 percent (118.9 MMTCE) over the seven year period and were responsible for over two-thirds of the increase in national emissions. The largest annual increase in emissions from this source was also registered in 1996, when increased fuel consumption drove CO<sub>2</sub> emissions up by 3.7 percent. The primary factors for this later increase in 1996 were (1) fuel switching by electric utilities from natural gas to more carbon intensive coal as gas prices rose sharply, (2) higher petroleum consumption in the transportation sector as travel increased and fuel efficiency stagnated, (3) greater natural gas consumption for heating in the residential sector due to colder weather, and (4) overall robust economic growth.

Other significant trends in emissions over the seven year period of 1990 through 1996 included:

- Combined N<sub>2</sub>O and CH<sub>4</sub> emissions from mobile source fossil fuel combustion rose 17.8 MMTCE (47 percent), primarily due to increased rates of N<sub>2</sub>O generation in new vehicles.
- Aggregate HFC and PFC emissions increased dramatically (by 11.6 MMTCE) as they found applications as substitutes for ozone depleting substances (e.g., CFCs).
- Methane emissions from the decomposition of waste in municipal and industrial landfills rose by 9.9 MMTCE (16 percent) as the amount of organic matter in landfills steadily accumulated.
- Emissions from coal mining dropped by 4.8 MMTCE (20 percent) as the use of methane from degasification systems—with and without energy recovery—increased significantly.
- Nitrous oxide emissions from agricultural soil management increased by 4.5 MMTCE (9 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.

Overall, from 1990 to 1996 total emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O increased by 122.8 (9 percent), 8.5 (5 percent), and 24.4 MMTCE (23 percent), respectively. During the same period, weighted emissions of HFCs, PFCs, and SF<sub>6</sub> rose by 14.2 MMTCE (64 percent). Emissions HFC, PFC, and SF<sub>6</sub> are significant because of their extremely high global warming potentials and, in the cases of PFCs and SF<sub>6</sub>, their long atmospheric lifetimes. Greenhouse gas emissions were partly offset by carbon sequestration in forests.

The following sections present the anthropogenic sources 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.

### ***Global Warming Potentials***

Gases 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 produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The concept of 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<sub>x</sub>, NMVOCs, and SO<sub>2</sub> because there is no agreed upon method to estimate their contribution to climate change. These gases affect radiative forcing indirectly (IPCC 1996).

All gases in this inventory are presented in units of million metric tons of carbon equivalents (MMTCE). Carbon comprises 12/44<sup>ths</sup> of carbon dioxide by weight. In order to convert emissions reported in teragrams (Tg) of GHG to MMTCE, use the following equation:

$$\text{MMTCE} = (\text{Tg of gas}) \times (\text{GWP}) \times \left( \frac{12}{44} \right)$$

The GWP of a greenhouse gas is the ratio of global warming, or radiative forcing (both direct and indirect), from one unit mass of a greenhouse gas to 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 U.S. for policy making and reporting purposes, are used in this report (IPCC 1996). A tabulation of GWPs and is given below in Table ES-2.

Table ES-2: Global Warming Potentials (100 year)

Gas	GWP
Carbon dioxide (CO <sub>2</sub> )	1
Methane (CH <sub>4</sub> )*	21
Nitrous oxide (N <sub>2</sub> O)	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 <sub>4</sub>	6,500
C <sub>2</sub> F <sub>6</sub>	9,200
C <sub>4</sub> F <sub>10</sub>	7,000
C <sub>6</sub> F <sub>14</sub>	7,400
SF <sub>6</sub>	23,900

Source: (IPCC 1997)

\* 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<sub>2</sub> is not included.

## Carbon Dioxide Emissions

Figure ES-3: 1996 Sources of CO<sub>2</sub>

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<sub>2</sub> 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 has been increasingly compromised. Atmospheric concentrations of CO<sub>2</sub> have risen about 28 percent, principally because of fossil fuel combustion, which accounts for 99 percent of total U.S. CO<sub>2</sub> emissions (IPCC 1996). Changes in land-use and forestry practices can emit CO<sub>2</sub> (e.g., through conversion of forest land to agricultural or urban use) or can act as a sink for CO<sub>2</sub> (e.g., through net additions to forest biomass).

