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Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1996

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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.

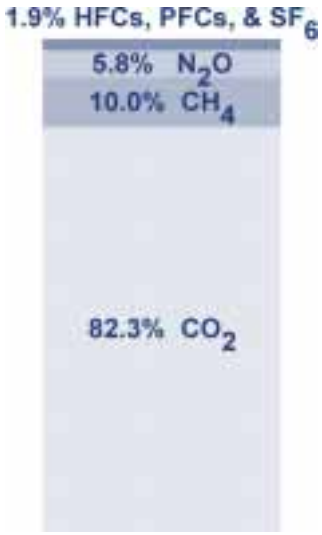
Beginning in the 1950s, the use of CFCs and other ozone depleting substances (ODSs) increased by nearly 10 percent a year, until the mid-1980s when international concern about ozone depletion led to the signing of the *Montreal Protocol*. Since then, the consumption of ODSs has rapidly declined as they 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).

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

Figure ES-1

Recent Trends in U.S. Greenhouse Gas Emissions

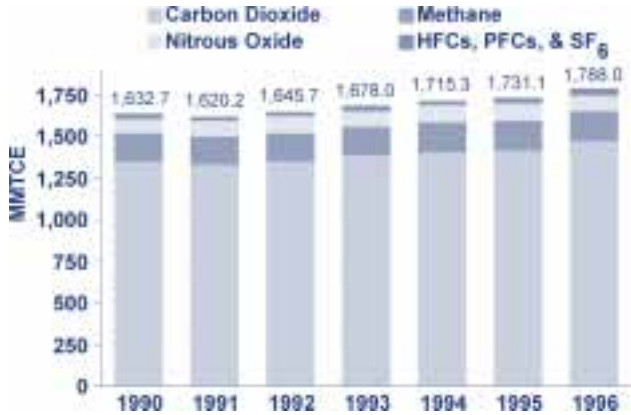


Table ES-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO_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.

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

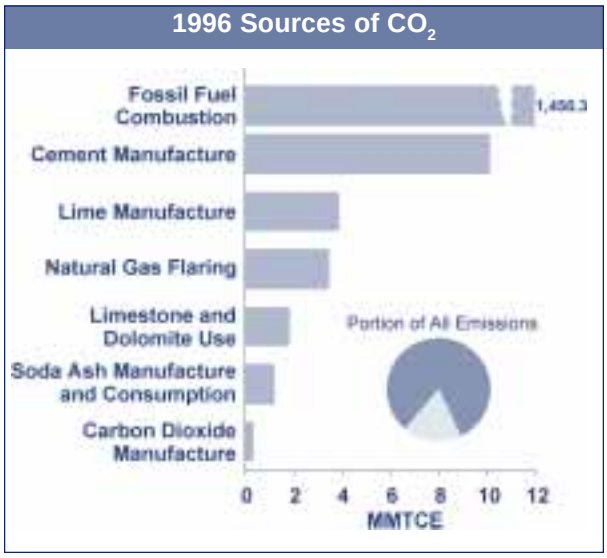
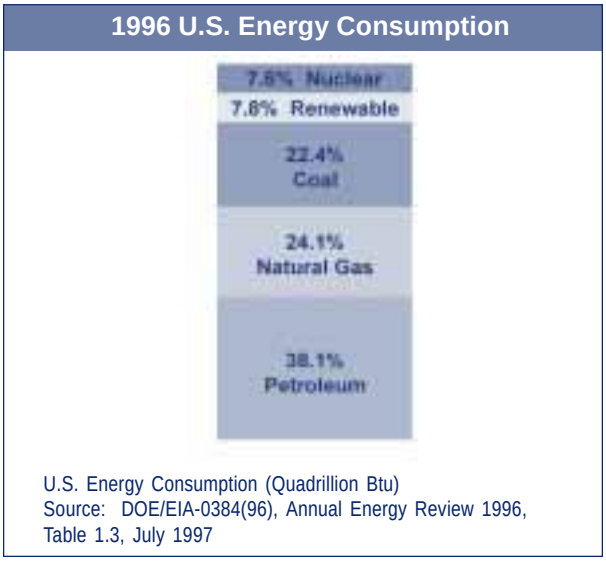


Figure ES-4



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.

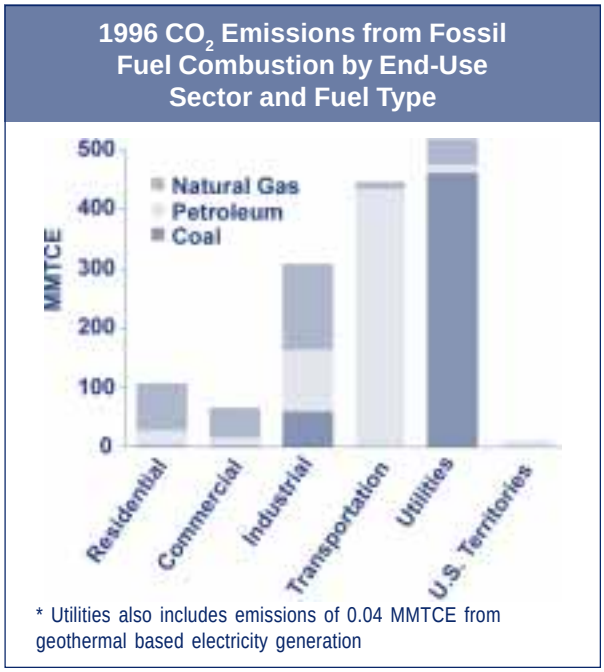
Of all fossil fuel combustion related emissions from 1995 to 1996, emissions from coal grew the most (an increase of 25.5 MMTCE or 5 percent), while emissions from natural gas changed the least (an increase of 3.8 MMTCE or 1 percent) as electric utilities increased their consumption of coal, while shifting 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



