Executive Summary

Central to any study of climate change is the development of an emission inventory that identifies and quantifies a country's primary anthropogenic 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 (FCCC) 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 1996.[1] 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 1997). For emission sources related to energy consumption, land-use change and forestry, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and select methane (CH_4) sources, the IPCC default methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

Recent Trends in U.S. Greenhouse Gas 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, although they do not have a direct global warming effect, do influence the formation and destruction of ozone, which does have such a terrestrial radiation absorbing effect. These gases–referred to here as ozone precursors–include carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane volatile organic compounds (NMVOCs).[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.

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[1] See Introduction chapter for discussion of changes in this inventory relative to previous U.S. greenhouse gas inventories.

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

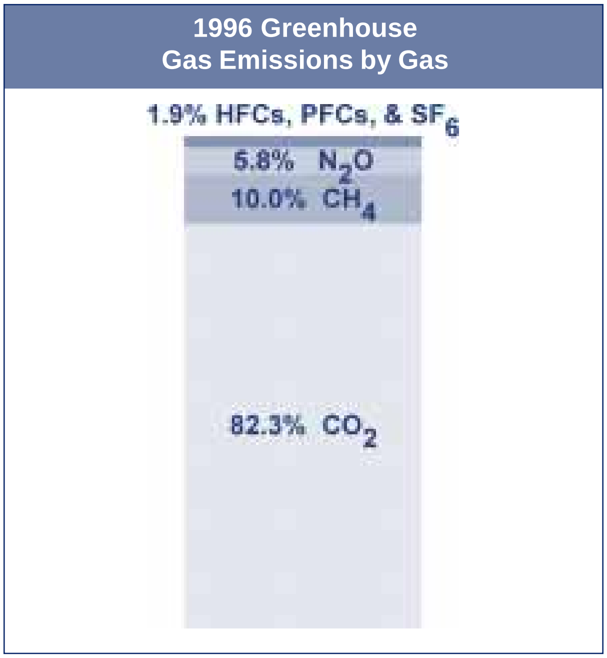
Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, the atmospheric concentration of each of them has risen, largely as a result of human activities. Since 1800, atmospheric concentrations of these greenhouse gases have increased by 30, 145, and 15 percent, respectively (IPCC 1996). This build-up has altered the composition of the earth's atmosphere, and may affect the global climate system.

Beginning in the 1950s, the use of CFCs and other ozone depleting substances (ODSs) increased by nearly 10 percent a year, until the mid-1980s 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_6 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-2 illustrates the relative contribution of the primary greenhouse gases to total U.S. emissions in 1996. The largest source of CO_2 and of overall GHG 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 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. PFC emissions came mainly from primary aluminum production, while electrical transmission and distribution systems emitted the majority of SF_6.

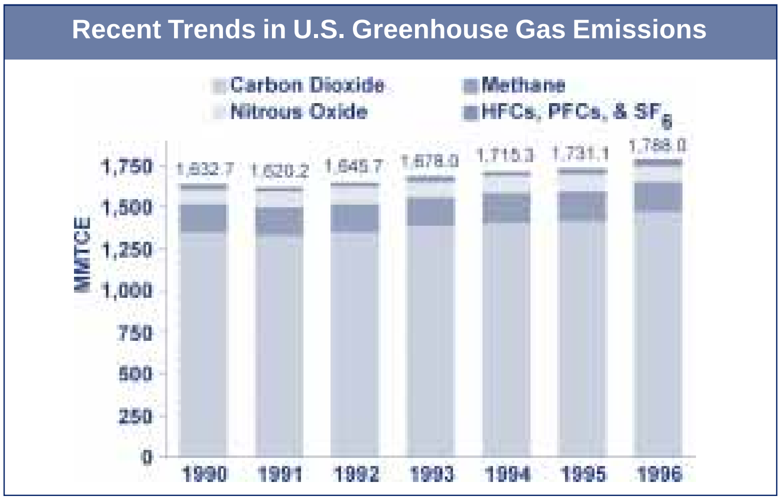
Figure ES-2



1996 Greenhouse Gas Emissions by Gas

Total U.S. greenhouse gas emissions rose in 1996 to 1,788.0 MMTCE (9.5 percent above 1990 baseline levels). The largest single year increase in emissions over this time period was registered in 1996 (57.0 MMTCE or 3.3 percent).