Table ES-3 summarizes U.S. sources and sinks of CO<sub>2</sub>, while the remainder of this section discusses CO<sub>2</sub> emission trends in greater detail.

Table ES-3: U.S. Sources of CO<sub>2</sub> Emissions and Sinks (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996
Fossil Fuel Combustion	1,331.4	1,316.4	1,336.6	1,367.5	1,389.6	1,398.7	1,450.3
Natural Gas Flaring	2.0	2.2	2.2	3.0	3.0	3.7	3.5
Cement Manufacture	8.9	8.7	8.8	9.3	9.6	9.9	10.1

Lime Manufacture	3.3	3.2	3.3	3.4	3.5	3.7	3.8
Limestone and Dolomite Use	1.4	1.3	1.2	1.1	1.5	1.8	1.8
Soda Ash Manufacture and Consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2
Carbon Dioxide Manufacture	0.3	0.3	0.4	0.4	0.4	0.4	0.5
Land-Use Change and Forestry (Sink)*	(311.5)	(311.5)	(311.5)	(208.6)	(208.6)	(208.6)	(208.6)
Total Emissions	1,348.4	1,333.3	1,353.5	1,385.7	1,408.7	1,419.3	1,471.2
Net Emissions (Sources and Sinks)	1,036.9	1,021.8	1,042.0	1,177.1	1,200.1	1,210.8	1,262.7

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

## Energy Sector

Energy related activities accounted for 86 percent of U.S. greenhouse gas emissions in 1996. Carbon dioxide from fossil fuel combustion was the main contributor, although CH<sub>4</sub> and N<sub>2</sub>O were also emitted. Approximately 85 percent of U.S. energy was produced through the combustion of fossil fuels in 1996. The remaining 15 percent came from renewable or other energy sources such as hydropower, biomass, and nuclear energy (see Figure ES-4). 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 methane). A discussion of specific Energy sector trends is presented below.

Figure ES-4: 1996 U.S. Energy Consumption

### Fossil Fuel Combustion

As fossil fuels are combusted, the carbon stored in them is emitted as CO<sub>2</sub>. The amount of carbon in the fuel 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. Petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent of total energy consumption over the 1990 through 1996 period. Natural gas and coal followed in order of importance, accounting for an average of 24 and 22 percent of total consumption, respectively. Most petroleum was consumed in the transportation sector, while the vast majority of coal is used by electric utilities, with natural gas consumed largely in the industrial and residential sectors.

Emissions of CO<sub>2</sub> from fossil fuel combustion increased at an annualized rate of 1.4 percent from 1990 to 1996. The primary factors behind this trend were (1) a robust domestic economy, (2) relatively low energy prices, and (3) fuel switching by electric utilities. After 1990, when CO<sub>2</sub> emissions from fossil fuel combustion were 1,331 MMTCE, there was a slight decline in emissions in 1991, followed by an increase to 1,454 MMTCE in 1996. Overall, CO<sub>2</sub> emissions from fossil fuel combustion increased by 9 percent over the seven year period and rose by a dramatic 3.7 percent in the final year alone.

From 1995 to 1996, absolute emissions from coal grew the most (an increase of 25.5 MMTCE or 5 percent), while emissions from natural gas changed the least (an increase of 3.8 MMTCE or 1 percent) as electric utilities increased their consumption of coal, while shifting away from natural gas because of higher gas prices. Alone, emissions from electric utility coal combustion increased by over 6 percent from 1995 to 1996.

Despite slightly higher prices, the consumption of petroleum products in 1996 increased 3.5 percent from the previous year, accounting for about 43 percent of the increase in CO<sub>2</sub> emissions from fossil fuel combustion. More than half of the increase in emissions from petroleum was due to higher fuel consumption for transportation purposes.

From 1995 to 1996, emissions from natural gas rose only 1.2 percent, largely due to higher natural gas prices in 1996 that reversed a 10 year long trend of declining prices. The U.S. Department of Energy's Energy Information Administration cited low levels of storage and unusually cold weather as the two main reasons for this price increase (EIA 1997). Natural gas related emissions from the residential sector rose by 7.9 percent while the utility sector experienced a dramatic 14.6 percent decrease. This sharp reduction can be explained by a 33 percent increase in the price of natural gas for utilities (EIA 1997).