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

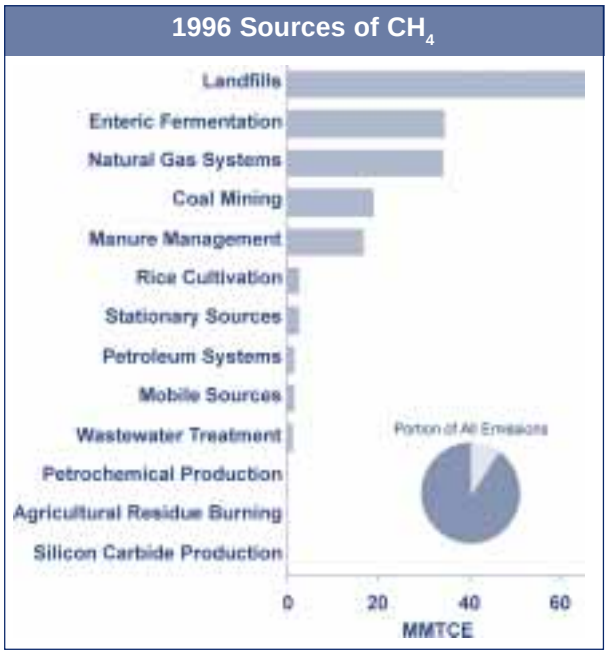


Table ES-7: U.S. Sources of Methane Emissions (MMTCE)

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

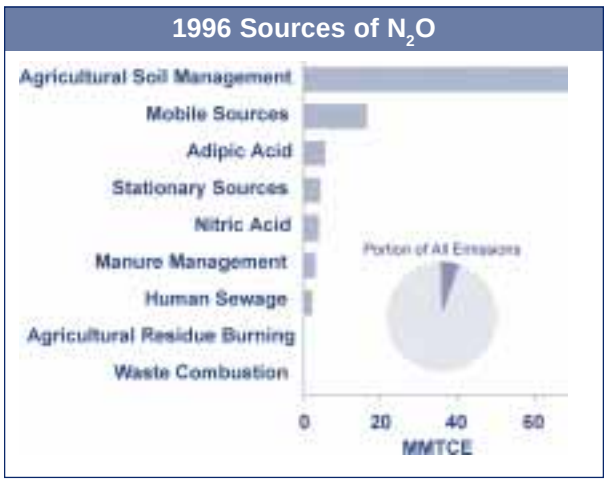
Nitrous oxide (N_2O) is produced naturally in soils through microbial processes. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as N_2O by these microbial processes. Direct additions of nitrogen occur through the application of synthetic and organic fertilizers,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

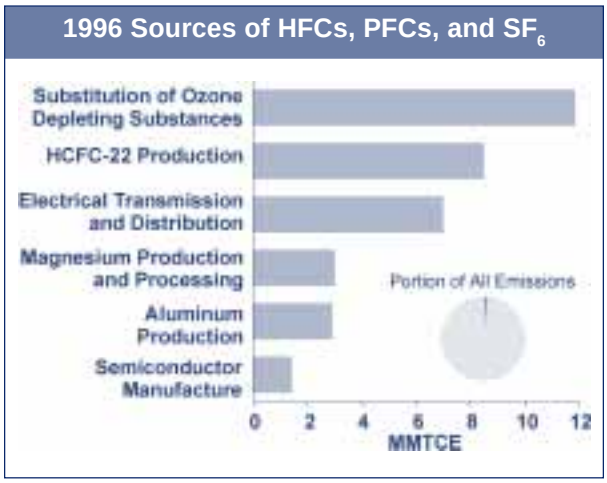
Other sources of N_2O included agricultural reside burning, waste combustion, and human sewage in wastewater treatment systems. In 1996, agricultural residue burning and municipal solid waste combustion each emitted approximately 0.1 MMTCE of N_2O. Although N_2O emissions from wastewater treatment were 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



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 non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from the combustion of fossil fuels and by the metals industry.

In part because of their contribution to the formation of urban smog (and acid rain in the case of SO_2), criteria pollutants are regulated under the Clean Air Act.

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.

1. Introduction

This report presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 1996.[1] A summary of these estimates is provided in Table 1-2 and Table 1-3 by gas and source category. The emission estimates in these tables are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis in order to show the relative contribution of each gas to global average radiative forcing.[2,3] This report also discusses the methods and data used to calculate these emission estimates.

In June of 1992, the United States signed the United Nations Framework Convention on Climate Change (FCCC). The objective of the FCCC is "to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[4,5]

Parties to the Convention, by signing, make commitments "to develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"[6] The United States views this report as an opportunity to fulfill this commitment under FCCC.

In 1988, preceding the creation of the FCCC, the Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The charter of the IPCC is to assess available scientific information on climate change, assess the environmental and socio-economic impacts of climate change, and formulate response strategies (IPCC 1996). Under Working Group 1 of the IPCC, nearly 140 scientists and national experts from more than thirty countries corroborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) to ensure that the emission inventories submitted to the FCCC are consistent and comparable across sectors and between nations. The *Revised 1996 IPCC Guidelines* were accepted by the IPCC at its Twelfth Session (Mexico City, 11-13 September 1996). The information provided in this inventory is presented in accordance with these guidelines, unless otherwise noted. Additionally, in order to fully comply with the *Revised 1996 IPCC Guidelines*, the United States has provided a copy of the IPCC reporting tables in Annex N and in Annex O estimates of carbon dioxide emissions from fossil fuel combustion using the IPCC Reference Approach.

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1 Preliminary U.S. greenhouse gas emission estimates for the year 1997 are also provided in Annex P.

2 See the section below entitled *Global Warming Potential Concept* for an explanation of GWP values.

3 See the section below entitled *What is Climate Change?* for an explanation of radiative forcing.

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

5 Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change.

6 Article 4 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (also identified in Article 12).

Overall, the purpose of an inventory of anthropogenic greenhouse gas emissions is (1) to provide a basis for the ongoing development of methodologies for estimating sources and sinks of greenhouse gases; (2) to provide a common and consistent mechanism through which Parties to the FCCC can estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change; and (3) as a prerequisite for evaluating the cost-effectiveness and feasibility of pursuing possible mitigation strategies.

What is Climate Change?

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation, though, is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 34°C lower (IPCC 1996).