Figure ES-1



Recent Trends in U.S. Greenhouse Gas Emissions

The largest source of U.S. GHG emissions was CO_2 from fossil fuel combustion, which accounted for 81 percent in 1996. Emissions of CO_2 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_2 emissions up by 3.7 percent. The primary factors for this later single year increase

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

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO_2	**1,348.3**	**1,333.2**	**1,353.4**	**1,385.6**	**1,408.5**	**1,419.2**	**1,471.1**
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	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Land-Use Change and Forestry (Sink)*	(311.5)	(311.5)	(311.5)	(208.6)	(208.6)	(208.6)	(208.6)
CH_4	**169.9**	**171.1**	**172.5**	**171.9**	**175.9**	**179.2**	**178.6**
Stationary Sources	2.3	2.3	2.4	2.3	2.3	2.4	2.5
Mobile Sources	1.5	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
Natural Gas Systems	32.9	33.3	33.9	34.1	33.9	33.8	34.1
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_2O	**92.3**	**94.4**	**96.8**	**97.1**	**104.9**	**101.9**	**103.7**
Stationary Sources	3.7	3.7	3.7	3.8	3.8	3.8	4.0
Mobile Sources	13.2	13.9	14.8	15.6	16.3	16.6	16.5
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	2.6	2.8	2.8	2.9	2.9	2.9	3.0
Agricultural Soil Management	62.4	63.4	65.2	64.1	70.4	67.2	68.6
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Human Sewage	2.1	2.1	2.2	2.2	2.3	2.2	2.3
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HFCs, PFCs, and SF_6	**22.2**	**21.6**	**23.0**	**23.4**	**25.9**	**30.8**	**34.7**
Substitution of Ozone Depleting Substances	0.3	0.2	0.4	1.4	4.0	9.5	11.9
Aluminum Production	4.9	4.7	4.1	3.5	2.8	2.7	2.9
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	3.0
Total Emissions	**1,632.7**	**1,620.2**	**1,645.7**	**1,678.0**	**1,715.3**	**1,731.1**	**1,788.0**
Net Emission (Sources and Sinks)	**1,321.2**	**1,308.7**	**1,334.2**	**1,469.4**	**1,506.7**	**1,522.5**	**1,579.5**

+ Does not exceed 0.05 MMTCE

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

Note: Totals may not sum due to independent rounding.

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 end-use sector as travel increased and fuel efficiency stagnated, (3) greater natural gas consumption for heating in the residential end-use sector due to colder weather, and (4) overall robust domestic economic growth.

- Other significant trends in emissions over the seven year period of 1990 through 1996 included:
- Combined N_2O and CH_4 emissions from mobile source fossil fuel combustion rose 3.2 MMTCE (22 percent), primarily due to increased rates of N_2O generation in highway vehicles.
- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased dramatically (by 11.6 MMTCE); however PFC emissions from aluminum production decreased significantly (41 percent) as a result of both voluntary industry emission reduction efforts and falling domestic aluminum production.
- Methane emissions from the decomposition of waste in municipal and industrial landfills rose by 8.9 MMTCE (16 percent) as the amount of organic matter in landfills steadily accumulated.
- Emissions from coal mining dropped by 5.1 MMTCE (21 percent) as the use of methane from degasification systems increased significantly.
- Nitrous oxide emissions from agricultural soil management increased by 6.2 MMTCE (10 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.