Table ES-4: CO<sub>2</sub> Emissions from Fossil Fuel Combustion by End-Use Sector (MMTCE)

End-Use Sector	1990	1991	1992	1993	1994	1995	1996
Residential	253.0	257.0	255.7	271.6	268.6	269.7	286.7
Commercial	206.7	206.4	205.3	212.2	214.1	219.2	229.9
Industrial	453.1	441.6	459.0	459.0	468.1	465.7	477.5
Transportation	409.6	400.8	406.7	414.1	427.4	432.8	445.5
U.S. Territories	9.1	10.7	9.8	10.6	11.4	11.2	10.8
Total	1331.4	1316.4	1336.6	1367.5	1389.6	1398.7	1450.3

Note: Totals may not sum due to independent rounding.

Figure ES-5: 1996 CO<sub>2</sub> Emissions from Fossil Fuel Combustion by End-Use Sector and Fuel Type

*Industrial Sector.* Industry accounted for the largest percentage of U.S. emissions from fossil fuel consumption (see Figure ES-5). About two-thirds of these emissions result from producing steam and process heat from fossil fuel combustion, while the remaining third results from providing electricity for such uses as motors, electric furnaces, ovens, and lighting.

*Transportation Sector.* Transportation activities accounted for 31 percent of CO<sub>2</sub> emissions from fossil fuel combustion. Virtually all of the energy consumed in this sector came from petroleum products. Nearly two thirds of the emissions resulted from gasoline consumption motor vehicles. The remaining emissions result from other transportation activities, including the combustion of diesel fuel for heavy-duty vehicles and jet fuel for aircraft.

*Residential and Commercial Sectors.* The residential and commercial sectors accounted for, on average, 19 and 16 percent, respectively, of CO<sub>2</sub> emissions from fossil fuel consumption. Both sectors relied heavily on electricity for meeting energy needs, with about two-thirds and three-quarters of their emissions attributable to electricity consumption, respectively, 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 27 percent of U.S. energy and are the largest emitters of CO<sub>2</sub> from fossil fuel consumption (36 percent). The type of fuel combusted by utilities has a significant effect on their emissions. For example, some electricity is generated with low CO<sub>2</sub> 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 U.S. in 1996. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO<sub>2</sub> emissions.

### Natural Gas Flaring

Carbon dioxide is produced when methane trapped in natural gas systems or oil wells is flared (i.e., combusted) to relieve the rising pressure or to dispose of small quantities of gas that are not commercially marketable. In 1996, flaring activities emitted approximately 3.5 MMTCE, or about 0.2 percent of total U.S. CO<sub>2</sub> emissions.

### Biomass Combustion

Biomass in the form of fuel wood and wood waste is used primarily by the industrial sector, while the transportation sector dominates the use of biomass-based fuel, 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<sub>2</sub>, in the long run the CO<sub>2</sub> emitted from biomass consumption does not increase atmospheric carbon dioxide concentrations, assuming 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 the Land-Use Change and Forestry sector.

CO<sub>2</sub> emissions from biomass combustion were 54.6 MMTCE, with the industrial sector accounting for 71 percent of the emissions, and the residential sector, 24 percent. Ethanol consumption by the transportation sector accounted for only 3 percent of CO<sub>2</sub> 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 from one state to another. This transformation often releases greenhouse gases such as CO<sub>2</sub>. The production processes that emit CO<sub>2</sub> include cement manufacture, lime manufacture, limestone and dolomite use (e.g., in iron and steel making), soda ash manufacture and consumption, and CO<sub>2</sub> manufacture. Total carbon dioxide emissions from these sources were approximately 17.4 MMTCE in 1996, accounting for about 1 percent of total CO<sub>2</sub> emissions. Since 1990, emissions from each of these sources increased, while emissions from soda ash production remained relatively constant.

### **Cement Manufacture (10.1 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<sub>2</sub> is created when calcium carbonate (CaCO<sub>3</sub>) is heated in a cement kiln to form lime and CO<sub>2</sub>. This lime combines with other materials to produce clinker, while the CO<sub>2</sub> is released into the atmosphere.