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither play a significant role in this greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide, and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 1996). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC 1996). Holding everything else constant, increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth).

Under the United Nations FCCC, the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."[7] Given that definition, in its 1995 assessment of the science of climate change, the IPCC concluded that:

Human activities are changing the atmospheric concentrations and distributions of greenhouse gases and aerosols. These changes can produce a radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation (IPCC 1996).

The IPCC went on to report in its assessment that the "[g]lobal mean surface temperature [of the Earth] has increased by between about 0.3 and 0.6 °C since the late 19th century…" (IPCC 1996) and finally concluded with the following statement:

Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long term natural variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of the evidence suggests that there is a discernable human influence on global climate (IPCC 1996).

Greenhouse Gases

Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases (IPCC 1996).

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of haloge-

[7] Article 1 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change.

nated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, emitted solely by human 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 radiative forcing 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).[8] 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.

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes—except when directly or indirectly perturbed out of equilibrium by anthropogenic activities—generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems.

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of Global Warming Potentials (GWPs), which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well-mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to directly affect the average global concentration of water vapor; however, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. A warmer atmosphere has an increased water holding capacity; yet, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect solar and terrestrial radiation.

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric carbon dioxide is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere, as of 1994, increased from approximately 280 parts per million by volume (ppmv) in pre-industrial[9] times to 358 ppmv, a more than 25 percent increase (IPCC 1996).[10] The IPCC has stated that "[t]here is no doubt that this increase is largely due to human activities, in particular fossil fuel combustion…" (IPCC 1996). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

In its latest scientific assessment, the IPCC also stated that "[t]he increased amount of carbon dioxide [in the atmosphere] is leading to climate change and will produce, on average, a global warming of the Earth's

8 Also referred to in the U.S. Clean Air Act as "criteria pollutants."

9 The pre-industrial period is defined as the time preceding the year 1750 (IPCC 1996).

10 Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (1650-1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 1996).

surface because of its enhanced greenhouse effect—although the magnitude and significance of the effects are not fully resolved" (IPCC 1996).

Methane (CH_4). Methane is produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. The average global concentration of methane in the atmosphere was 1,720 parts per billion by volume (ppbv) in 1994, a 145 percent increase from the pre-industrial concentration of 700 ppbv (IPCC 1996). It is estimated that 60 to 80 percent of current CH_4 emissions are the result of anthropogenic activities. Carbon isotope measurements indicate that roughly 20 percent of methane emissions are from fossil fuel consumption, and an equal percentage is produced by natural wetlands, which will likely increase with rising temperatures and rising microbial action (IPCC 1996).

Methane is removed from the atmosphere by reacting with the hydroxyl radical (OH) and is ultimately converted to CO_2. Increasing emissions of methane, though, reduces the concentration of OH, and thereby the rate of further methane removal (IPCC 1996).

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially the use of synthetic and manure fertilizers; fossil fuel combustion, especially from mobile sources; adipic (nylon) and nitric acid production; wastewater treatment and waste combustion; and biomass burning. The atmospheric concentration of nitrous oxide (N_2O) in 1994 was about 312 parts per billion by volume (ppbv), while pre-industrial concentrations were roughly 275 ppbv. The majority of this 13 percent increase has occurred after the pre-industrial period and is most likely due to anthropogenic activities (IPCC 1996). Nitrous oxide is removed from the atmosphere primarily by the photolytic action of sunlight in the stratosphere.

Ozone (O_3). Ozone is present in both the stratosphere,[11] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere[12], where it is the main component of anthropogenic photochemical "smog". During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as chlorofluorocarbons (CFCs), have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 1996).

Tropospheric ozone, which is also a greenhouse gas, is produced from the oxidation of methane and from reactions with precursor gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs). This latter group of ozone precursors are included in the category referred to as "criteria pollutants" in the United States under the Clean Air Act[13] and its subsequent amendments. The tropospheric concentrations of both ozone and these precursor gases are short-lived and, therefore, spatially variable.

Halocarbons. Halocarbons are for the most part man-made chemicals that have both direct and indirect radiative forcing effects. Halocarbons that contain chlorine—chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform, and carbon tetrachloride—and bromine—halons and methyl bromide—result in stratospheric ozone depletion and are therefore controlled under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced be-

11 The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone-layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

12 The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

13 [42 U.S.C § 7408, CAA § 108]

cause they cause stratospheric ozone depletion, which is itself an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation. Under the *Montreal Protocol*, the United States phased-out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the *Protocol*, a cap was placed on the production and importation of HCFCs by non-Article 5[14] countries beginning in 1996, and then followed by a complete phase-out by the year 2030. The ozone depleting gases covered under the *Montreal Protocol* and its Amendments are not covered by the FCCC; however, they are reported in this inventory under Annex K.

Perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) are not ozone depleting substances, and therefore are not covered under the *Montreal Protocol*. They are, however, powerful greenhouse gases. HFCs—primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process—currently have a small aggregate radiative forcing impact; however, it is anticipated that their contribution to overall radiative forcing will increase (IPCC 1996). PFCs and SF_6 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, and SF_6 is also small; however, because they have extremely long atmospheric lifetimes, their concentrations tend to irreversibly accumulate in the atmosphere.

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect and result from their role in promoting the formation of tropospheric, and to a lesser degree, lower stratospheric, ozone. (NO_x emissions injected higher in the stratosphere[15] can lead to stratospheric ozone depletion.). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires), fossil fuel combustion, and, in the stratosphere, from nitrous oxide (N_2O). Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Nonmethane Volatile Organic Compounds (NMVOCs). Nonmethane volatile organic compounds include compounds such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere. They can be produced by natural events such as dust storms and volcanic activity or by anthropogenic processes such as fuel combustion. Their effect upon radiative forcing is to both absorb radiation and to alter cloud formation, thereby affecting the reflectivity (i.e., albedo) of the Earth. Aerosols are removed from the atmosphere primarily by precipitation, and generally have short atmospheric lifetimes. Like ozone precursors, aerosol concentrations and composition vary by region (IPCC 1996).