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 15 percent since 1990–and gallons of gasoline consumed each year in the United States has 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 was 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 were major sources of carbon monoxide, carbon dioxide (CO_2), methane (CH_4), nonmethane volatile organic compounds, nitrogen oxides, nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). Motor vehicles were 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 recently 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. Now, 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-2 summarizes greenhouse gas emissions from all transportation related activities. Overall, transportation activities accounted for an almost constant 26 percent of total U.S. greenhouse gas emissions from 1990 to 1996. These emissions were primarily CO_2 from fuel combustion, which increased by 8.8 percent from 1990 to 1996. However, because of larger increases in N_2O and HFC emissions during this period, overall emissions from transportation activities actually increased by 10.1 percent.

Table ES-2: Transportation Related Greenhouse Gas Emissions (MMTCE)

Gas/Vehicle Type	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
CO_2	**409.6**	**400.8**	**406.7**	**414.1**	**427.4**	**432.8**	**445.5**
Passenger Cars[a]	169.3	167.8	172.0	173.5	172.5	160.0	163.2
Light-Duty Trucks[a]	77.5	77.2	77.2	80.5	87.2	104.9	107.1
Other Trucks	56.8	54.7	56.6	59.7	62.4	64.0	67.0
Buses	2.7	2.9	2.9	3.0	3.3	3.5	3.7
Aircraft	55.9	53.8	53.0	53.5	55.6	55.0	57.4
Boats and Vessels	16.3	15.0	15.3	13.4	13.7	12.5	13.2
Locomotives	7.4	6.9	7.4	6.7	8.0	8.1	8.5
Other[b]	23.7	22.4	22.4	23.7	24.8	24.9	25.5
CH_4	**1.5**	**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
Light-Duty Trucks	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Other Trucks and Buses	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Aircraft	+	+	+	+	+	+	+
Boats and Vessels	0.1	0.1	0.1	+	+	+	+
Locomotives	+	+	+	+	+	+	+
Other[c]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**13.2**	**13.9**	**14.8**	**15.6**	**16.3**	**16.6**	**16.5**
Passenger Cars	8.7	9.1	9.7	10.1	10.0	10.1	10.1
Light-Duty Trucks	3.4	3.7	3.9	4.2	5.1	5.2	5.1
Other Trucks and Buses	0.7	0.7	0.7	0.7	0.8	0.8	0.9
Aircraft[d]	+	+	+	+	+	+	+
Boats and Vessels	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other[c]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
HFCs	**+**	**+**	**0.2**	**0.7**	**1.3**	**2.5**	**3.6**
Mobile Air Conditioners[e]	+	+	0.2	0.7	1.3	2.5	3.6
Total	**424.3**	**416.1**	**423.2**	**431.7**	**446.4**	**453.3**	**467.0**

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

[a] In 1995, 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 1994 to 1995 was observed. This gap, however, was offset by an equivalent rise in CO_2 emissions from light-duty trucks.

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

[c] "Other" CH_4 and N_2O emissions includes 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.

[d] Aircraft N_2O emissions include aviation gasoline combustion but exclude jet fuel combustion due to insufficient data availability.

[e] Includes primarily HFC-134a

Overall, from 1990 to 1996 total emissions of CO_2, CH_4, and N_2O increased by 122.8 (9 percent), 8.6 (5 percent), and 11.4 MMTCE (12 percent), respectively. During the same period, weighted emissions of HFCs, PFCs, and SF_6 rose by 12.5 MMTCE (56 percent). Despite being emitted in smaller quantities, 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. U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests.

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.

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-3 presents greenhouse gas emissions from electric utility related activities. Overall emissions from electric utilities increased by 8.6 percent from 1990 to 1996, and accounted for just under 30 percent of total U.S. greenhouse emissions during the same period.