### **Lime Manufacture (3.8 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<sub>3</sub>) in a kiln, creating calcium oxide (quicklime) and CO<sub>2</sub>, which is normally emitted to the atmosphere.

### **Limestone and Dolomite Use (1.8 MMTCE)**

Limestone (CaCO<sub>3</sub>) and dolomite (CaCO<sub>3</sub>MgCO<sub>3</sub>) are a 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<sub>2</sub> 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<sub>2</sub>CO<sub>3</sub>) is used in many consumer products, such as glass, soap and detergents, paper, textiles, and food. During the manufacturing of these products, natural sources of sodium carbonate are heated and transformed into a crude soda ash, in which CO<sub>2</sub> is generated as a by-product. In addition, CO<sub>2</sub> is released when the soda ash is consumed.

### **Carbon Dioxide Manufacture (0.5 MMTCE)**

Carbon dioxide is used in many segments of the economy, including food processing, beverage manufacturing, chemical processing, crude oil drilling, and a host of industrial and miscellaneous applications. For the most part, the CO<sub>2</sub> used in these applications is eventually released to the atmosphere.

## Land-Use Change and Forestry

When humans use and alter the biosphere through changes in land-use and forest management practices, they alter the natural balance between carbon stored in the atmosphere and in biomass and soils. These practices include forest clearing to create cropland or pasture, timber re-growth on logged forest lands, wetland draining, and reversion of pasture to a grassland or forest.

Forests, which cover about 295 million hectares (737 million acres) of U.S. land in the contiguous 48 states (Powell 1993), are an important terrestrial sink for CO<sub>2</sub>. Because approximately half the dry weight of wood is carbon, as trees add mass to trunks, limbs, and roots, carbon is stored in relatively long-lived biomass instead of being released to the atmosphere. Soils and vegetative cover also provide potential sinks for carbon emissions.

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. 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.

As a result of these activities, the net CO<sub>2</sub> flux in 1996 was estimated to have been an uptake of 208.6 MMTCE. This net sequestration of carbon includes forest trees, understory, forest floor litter, soils, and carbon stored in the U.S. wood product pools and landfills. This carbon uptake represents an offset of about 14 percent of the 1996 CO<sub>2</sub> emissions from fossil fuel combustion during this period. The amount of carbon sequestered through changes in U.S. forestry and land-use practices continued to decline, as the expansion of eastern forest cover slowed.

## Methane Emissions

Figure ES-6: 1996 Sources of CH<sub>4</sub>

Atmospheric methane (CH<sub>4</sub>) is an integral component of the greenhouse effect, second only to CO<sub>2</sub> as a contributor to anthropogenic greenhouse gas emissions. Methane's overall contribution to global warming is significant because it is estimated to be twenty-one times more effective at trapping heat in the atmosphere than CO<sub>2</sub>. Over the last two centuries, methane's concentration in the atmosphere has more than doubled (IPCC 1996). Scientists believe these atmospheric increases are due largely to increasing emissions from anthropogenic sources, such as landfills, natural gas and petroleum systems, agricultural activities, coal mining, fossil fuel combustion, wastewater treatment, and certain industrial processes (see Table ES-5).

Table ES-5: U.S. Sources of Methane Emissions (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996
Stationary Sources	2.4	2.4	2.5	2.4	2.4	2.5	2.6
Mobile Sources	1.5	1.4	1.4	1.4	1.4	1.4	1.4
Coal Mining	24.4	23.3	22.4	20.1	20.8	21.1	19.6
Natural Gas Systems	30.6	31.0	31.5	31.5	31.2	31.0	31.4
Petroleum Systems	1.6	1.6	1.6	1.6	1.6	1.6	1.5
Petrochemical Production	0.3	0.3	0.3	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
Manure Management	14.9	15.4	16.0	16.1	16.7	16.9	16.6
Rice Cultivation	2.5	2.5	2.8	2.5	3.0	2.8	2.5
Agricultural Residue Burning	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
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Total	168.2	169.4	170.7	170.4	174.8	177.3	176.7

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

## 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<sub>2</sub>.

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 1996 were 65.1 MMTCE, a 16 percent increase since 1990 due the steady accumulation of wastes in landfills. Emissions from U.S. municipal solid waste landfills, which received about 62 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 1996 was recovered and combusted, often for energy recovery.