Anthropogenic aerosols in the troposphere are primarily the result of sulfur dioxide (SO_2)[16] emissions from fossil fuel and biomass burning. Overall, aerosols tend

14 Article 5 of the *Montreal Protocol* covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

15 Primarily from fuel combustion emissions from high altitude aircraft.

16 Sulfur dioxide is a primary anthropogenic contributor to the formation of “acid rain” and other forms of atmospheric acid deposition.

to produce a negative radiative forcing effect (i.e., net cooling effect on the climate), although because they are short-lived in the atmosphere—lasting days to weeks—their concentrations respond rapidly to changes in emissions.[17] Locally, the negative radiative forcing effects of aerosols can offset the positive forcing of greenhouse gases (IPCC 1996). "However, the aerosol effects do not cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result" (IPCC 1996). Emissions of sulfur dioxide are provided in Annex L of this report.

Global Warming Potentials

The Global Warming Potential (GWP) is intended as a quantified measure of the relative radiative forcing impacts of various greenhouse gases. It is defined as the cumulative radiative forcing—both direct and indirect effects—over a specified time horizon resulting from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The reference gas used is CO_2, in which case GWP weighted emissions are measured in 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 a gas to MMTCE, the following equation is used:

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

where,

MMTCE = Million Metric Tons of Carbon Equivalents

Tg = Teragrams (equivalent to million metric tons)

GWP = Global Warming Potential

$\left(\frac{12}{44}\right)$ = Carbon to CO_2 molecular weight ratio.

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±35 percent. The parties to the FCCC have also agreed to use GWPs based upon a 100 year time horizon although other time horizon values are available (see Table 1-1).

In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons.[18]

Table 1-1: Global Warming Potentials and Atmospheric Lifetimes (Years)

Gas	Atmospheric Lifetime	GWP[a]
Carbon dioxide (CO_2)	50-200	1
Methane (CH_4)[b]	12±3	21
Nitrous oxide (N_2O)	120	310
HFC-23	264	11,700
HFC-125	32.6	2,800
HFC-134a	14.6	1,300
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-227ea	36.5	2,900
HFC-236fa	209	6,300
HFC-4310mee	17.1	1,300
CF_4	50,000	6,500
C_2F_6	10,000	9,200
C_4F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

Source: (IPCC 1996)

[a] 100 year time horizon

[b] The 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.

17 Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer negative forcing effect (i.e., a few years) (IPCC 1996).

18 Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties on Its Second Session; Held at Geneva from 8 To 19 July 1996; Addendum; Part Two: Action Taken By The Conference Of The Parties At Its Second Session; Decision 9/CP.2; Communications from Parties included in Annex I to the Convention: guidelines, schedule and process for consideration; Annex: Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention; p. 18.

Greenhouse gases with long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, tropospheric ozone, ozone precursors (e.g., NO_x, CO, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. No GWP values are attributed to gases that are short-lived and spatially inhomogeneous in the atmosphere. Other greenhouse gases not yet listed by the Intergovernmental Panel on Climate Change (IPCC), but are already or soon will be in commercial use include: HFC-245fa, hydrofluoroethers (HFEs), and nitrogen trifluoride (NF_3).

Organization of Report

In accordance with the IPCC guidelines for reporting contained in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), this U.S. inventory of greenhouse gas emissions is segregated into six sector-specific chapters, listed below:

Within each chapter, emissions are identified by the anthropogenic activity that is the source of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/Sector: Overview of emission trends for sector

***Source*:** Description of source pathway and emission trends from 1990 through 1996

- Methodology: Description of analytical methods employed to produce emission estimates
- Data Sources: Identification of primary data references, primarily for activity data and emission factors
- Uncertainty: Discussion of relevant issues related to the uncertainty in the emission estimates presented

Special attention is given to carbon dioxide from fossil fuel combustion relative to other sources because of its share of emissions relative to other sources. For it, each energy consuming end-use is treated individually. Additional information is also provided in the Annexes (see box on following page).

Recent Trends in U.S. Greenhouse Gas Emissions

Total U.S. greenhouse gas (GHG) 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) (see Figure 1-1).

Sectors	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions.
Industrial Processes	By-product or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion.
Solvent Use	Emissions, of primarily non-methane volatile organic compounds (NMVOCs), resulting from the use of solvents.
Agriculture	Anthropogenic emissions from agricultural activities except fuel combustion and sewage emissions, which are addressed under the Energy and Waste sectors, respectively.
Land-Use Change and Forestry	Emissions and removals from forest and land-use change activities, primarily carbon dioxide.
Waste	Emissions from waste management activities.

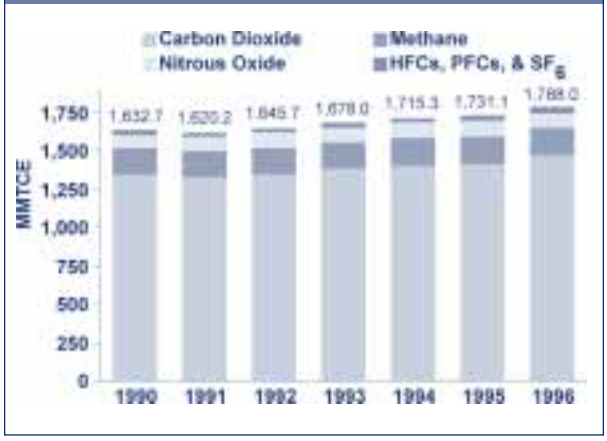
Source: (IPCC/UNEP/OECD/IEA 1997)

ANNEX A	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
ANNEX B	Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Stationary Combustion
ANNEX C	Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Mobile Combustion
ANNEX D	Methodology for Estimating Methane Emissions from Coal Production
ANNEX E	Methodology for Estimating Methane Emissions from Natural Gas Systems
ANNEX F	Methodology for Estimating Methane Emissions from Petroleum Systems
ANNEX G	Methodology for Estimating Methane Emissions from Enteric Fermentation
ANNEX H	Methodology for Estimating Methane Emissions from Manure Management
ANNEX I	Methodology for Estimating Methane Emissions from Landfills
ANNEX J	Global Warming Potentials
ANNEX K	Ozone Depleting Substance Emissions
ANNEX L	Sulfur Dioxide Emissions
ANNEX M	Complete List of Sources
ANNEX N	IPCC Reporting Tables
ANNEX O	IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion
ANNEX P	Preliminary 1997 Estimates of U.S. Greenhouse Gas Emissions and Sinks
ANNEX Q	Sources of Greenhouse Gas Emissions Excluded

The largest source of U.S. GHG emissions was carbon dioxide (CO_2) from fossil fuel combustion, which accounted for 81 percent of weighted emissions in 1996. Emissions from this source 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 was registered in 1996, when increased fossil fuel consumption drove up energy related CO_2 emissions by 3.7 percent.