Table ES-3: Electric Utility Related Greenhouse Gas Emissions (MMTCE)

Gas/Fuel Type or Source	1990	1991	1992	1993	1994	1995	1996
CO_2	**476.8**	**473.4**	**472.5**	**490.7**	**494.8**	**493.8**	**516.8**
Natural Gas	41.2	41.1	40.7	39.5	44.0	47.2	40.3
Petroleum	26.6	25.1	19.9	22.5	20.6	14.0	15.6
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**
Stationary Sources (Utilities)	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**
Stationary Sources (Utilities)	2.0	2.0	2.0	2.1	2.1	2.1	2.2
SF_6	**5.6**	**5.9**	**6.2**	**6.4**	**6.7**	**7.0**	**7.0**
Electrical Transmission and Distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0
Total	**484.6**	**481.4**	**480.8**	**499.3**	**503.7**	**503.1**	**526.2**

+ 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 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 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 12/44ths of carbon dioxide by weight. In order to convert emissions reported in teragrams (Tg) of greenhouse gas to MMTCE, the following equation was used:

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

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 United States for policy making and reporting purposes, were used in this report (IPCC 1996). A tabulation of GWPs is shown in Table ES-4.

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, the equilibrium of atmospheric carbon has been increasingly compromised. Atmospheric concentrations of CO_2 have risen about 28 percent (IPCC 1996), principally because of fossil fuel combustion, which accounted for 99 percent of total U.S.

Table ES-4: Global Warming Potentials (100 Year Time Horizon)

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

CO_2 emissions in 1996. 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).

Table ES-5 and Figure ES-3 summarizes U.S. sources and sinks of CO_2, while the remainder of this section discusses CO_2 emission trends in greater detail.

Energy Sector

Energy related activities accounted for 86 percent of all U.S. greenhouse gas emissions in 1996. Carbon dioxide from fossil fuel combustion was the main contributor, although CH_4 and N_2O 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.

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 with a given 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. Petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent of total energy consump-

Table ES-5: U.S. Sources of CO_2 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	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Land-Use Change and Forestry (Sink)*	(311.5)	(311.5)	(311.5)	(208.6)	(208.6)	(208.6)	(208.6)
Total Emissions	**1,348.3**	**1,333.2**	**1,353.4**	**1,385.6**	**1,408.5**	**1,419.2**	**1,471.1**
Net Emissions (Sources and Sinks)	**1,036.8**	**1,021.7**	**1,041.9**	**1,177.0**	**1,200.0**	**1,210.6**	**1,262.5**

+ Does not exceed 0.05 MMTCE

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

Note: Totals may not sum due to independent rounding.

Figure ES-3

1996 Sources of CO$_2$

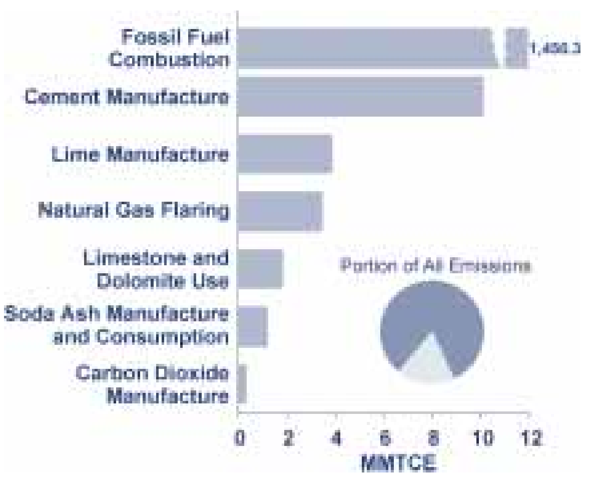


Figure ES-4

1996 U.S. Energy Consumption

U.S. Energy Consumption (Quadrillion Btu)
Source: DOE/EIA-0384(96), Annual Energy Review 1996, Table 1.3, July 1997

tion 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 end-use sector, while the vast majority of coal was used by electric utilities, with natural gas consumed largely in the industrial and residential end-use sectors.

Emissions of CO$_2$ 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$_2$ emissions from fossil fuel combustion were 1,331.4 MMTCE, there was a slight decline in emissions in 1991, followed by a steady increase to 1,450.3 MMTCE in 1996. Overall, CO$_2$ 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.