A regulation promulgated in March 1996 requires the largest U.S. landfills to collect and combust their landfill gas to reduce emissions of nonmethane volatile organic compounds (NMVOCs). It is estimated that by the year 2000, this regulation will have reduced landfill methane emissions by more than 50 percent.

## Natural Gas and Petroleum Systems

Methane is the major component of natural gas. During the production, processing, transmission, and distribution of natural gas, fugitive emissions of methane often occur. Because natural gas is often found in conjunction with petroleum deposits, leakage from petroleum systems is also a source of emissions. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment condition. In 1996, emissions from U.S. natural gas systems were estimated to be 31.4 MMTCE, accounting for approximately 18 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 1996, emissions from petroleum systems were estimated to be 1.5 MMTCE, or 1 percent of U.S. methane emissions.

From 1990 to 1996, combined emissions from natural gas and petroleum systems increased by just 2 percent as the number of gas producing wells and miles of distribution pipeline rose.

## Agriculture Sector

The Agricultural sector accounted for approximately 30 percent of U.S. methane emissions in 1996, 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. Between 1990 and 1996, methane emissions from domestic livestock enteric fermentation and manure management increased by about 6 percent and 11 percent, respectively. During this same time period, methane emissions from rice cultivation decreased slightly.

### **Enteric Fermentation in Domestic Livestock (34.5 MMTCE)**

During animal digestion, methane is produced through the process of enteric fermentation, in which microbes that reside 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 1996, enteric fermentation was the source of about 20 percent of U.S. methane emissions, and about 64 percent of methane emissions from the Agricultural sector. From 1990 to 1996, emissions from this source increased by almost 6 percent due mainly to increased livestock populations.

### **Manure Management (16.6 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 1996, and about 31 percent of methane emissions from the Agriculture sector. From 1990 to 1996, emissions from this source increased by 11 percent because of larger farm animal populations and expanded use of liquid manure management systems.

### **Rice Cultivation (2.5 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 1996, rice cultivation was the source of less than 2 percent of total U.S. methane emissions, and about 5 percent of U.S. methane emissions from the Agricultural sector. Emissions estimates from this source did not change significantly from 1990 levels.

### **Agricultural Residue Burning (0.2 MMTCE)**

Burning crop residues releases a number of greenhouse gases, including methane. Agricultural residue burning is not considered to be a net source of carbon dioxide emissions because the CO<sub>2</sub> released during burning is 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 1996.

## **Coal Mining**

Produced millions of years ago during the formation of coal, methane is trapped within coal seams and surrounding rock strata that 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 is 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 1996, coal mining activities emitted 19.6 MMTCE of methane, or 11 percent of U.S. methane emissions. From 1990 to 1996, emissions from this source decreased by almost 5 percent due to increased use of degasification systems, which combust the methane with and without energy recovery.

## **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 2.6 and 1.4 MMTCE, respectively in 1996. 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**

Figure ES-7: 1996 Sources of N<sub>2</sub>O

Nitrous oxide (N<sub>2</sub>O) is a chemically and radiatively active greenhouse gas that is produced naturally from a wide variety of biological sources in soil and water. While N<sub>2</sub>O emissions are much lower than CO<sub>2</sub> emissions, N<sub>2</sub>O is approximately 310 times more powerful than CO<sub>2</sub> at trapping heat in the atmosphere (IPCC 1996).

During the past two centuries, human activities have raised atmospheric concentrations of N<sub>2</sub>O by approximately 13 percent. The main anthropogenic activities producing N<sub>2</sub>O were fossil fuel combustion, agricultural soil management, and adipic and nitric acid production (see Table ES-6).