Figure 1-1

Recent Trends in U.S. GHG Emissions



The primary factors for this later single year increase 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 nitrous oxide (N_2O) and methane (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 hydrofluorocarbon (HFC) and perfluorocarbon (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.

Figure 1-2

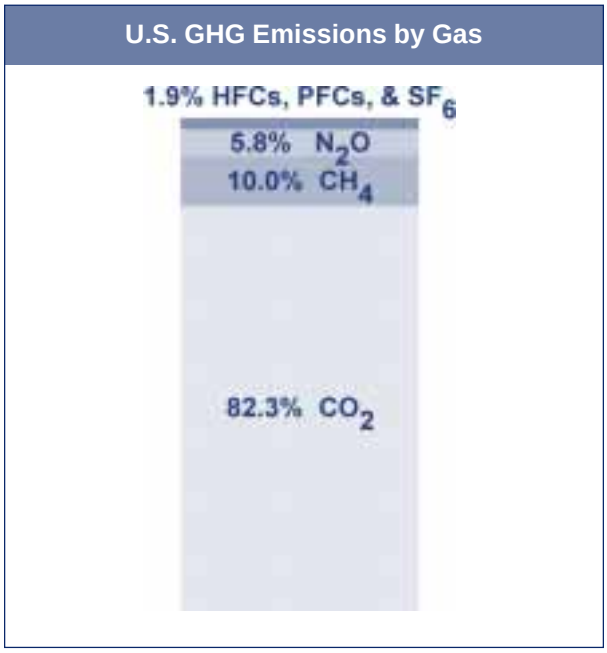
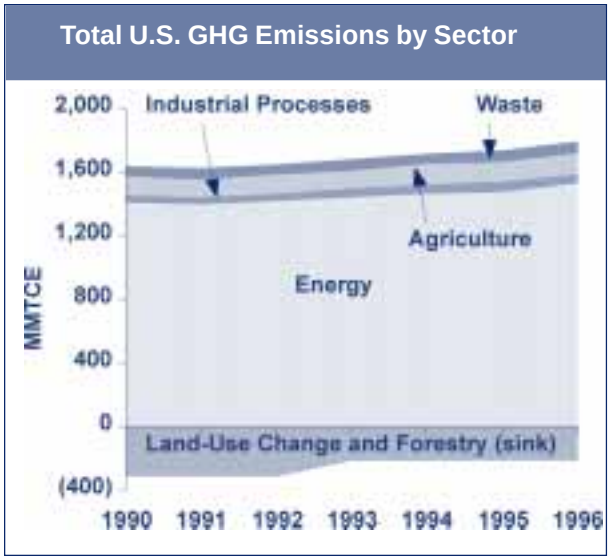


Figure 1-3



- 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.

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.

Alternatively, over the seven year period emissions from the Energy, Industrial Processes, Agriculture, and Waste sectors climbed by 120.2 (9 percent), 16.1 (35 percent), 9.9 (9 percent), and 9.1 MMTCE (15 percent), respectively. Estimates of the quantity of carbon sequestered under the Land-Use Change and Forestry sector, although based on projections, declined in absolute value by 103.0 MMTCE (33 percent).

Table 1-2 summarizes emissions and sinks from all U.S. anthropogenic sources weighted units of MMTCE, while unweighted gas emissions and sinks in teragrams (Tg) are provided in Table 1-3. Alternatively, emissions and sinks are aggregated by sector in Table 1-4 and Figure 1-3.

Table 1-2: 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.

Table 1-3: U.S. Greenhouse Gas Emissions and Sinks (Tg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO_2	**4,943.7**	**4,888.5**	**4,962.5**	**5,080.4**	**5,164.7**	**5,203.7**	**5,393.9**
Fossil Fuel Combustion	4,881.9	4,826.9	4,900.7	5,014.1	5,095.2	5,128.5	5,317.8
Natural Gas Flaring	7.3	8.2	8.1	11.0	11.1	13.7	12.7
Cement Manufacture	32.6	31.9	32.1	33.9	35.4	36.1	37.1
Lime Manufacture	11.9	11.7	12.1	12.4	12.8	13.6	14.1
Limestone and Dolomite Use	5.1	4.9	4.5	4.1	5.3	6.5	6.7
Soda Ash Manufacture and Consumption	4.1	4.0	4.1	4.0	4.0	4.3	4.3
Carbon Dioxide Manufacture	0.8	0.8	0.9	0.9	0.9	1.0	1.1
Land-Use Change and Forestry (Sink)[a]	(1,142.2)	(1,142.2)	(1,142.2)	(764.7)	(764.7)	(764.7)	(764.7)
CH_4	**29.7**	**29.9**	**30.1**	**30.0**	**30.7**	**31.3**	**31.2**
Stationary Sources	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Mobile Sources	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Coal Mining	4.2	4.0	3.8	3.4	3.4	3.6	3.3
Natural Gas Systems	5.7	5.8	5.9	5.9	5.9	5.9	5.9
Petroleum Systems	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Petrochemical Production	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Silicon Carbide Production	+	+	+	+	+	+	+
Enteric Fermentation	5.7	5.7	5.8	5.9	6.0	6.1	6.0
Manure Management	2.6	2.7	2.8	2.8	2.9	2.9	2.9
Rice Cultivation	0.4	0.4	0.5	0.4	0.5	0.5	0.4
Agricultural Residue Burning	+	+	+	+	+	+	+
Landfills	9.8	10.0	10.1	10.4	10.8	11.1	11.4
Wastewater Treatment	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**1.1**	**1.1**	**1.1**	**1.1**	**1.2**	**1.2**	**1.2**
Stationary Source	+	+	+	+	+	+	+
Mobile Sources	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Adipic Acid	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Nitric Acid	+	+	+	+	+	+	+
Manure Management	+	+	+	+	+	+	+
Agricultural Soil Management	0.7	0.8	0.8	0.8	0.8	0.8	0.8
Agricultural Residue Burning	+	+	+	+	+	+	+
Human Sewage	+	+	+	+	+	+	+
Waste Combustion	+	+	+	+	+	+	+
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
HCFC-22 Production[b]	+	+	+	+	+	+	+
Semiconductor Manufacture	M	M	M	M	M	M	M
Electrical Transmission and Distribution[c]	+	+	+	+	+	+	+
Magnesium Production and Processing[c]	+	+	+	+	+	+	+
NO_x	**21.6**	**21.6**	**21.9**	**22.2**	**22.6**	**21.7**	**21.3**
CO	**83.7**	**85.4**	**82.4**	**82.4**	**86.5**	**77.2**	**76.4**
NMVOCs	**18.8**	**18.9**	**18.5**	**18.7**	**19.3**	**18.4**	**17.0**