Of all fossil fuel combustion related emissions from 1995 to 1996, 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 coal combustion by electric utilities increased by over 6 percent from 1995 to 1996.

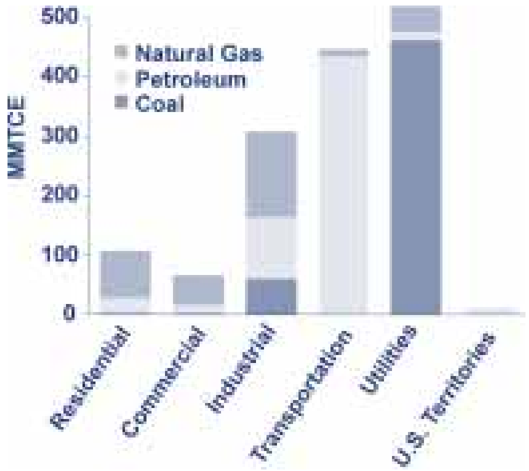
Despite slightly higher prices, the consumption of petroleum products in 1996 increased 3.5 percent from the previous year, accounting for about 43 percent of the increase in CO$_2$ emissions from fossil fuel combustion. More than half of the increase in emissions from petroleum was due to an increase in fuel consumption for transportation activities.

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 end-use sector rose by 7.9 percent while electric utilities experienced a dramatic 14.5 percent decrease. This sharp reduction in utilities' gas consumption can be explained, in large part, by a 33 percent increase in the price of natural gas for utilities (EIA 1997).

Industrial End-Use Sector. Industry accounted for 33 percent of U.S. emissions from fossil fuel consumption (see Figure ES-5 and Table ES-6). 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 such uses as motors, electric furnaces, ovens, and lighting.

Figure ES-5

1996 CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector and Fuel Type



* Utilities also includes emissions of 0.04 MMTCE from geothermal based electricity generation

Transportation End-Use Sector. Transportation activities accounted for 31 percent of CO_2 emissions from fossil fuel combustion in 1996. Virtually all of the energy consumed in this sector came from petroleum products. Nearly 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 for heavy-duty vehicles and jet fuel for aircraft.

Residential and Commercial End-Use Sectors. The residential and commercial sectors accounted for 20 and 16 percent, respectively, of CO_2 emissions from fossil fuel consumption in 1996. 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 emitted 36 percent of CO_2 from fossil fuel consumption in 1996. 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 1996. 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 trapped in natural gas systems or 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 1996, flaring activities emitted approximately 3.5 MMTCE, or about 0.2 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 dominates the use of

Table ES-6: CO_2 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**

* 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.

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 biomass consumption does not increase atmospheric CO_2 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_2 emissions from biomass combustion were 54.6 MMTCE, with the industrial end-use sector accounting for 71 percent of the emissions, and the residential end-use sector, 24 percent. Ethanol consumption by the transportation end-use 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 from one state to another. 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 manufacture. Total carbon dioxide emissions from these sources were approximately 17.3 MMTCE in 1996, 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 (10.1 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_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 (3.8 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, $CaCO_3$) in a kiln, creating calcium oxide (quicklime) and CO_2, which is normally emitted to the atmosphere.

Limestone and Dolomite Use (1.8 MTCE)

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 these products, 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 Manufacture (0.3 MMTCE)

Carbon dioxide is used directly in many segments of the economy, including food processing, beverage manufacturing, chemical processing, crude oil drilling, 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 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 grassland or forest.

Forests, which cover about 298 million hectares (737 million acres) of U.S. land (Powell et al. 1993), can be an important terrestrial sink for CO_2. Because approximately half the dry weight of wood is carbon, tree growth results in a net accumulation of carbon in relatively long-lived biomass. Other types of vegetative cover, as well as soils, can also act as sinks of carbon.