Table ES-6: U.S. Sources of Nitrous Oxide Emissions (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996
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Stationary Sources	4.3	4.3	4.3	4.4	4.4	4.4	4.6
Mobile Sources	36.7	39.2	42.2	45.0	48.7	52.0	54.7
Adipic Acid	4.7	4.9	4.6	4.9	5.2	5.2	5.4
Nitric Acid	3.4	3.3	3.4	3.5	3.7	3.7	3.8
Manure Management	3.3	3.5	3.5	3.6	3.7	3.6	3.7
Agricultural Soil Management	52.0	52.9	53.5	54.8	56.6	55.9	56.5
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Waste Combustion	1.3	1.4	1.4	1.4	1.4	1.4	1.4
Human Sewage	0.1	0.1	0.1	0.1	0.1	0.1	0.1
<b>Total Emissions</b>	<b>105.8</b>	<b>109.7</b>	<b>113.0</b>	<b>117.7</b>	<b>123.9</b>	<b>126.5</b>	<b>130.2</b>

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

## 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, or pollution control device used, as well as maintenance and operating practices.

For example, catalytic converters installed to reduce mobile source pollution have unintentionally promoted the formation of  $N_2O$ . As the number of catalytic converter-equipped vehicles has risen in the U.S. motor vehicle fleet, so have emissions of  $N_2O$  from mobile sources.

In 1996,  $N_2O$  emissions from mobile sources totaled 54.7 MMTCE, or 42 percent of U.S.  $N_2O$  emissions. Emissions of  $N_2O$  from stationary sources were 4.6 MMTCE, or less than 4 percent of U.S.  $N_2O$  emissions. From 1990 to 1996, combined  $N_2O$  emissions from stationary and mobile sources increased by more than 44 percent, primarily due to increased rates of  $N_2O$  generation in new vehicles.

## Agricultural Soil Management

Nitrous oxide ( $N_2O$ ) is produced naturally in soils through microbial processes. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as  $N_2O$  by these microbial processes. Direct additions of nitrogen occur through the application of synthetic and organic fertilizers, production of nitrogen-fixing crops, cultivation of high organic content soils, and the application of livestock manure on croplands and pasture. Indirect additions occur through volatilization and subsequent atmospheric deposition of ammonia ( $NH_3$ ) and oxides of nitrogen ( $NO_x$ ) that originate from the direct application of nitrogen.

In 1996, agricultural soil management accounted for 56.5 MMTCE, or approximately 43 percent of U.S.  $N_2O$  emissions. From 1990 to 1996, emissions from this source increased by more than 4 percent as fertilizer consumption and cultivation of nitrogen fixing crops rose.

## Adipic Acid Production

The vast majority of all 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 1996, U.S. adipic acid production emitted 5.4 MMTCE of nitrous oxide, or 4 percent of U.S.  $N_2O$  emissions. By the end of 1997, all adipic acid production plants in the United States are expected to have  $N_2O$  controls in place that will almost eliminate emissions. (Half of the plants had these controls in place and operating in 1996.) From 1990 to 1996, emissions from this source increased by 14 percent as adipic acid production grew.

## 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 1996,  $N_2O$  emissions from nitric acid production were 3.8

MMTCE, or for 4 percent of U.S. N<sub>2</sub>O emissions. From 1990 to 1996, emissions from this source increased by 14 percent as nitric acid production grew.

## Manure Management

Nitrous oxide is produced as part of microbial denitrification processes in managed and unmanaged manure, the latter of which is addressed under agricultural soil management. Total N<sub>2</sub>O emissions from managed manure systems in 1996 were 3.7 MMTCE, accounting for less than 3 percent of U.S. N<sub>2</sub>O emissions. Emission increased by 12 percent from 1990 to 1996, most of which can be attributed to increased quantities of managed manure from beef cattle in feedlots.

## Other Sources

Other sources of N<sub>2</sub>O include agricultural residue burning, waste combustion, and human sewage in wastewater treatment systems. In 1996, agricultural residue burning and municipal solid waste combustion each emitted approximately 0.1 MMTCE of N<sub>2</sub>O. Although N<sub>2</sub>O emissions from wastewater treatment were not fully estimated because insufficient data was available, the human sewage component of domestic wastewater produced 1.4 MMTCE in 1996.