+ Does not exceed 0.05 Tg
M Mixture of multiple gases
[a] Sinks are not included in CO_2 emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.
[b] HFC-23 emitted
[c] SF_6 emitted
Note: Totals may not sum due to independent rounding.

Table 1-4: U.S. Greenhouse Gas Emissions and Sinks by Sector (MMTCE)

Sector	1990	1991	1992	1993	1994	1995	1996
Energy	1,412.5	1,397.6	1,418.6	1,448.4	1,471.3	1,482.3	1,532.7
Industrial Processes	45.5	44.7	45.9	47.2	51.2	56.9	61.5
Agriculture	115.5	117.3	120.3	119.5	127.9	125.0	125.4
Land-Use Change and Forestry (Sink)*	(311.5)	(311.5)	(311.5)	(208.6)	(208.6)	(208.6)	(208.6)
Waste	59.3	60.6	61.0	62.8	64.8	66.9	68.4
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**

* 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.

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 1-5 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 1-5: 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

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 1-6 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 1-6: 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**
Coal	409.0	407.2	411.8	428.7	430.2	432.7	460.9
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.

Methodology and Data Sources

Emissions of greenhouse gases from various sources have been estimated using methodologies that are consistent with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) except were noted otherwise. To the extent possible, the present U.S. inventory relies on published activity and emission factor data. Depending on the emission source category, *activity data* can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, etc.; *emission factors* are factors that relate quantities of emissions to an activity. For some sources, IPCC default methodologies and emission factors have been employed. However, for emission sources considered to be major sources in the United States, the IPCC default methodologies were expanded and more comprehensive methods were applied.

Inventory emission estimates from energy consumption and production activities are based primarily on the latest official fuel consumption data from the Energy Information Administration of the Department of Energy (EIA). Emission estimates for NO_x, CO, and NMVOCs were taken directly, except where noted, from the United States Environmental Protection Agency's (EPA) report, *National Air Pollutant Emission Trends 1900 - 1996* (EPA 1997), which is an annual EPA publication that provides the latest estimates of regional and national emissions for ozone precursors (i.e., criteria pollutants). Emissions of these pollutants are estimated by the EPA based on statistical information about each source category, emission factors, and control efficiencies. While the EPA's estimation methodologies for criteria pollutants are conceptually similar to the IPCC recommended methodologies, the large number of sources EPA used in developing its estimates makes it difficult to reproduce the methodologies from EPA (1997) in this inventory document. In these instances, the sources containing detailed documentation of the methods used are referenced for the interested reader. For agricultural sources, the EPA criteria pollutant emission estimates were supplemented using available activity data from other agencies. Complete documentation of the methodologies and data sources used is provided in conjunction with the discussion of each source and in the various annexes.

Carbon dioxide emissions from fuel combusted in ships or aircraft engaged in the international transport of

passengers or cargo are not included in U.S. totals, but are reported separately as international bunkers in accordance with IPCC reporting guidelines (IPCC/UNEP/OECD/IEA 1997). Carbon dioxide emissions from fuel combusted within U.S. territories, however, are included in U.S. totals.

Uncertainty in and Limitations of Emission Estimates

While the current U.S. emissions inventory provides a solid foundation for the development of a more detailed and comprehensive national inventory, it has several strengths and weaknesses.

First, this inventory by itself does not provide a complete picture of past or future emissions in the United States; it only provides an inventory of U.S. emissions for the years 1990 through 1996. However, the United States believes that common and consistent inventories taken over a period of time can and will contribute to understanding future emission trends. The United States produced its first comprehensive inventory of greenhouse gas emissions and sinks in 1993, and intends to annually update this inventory in conjunction with its commitments under the FCCC. The methodologies used to estimate emissions will be periodically updated as methods and information improve, and as further guidance is received from the IPCC.

Secondly, there are uncertainties associated with the emissions estimates. Some of the current estimates, such as those for CO_2 emissions from energy-related activities and cement processing, are considered to be fairly accurate. For other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated limit the scope or accuracy of the estimates presented. Within the discussion of each emission source, specific factors affecting the accuracy of the estimates are discussed.

Finally, while the IPCC methodologies provided in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) represent baseline methodologies for a variety of source categories, many of these methodologies continue to be improved and refined as new research and data becomes available. The current U.S. inventory uses the IPCC methodologies where possible, and supplements them with other available methodologies and data where possible. The United States realizes that additional efforts are still needed to improve methodologies and data collection procedures. Specific areas requiring further research include:

Incorporating excluded emission sources. Quantitative estimates of some of the sources and sinks of greenhouse gas emissions are not available at this time. In particular, emissions from some land-use activities and industrial processes are not included in the inventory either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex Q for a discussion of the sources of greenhouse gas emissions excluded from this report.