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 CO_2 flux in 1996 was estimated to have been an net uptake of 208.6 MMTCE. This net sequestration of carbon includes forest trees, understory, 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 CO_2 emissions from fossil fuel combustion in 1996. The amount of carbon sequestered through changes in U.S. forestry and land-use practices declined by 33 percent between 1990 and 1996 due to the maturation of existing U.S. forests and the slowed expansion of Eastern forest cover.

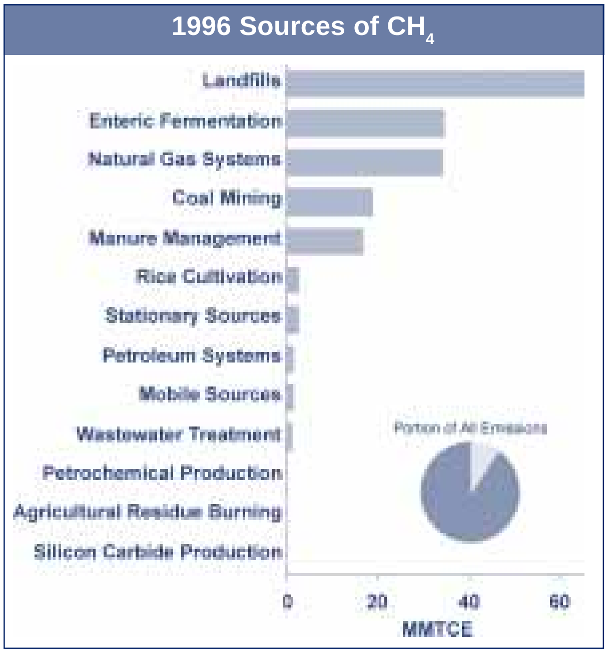
Methane Emissions

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. 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, fossil fuel combustion, wastewater treatment, and certain industrial processes (see Table ES-7).

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 nonex-

Figure ES-6



1996 Sources of CH_4

Table ES-7: U.S. Sources of Methane Emissions (MMTCE)

Source	1990	1991	1992	1993	1994	1995	1996
Stationary Sources	2.3	2.3	2.4	2.3	2.3	2.4	2.5
Mobile Sources	1.5	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
Natural Gas Systems	32.9	33.3	33.9	34.1	33.9	33.8	34.1
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	**169.9**	**171.1**	**172.5**	**171.9**	**175.9**	**179.2**	**178.6**

+ Does not exceed 0.05 MMTCE

Note: Totals may not sum due to independent rounding.

istent, 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 1996 were 65.1 MMTCE, a 16 percent increase since 1990 due to 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. EPA is currently reviewing site specific information on landfill gas recovery and anticipates that this new information will lead to an estimate of greater higher national recovery total, and thus lower net methane emissions. This new information will be available in future inventories.

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 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 34.1 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 1996, emissions from petroleum systems were estimated to be 1.5 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 1996, combined emissions from natural gas and petroleum systems increased by just over 3 percent as the number of gas producing wells and miles of distribution pipeline rose.

Agriculture Sector

The Agricultural sector accounted for 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 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 1996, enteric fermentation was the source of about 19 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 just over 1 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 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 is 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 1996.

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 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 18.9 MMTCE of methane, or 11 percent of U.S. methane emissions. From 1990 to 1996, emissions from this source decreased by 21 percent due to increased use of the methane collected by mine degasification systems.

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 2.5 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

Nitrous oxide (N_2O) is a greenhouse gas that is produced naturally from a wide variety of biological sources in soil and water. 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 has 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 Table ES-8).

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 1996, N_2O emissions from mobile sources totaled 16.5 MMTCE, or 16 percent of U.S. N_2O emissions. Emissions of N_2O from stationary sources were 4.0 MMTCE, or 9 percent of U.S. N_2O emissions. From 1990 to 1996, combined N_2O emissions from stationary and mobile sources increased by 21 percent, primarily due to increased rates of N_2O generation in motor vehicles.