## HFCs, PFCs and SF<sub>6</sub> Emissions

Figure ES-8: 1996 Sources of HFCs, PFCs, and SF<sub>6</sub>

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

However, many of these compounds, along with sulfur hexafluoride (SF<sub>6</sub>), are potent greenhouse gases. In addition to having high global warming potentials, SF<sub>6</sub> and most 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. Table ES-7 presents emission estimates for HFCs, PFCs, and SF<sub>6</sub>, which totaled 36.4 MMTCE in 1996.

Table ES-7: Emissions of HFCs, PFCs, and SF<sub>6</sub> (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996
Substitution of Ozone Depleting Substances	0.3	0.3	0.4	1.4	4.0	9.5	11.9
Aluminum Production	4.9	4.9	4.9	4.9	4.9	4.9	4.9
HCFC-22 Production	9.5	8.4	9.5	8.7	8.6	7.4	8.5
Semiconductor Manufacture	0.2	0.4	0.6	0.8	1.0	1.2	1.4
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0
Magnesium Production and Processing	1.7	2.0	2.2	2.5	2.7	3.0	2.7
Total	22.2	21.9	23.8	24.8	28.0	33.0	36.4

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 11.9 MMTCE in 1996. This increase was the result of efforts to phase-out CFCs and other ODSs in the U.S., especially the substitution of CFCs with HFC-134a 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

HFC, PFC, and SF<sub>6</sub> are also emitted from a number of other industrial processes. During the production of primary aluminum, two PFCs (CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>) are emitted as by-products of the smelting process. Emissions from aluminum production were estimated to have remained constant between 1990 and 1996 at 4.9 MMTCE.

HFC-23 is a by-product emitted during the production of HCFC-22. Emissions from this source were 8.5 MMTCE in 1996, and have decreased by 11 percent since 1990.

The semiconductor industry uses combinations of HFCs, PFCs, and SF<sub>6</sub> for plasma etching and chemical vapor deposition processes. For 1996, it was estimated that the U.S. semiconductor industry emitted a total of 1.3 MMTCE. These gases were not widely used in by the industry in 1990.

The primary use of SF<sub>6</sub> is as a dielectric in electrical transmission and distribution systems. Fugitive emissions of SF<sub>6</sub> 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 1996.

SF<sub>6</sub> is also used as a protective covergas for the casting of molten magnesium. Estimated emissions from primary magnesium production and magnesium die casting were 2.7 MMTCE in 1996, and increase of 59 percent since 1990.

### BOX: 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 U.S. 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 U.S. believes, however, that an emissions inventory is incomplete without these emissions; therefore, estimates for several Class I and Class II ODSs are provided in Table ES-8. Compounds are classified 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 large direct GWPs, their indirect effects from ozone—also a greenhouse gas—destruction are believed to be negative, and therefore could significantly reduce the 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-8: Emissions of Ozone Depleting Substances (Metric Tons)

Compound	1990	1991	1992	1993	1994	1995	1996
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Class I

CFC-11	53,500	48,300	45,100	45,400	36,600	36,200	26,600
CFC-12	112,600	103,500	80,500	79,300	57,600	51,800	35,500
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
CFC-115	4,200	4,000	3,800	3,600	3,300	3,000	3,200
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
Halon-1301	1,800	1,800	1,700	1,700	1,400	1,400	1,400
Class II							
HCFC-22	79,789	79,540	79,545	71,224	71,386	74,229	77,472
HCFC-123	+	+	285	570	844	1,094	1,335
HCFC-124	+	+	429	2,575	4,768	5,195	5,558
HCFC-141b	+	+	+	1,909	6,529	11,608	14,270
HCFC-142b	+	+	3,526	9,055	14,879	21,058	27,543
HCFC-225ca/cb	+	+	+	+	+	565	579

Source: EPA estimates

+ Does not exceed 10 Metric Tons

### Criteria Pollutant Emissions

In the United States, carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide (SO<sub>2</sub>) are commonly referred to as "criteria pollutants." CO is produced when carbon containing fuels are combusted incompletely. Oxides of nitrogen (NO and NO<sub>2</sub>) 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<sub>2</sub> is primarily emitted with the combustion of fossil fuels and by the metals industry.