Improving the accuracy of emission factors. Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to methane and nitrous oxide emissions from stationary and mobile source fossil fuel combustion are highly uncertain.

Collecting detailed activity data. Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied. For example, the ability to estimate emissions of methane and nitrous oxide from jet aircraft is limited due to a lack of activity data by aircraft type and number of landing and take-off cycles.

Applying Global Warming Potentials. GWP values have several limitations including that they are not applicable to unevenly distributed gases and aerosols such as tropospheric ozone and its precursors. They are also intended to reflect global averages and, therefore, do not account for regional effects (IPCC 1996).

Emissions calculated for the U.S. inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies, assumptions, and incomplete data. As new information becomes available in the future, the United States will continue to improve and revise its emission estimates.

Changes in the U.S. Greenhouse Gas Inventory Report

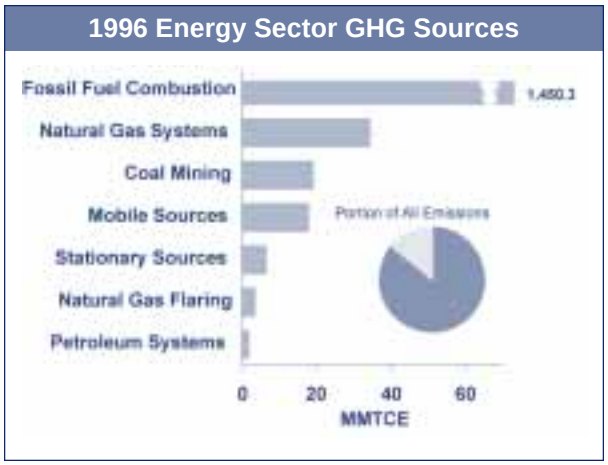
In 1997, the Intergovernmental Panel on Climate Change released the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) that included multiple methodological changes and wholly new source categories. These revised IPCC guidelines along with other unrelated additions and methodological changes have been incorporated into this year's inventory of greenhouse gas emissions and sinks which, depending on the source, improve the accuracy, precision, or comprehensiveness of the estimates presented relative to previous U.S. inventories. In particular, several new N_2O sources have been included for the first time and revisions have been made to some existing sources that significantly increase overall N_2O emissions relative to previous U.S. inventories. A summary of the additions and changes made to this report is provided below:

- An improved methodology for estimating methane and nitrous oxide emissions from mobile sources was employed that accounts for changes in emission control technologies over time and vehicle miles traveled by model year. New N_2O emission factors were also used, based in part on new measurement data, which had the primary result of revising N_2O emission estimates from highway vehicles upward.
- An additional analysis of CO_2 emissions from fossil fuel combustion in the transportation end-use sector is provided showing emissions by fuel and vehicle type.
- Carbon sequestration from non-fuel uses of fossil fuels in U.S. territories was included for the first time in emission estimates of CO_2 from fossil fuel combustion.
- Due to inconsistencies in natural gas production and consumption data available from the Energy Information Administration, CO_2 emissions from unmetered natural gas consumption were not included. This exclusion had a insignificant effect on reported emissions.
- Carbon dioxide emissions from geothermal steam extraction for electric power generation were included for the first time, although its contribution to total emissions was less than 0.1 MMTCE.
- Improved emission factors and a more detailed analysis of activities contributing to methane emissions from natural gas systems were employed.
- Several new industrial processes were included for the first time. Methane emissions from the production of select petrochemicals and silicon carbide production were added, although their contribution was minor. Carbon dioxide emissions from ammonia, iron and steel, and ferroalloy production were explicitly estimated, even though their emissions are accounted for under the fossil fuel combustion of industrial coking coal and natural gas.
- The discussion of HFC, PFC, and SF_6 emissions has been expanded to include multiple sources and improved estimating methodologies.
- Estimates of nitrous oxide emissions from agricultural soil management have been considerably expanded to include direct and indirect emissions from organic fertilizers, cropping practices, and livestock manure management. Previous inventories simply accounted for emissions resulting from the application of synthetic fertilizers. As a result of this more comprehensive methodology, estimates have roughly tripled relative to previous years.
- Nitrous oxide emissions from manure management have been estimated for the first time.
- Additional crop types have been included in the analysis of emissions from agricultural residue burning.
- Carbon dioxide fluxes estimated from land-use change and forestry have been revised to include forest soils, forest understory, and non-forest soils. Additionally, estimates for carbon stocks in forest product pools now include wood harvested from public lands, which were previously excluded. These changes have more than doubled the flux estimates relative to previous year's inventories.
- An improved methodology for estimating methane emissions from landfills has been used, which tracks explicitly the shift to fewer, larger landfills.
- Nitrous oxide emissions from human sewage and waste combustion were estimated for the first time.

2. Energy

Energy-related activities were the primary source of anthropogenic greenhouse gas emissions, accounting for 86 percent of total U.S. emissions annually on a carbon equivalent basis in 1996. This included 99, 33, and 20 percent of the nation's carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 81 percent of national emissions from all sources on a carbon equivalent basis (see Figure 2-1), while the non-CO_2 emissions from energy represented a much smaller portion of total national emissions (4 percent collectively).

Figure 2-1



Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted. Due to the relative importance of fossil fuel combustion related CO_2 emissions, they are considered separately from other emissions. Fossil fuel combustion also emits CH_4 and N_2O, as well as criteria pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs). Fossil fuel combustion—from stationary and mobile sources—was the second largest source N_2O emissions in the United States, and overall energy related activities are the largest sources of criteria pollutant emissions.

Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of CH_4 from natural gas systems, petroleum systems, and coal mining. Smaller quantities of CO_2, CO, NMVOCs, and NO_x are also emitted.

The combustion of biomass and biomass-based fuels also emits greenhouse gases. Carbon dioxide emissions from these activities, however, are not included in national emissions totals under the Energy sector because biomass fuels are of biogenic origin. It is assumed that the carbon released when biomass is consumed is recycled as U.S. forests and crops regenerate, causing no net addition of CO_2 to be added to the atmosphere. The net impacts of land-use and forestry activities on the carbon cycle are accounted for under the Land-use change and Forestry sector.