Agricultural Soil Management

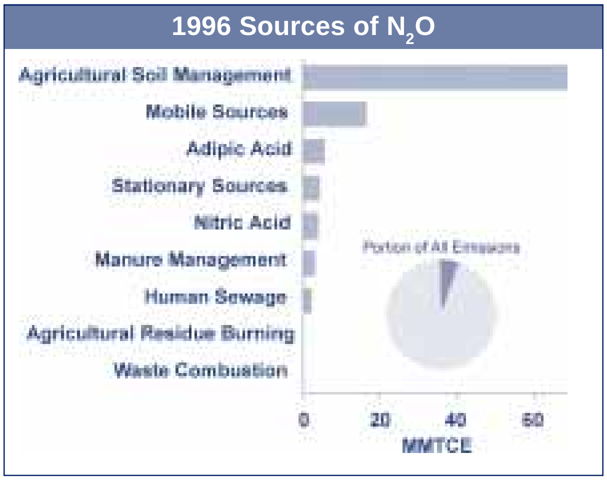
Nitrous oxide (N_2O) is produced naturally in soils through microbial processes. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as N_2O by these microbial processes. Direct additions of nitrogen occur through the application of synthetic and organic fertilizers, cultivation of nitrogen-fixing crops, cultivation of high organic content soils, and the application of livestock manure on croplands and pasture. 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.

Table ES-8: U.S. Sources of Nitrous Oxide Emissions (MMTCE)

Source	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
Stationary Sources	3.7	3.7	3.7	3.8	3.8	3.8	4.0
Mobile Sources	13.2	13.9	14.8	15.6	16.3	16.6	16.5
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	2.6	2.8	2.8	2.9	2.9	2.9	3.0
Agricultural Soil Management	62.4	63.4	65.2	64.1	70.4	67.2	68.6
Agricultural Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Human Sewage	2.1	2.1	2.2	2.2	2.3	2.2	2.3
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**92.3**	**94.4**	**96.8**	**97.1**	**104.9**	**101.9**	**103.7**

Note: Totals may not sum due to independent rounding.

Figure ES-7



In 1996, agricultural soil management accounted for 68.6 MMTCE, or approximately 66 percent of U.S. N_2O emissions. From 1990 to 1996, emissions from this source increased by 10 percent as fertilizer consumption and cultivation of nitrogen fixing crops rose.

Adipic Acid Production

The majority of the adipic acid produced in the United States is used to manufacture nylon. 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 5 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_2O 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_2O emissions from managed manure systems in 1996 were 3.0 MMTCE, accounting for 3 percent of U.S. N_2O 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_2O included agricultural reside 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_2O. Although N_2O emissions from wastewater treatment were not fully estimated because insufficient data was available, the human sewage component of domestic wastewater resulted in emission of 2.3 MMTCE in 1996.

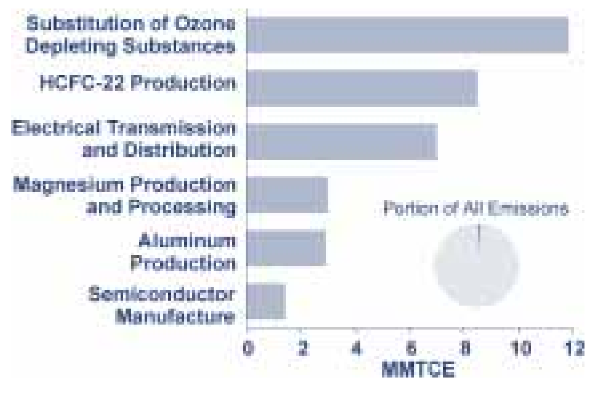
HFCs, PFCs and SF_6 Emissions

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

However, many of these compounds, along with sulfur hexafluoride (SF_6), are potent greenhouse gases. In addition to having high global warming potentials,

Figure ES-8

1996 Sources of HFCs, PFCs, and SF_6



SF_6 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-9 presents emission estimates for HFCs, PFCs, and SF_6, which totaled 34.7 MMTCE in 1996.