Because of their contribution to the formation of urban smog (and acid rain in the case of SO<sub>2</sub>), criteria pollutants are regulated under the Clean Air Act. These gases, however, also indirectly effect global climate by reacting with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Unlike other criteria pollutants, SO<sub>2</sub> emitted into the atmosphere affects the Earth's radiative budget negatively; therefore, it is discussed separately.

The most important of the indirect 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 (OH<sup>-</sup>)—the major atmospheric sink for methane emissions—to form CO<sub>2</sub>. Therefore, increased atmospheric concentrations of CO limit the number of OH<sup>-</sup> molecules available to destroy methane.

Since 1970, the United States has published estimates of annual emissions of criteria pollutants (EPA 1997). Table ES-9 shows that fuel consumption accounts for the majority of emissions of these gases. Fossil fuel combustion by mobile sources emitted approximately 83 percent of U.S. CO emissions in 1996. Mobile sources also emitted roughly half of U.S. NO<sub>x</sub> and NMVOC emissions. 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<sub>x</sub>, and NMVOCs.

Table ES-9: Emissions of NO<sub>x</sub>, CO, NMVOCs, and SO<sub>2</sub> (Gg)

Gas/Activity	1990	1991	1992	1993	1994	1995	1996
NO <sub>x</sub>	21,227	21,251	21,577	21,889	22,276	21,440	21,472
Stationary Fossil Fuel Combustion	9,635	9,532	9,664	9,816	9,728	9,558	9,775
Mobile Fossil Fuel Combustion	10,423	10,695	10,876	11,065	11,373	10,851	10,656
Oil and Gas Activities	139	110	134	112	106	100	100

Industrial Processes	922	802	783	759	932	814	820
Solvent Use	1	2	2	2	2	3	3
Agricultural Burning	30	30	34	27	37	30	34
Waste	77	81	83	106	98	84	85
CO	82,016	83,721	80,712	80,655	84,722	75,480	74,681
Stationary Fossil Fuel Combustion	4,911	5,226	5,496	4,979	4,920	5,294	5,320
Mobile Fossil Fuel Combustion	65,618	69,418	67,670	68,175	69,879	62,858	61,931
Oil and Gas Activities	302	313	337	337	307	316	316
Industrial Processes	9,526	7,124	5,437	5,453	7,744	5,329	5,338
Solvent Use	4	4	5	4	5	5	5
Agricultural Burning	768	718	833	674	858	704	783
Waste	887	917	934	1,033	1,010	973	988
NMVOCs	18,306	18,413	18,026	18,209	18,781	17,983	16,481
Stationary Fossil Fuel Combustion	900	964	999	889	883	960	962
Mobile Fossil Fuel Combustion	7,759	7,933	7,581	7,641	7,945	7,229	7,048
Oil and Gas Activities	539	565	558	573	572	566	456
Industrial Processes	3,038	2,842	2,665	2,745	2,890	2,699	1,970
Solvent Use	5,217	5,245	5,353	5,458	5,590	5,609	5,691
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
Waste	854	863	870	903	901	921	354
SO <sub>2</sub>	21,379	20,751	20,553	20,195	19,634	17,163	17,958
Stationary Fossil Fuel Combustion	18,407	17,958	17,683	17,458	17,134	14,723	15,514
Mobile Fossil Fuel Combustion	1,237	1,222	1,266	1,166	965	947	945
Oil and Gas Activities	390	343	377	347	344	335	334
Industrial Processes	1,307	1,188	1,187	1,159	1,136	1,116	1,122
Solvent Use	+	+	+	1	1	1	1
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
Waste	37	40	39	64	54	42	42

Source: (EPA 1997)

Note: Totals may not sum due to independent rounding.

#### BOX: Sources and Effects of Sulfur Dioxide

Sulfur dioxide (SO<sub>2</sub>) 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<sub>2</sub> derived aerosols on radiative forcing is believed to be negative (IPCC 1996). However, because SO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions in the Clean Air Act.

Electric utilities are the largest source of SO<sub>2</sub> emissions in the U.S., accounting for 67 percent in 1996. Coal combustion contributes nearly all of those emissions (approximately 95 percent). SO<sub>2</sub> emissions have significantly decreased in recent years, as electric utilities have switched from high sulfur coal to lower sulfur coal and natural gas.