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 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 1996 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 8.5 MMTCE in 1996, and have decreased by 11 percent since 1990.

The semiconductor industry uses combinations of HFCs, PFCs, and SF_6 for plasma etching and chemical vapor deposition processes. For 1996, it was estimated that the U.S. semiconductor industry emitted a total of 1.4 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 1996.

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 1996, and increased of 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 nonindustrial 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.

Table ES-9: Emissions of HFCs, PFCs, and SF_6 (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	4.7	4.1	3.5	2.8	2.7	2.9
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	3.0
Total	**22.2**	**21.6**	**23.0**	**23.4**	**25.9**	**30.8**	**34.7**

Note: Totals may not sum due to independent rounding.

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.

Since 1970, the United States has published estimates of annual emissions of criteria pollutants (EPA 1997). Table ES-11 shows that fuel combustion 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_x 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_x, and NMVOCs.

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-10. 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 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-10: Emissions of Ozone Depleting Substances (Mg)

Compound	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
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 Office of Air and Radiation estimates
+ Does not exceed 10 Mg

Table ES-11: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1991	1992	1993	1994	1995	1996
NO_x	**21,612**	**21,594**	**21,929**	**22,235**	**22,616**	**21,742**	**21,254**
Stationary Fossil Fuel Combustion	9,881	9,777	9,912	10,077	9,990	9,820	9,518
Mobile Fossil Fuel Combustion	10,554	10,788	10,975	11,145	11,445	10,884	10,688
Oil and Gas Activities	139	110	134	111	106	100	100
Industrial Processes	923	802	784	760	933	815	821
Solvent Use	1	2	2	2	2	3	3
Agricultural Burning	30	30	34	27	37	30	34
Waste	83	86	87	112	103	89	91
CO	**83,732**	**85,390**	**82,427**	**82,381**	**86,475**	**77,216**	**76,435**
Stationary Fossil Fuel Combustion	4,998	5,312	5,582	5,067	5,006	5,382	5,407
Mobile Fossil Fuel Combustion	67,101	70,865	69,158	69,668	71,402	64,363	63,455
Oil and Gas Activities	302	313	337	337	307	316	316
Industrial Processes	9,580	7,166	5,480	5,500	7,787	5,370	5,379
Solvent Use	4	4	5	4	5	5	5
Agricultural Burning	768	718	833	674	858	704	783
Waste	979	1,012	1,032	1,133	1,111	1,075	1,091
NMVOCs	**18,768**	**18,872**	**18,501**	**18,681**	**19,264**	**18,385**	**17,020**
Stationary Fossil Fuel Combustion	912	975	1,010	901	897	973	975
Mobile Fossil Fuel Combustion	7,997	8,167	7,822	7,878	8,184	7,380	7,192
Oil and Gas Activities	555	581	574	588	587	582	469
Industrial Processes	3,193	2,997	2,825	2,907	3,057	2,873	2,299
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	895	907	916	949	949	968	393
SO_2	**21,379**	**20,752**	**20,554**	**20,196**	**19,633**	**17,165**	**17,673**
Stationary Fossil Fuel Combustion	18,407	17,959	17,684	17,459	17,134	14,724	15,228
Mobile Fossil Fuel Combustion	1,237	1,222	1,267	1,166	965	947	946
Oil and Gas Activities	390	343	377	347	344	334	334
Industrial Processes	1,306	1,187	1,186	1,159	1,135	1,116	1,122
Solvent Use	+	+	+	1	1	1	1
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
Waste	38	40	40	65	54	43	43

Source: (EPA 1997)
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

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 66 percent in 1996. Coal combustion contributes nearly all of those emissions (approximately 96 percent). SO_2 emissions have significantly decreased in recent years, primarily as a result of electric utilities switching from high sulfur to low sulfur coal.