Overall, emissions from the Energy sector have increased from 1990 to 1996 due, in part, to the strong performance of the U.S. economy. Over this period, the U.S. Gross Domestic Product (GDP) grew approximately 13 percent, or at an annualized rate of about 2 percent. This robust economic activity increased the demand for fossil fuels, with an associated increase in greenhouse gas emissions. Table 2-1 summarizes emissions from the Energy sector in units of million metric tons of carbon equivalents (MMTCE), while unweighted gas emissions in teragrams

Table 2-1: Emissions from the Energy Sector (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO_2	**1,333.4**	**1,318.7**	**1,338.8**	**1,370.5**	**1,392.6**	**1,402.4**	**1,453.8**
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
Biomass-Ethanol*	1.6	1.2	1.5	1.7	1.8	2.0	1.4
Biomass-Wood*	47.0	46.9	49.0	47.6	48.4	50.2	53.2
International Bunker Fuels*	22.7	24.0	24.9	22.9	22.3	23.6	22.5
Non-fuel Use Carbon Stored*	(69.2)	(68.8)	(70.6)	(73.1)	(78.2)	(78.8)	(81.7)
CH_4	**62.2**	**61.4**	**61.3**	**58.5**	**58.6**	**59.5**	**58.4**
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
N_2O	**16.9**	**17.6**	**18.5**	**19.3**	**20.1**	**20.4**	**20.5**
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
Total	**1,412.5**	**1,397.6**	**1,418.6**	**1,448.4**	**1,471.3**	**1,482.3**	**1,532.7**

+ Does not exceed 0.05 MMTCE
* These figures are presented for informational purposes only and are not included or are already accounted for in totals.
Note: Totals may not sum due to independent rounding.

Table 2-2: Emissions from the Energy Sector (Tg)

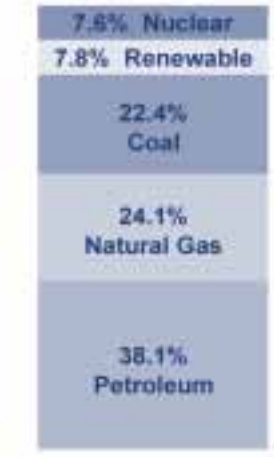
Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO_2	**4,889.2**	**4,835.2**	**4,908.8**	**5,025.1**	**5,106.3**	**5,142.2**	**5,330.6**
Fossil Fuel Combustion	4,881.9	4,826.9	4,900.7	5,014.1	5,095.2	5,128.5	5,317.8
Natural Gas Flaring	7.3	8.2	8.1	11.0	11.1	13.7	12.7
Biomass-Ethanol*	5.7	4.5	5.5	6.1	6.7	7.2	5.1
Biomass-Wood*	172.2	171.9	179.7	174.5	177.5	184.2	195.0
International Bunker Fuels*	83.4	87.8	91.3	83.8	81.7	86.7	82.4
Non-fuel Use Carbon Stored*	(253.8)	(252.3)	(258.8)	(268.2)	(286.6)	(289.1)	(299.7)
CH_4	**10.9**	**10.7**	**10.7**	**10.2**	**10.2**	**10.4**	**10.2**
Stationary Sources	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Mobile Sources	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Coal Mining	4.2	4.0	3.8	3.4	3.4	3.6	3.3
Natural Gas Systems	5.7	5.8	5.9	5.9	5.9	5.9	5.9
Petroleum Systems	0.3	0.3	0.3	0.3	0.3	0.3	0.3
N_2O	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Stationary Sources	+	+	+	+	+	+	+
Mobile Sources	0.2	0.2	0.2	0.2	0.2	0.2	0.2

+ Does not exceed 0.05 Tg
* These figures are presented for informational purposes only and are not included or are already accounted for in totals.
Note: Totals may not sum due to independent rounding.

(Tg) are provided in Table 2-2. Overall, emissions due to energy-related activities increased by more than 9 percent from 1990 to 1996, rising from 1,412.5 MMTCE in 1990 to 1,532.7 MMTCE in 1996. The growth in emissions from 1995 to 1996 (3.4 percent) was the largest percent increase over the seven year period. This growth rate in emissions actually exceeded the overall growth rate in the economy. Discussion of specific Energy sector trends is presented below.

Figure 2-2

1996 U.S. Energy Consumption



Source: DOE/EIA-0384(96), Annual Energy Review 1996, Table 1.3, July 1997

Carbon Dioxide Emissions from Fossil Fuel Combustion

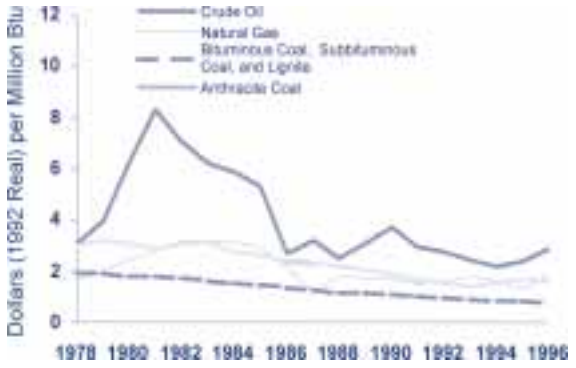
The majority of energy consumed in the United States, approximately 84.5 percent, was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum in 1996 (see Figure 2-2). Of the remaining, 7.6 percent was supplied by nuclear electric power and 7.8 percent from renewable sources (EIA 1997a).

As fossil fuels are combusted, the carbon stored in the fuels is emitted as CO_2 and smaller amounts of other gases, including methane (CH_4), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs). These other gases are emitted as a by-product of incomplete fuel combustion. The amount of carbon in the fuel varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about 55 percent.[1] Petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent of total energy consumption over the period of 1990 through 1996 (see Figure 2-2). 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 major factor behind this trend was a robust domestic economy, combined with relatively low energy prices. For example, petroleum prices had changed little in real terms since the 1970s, with coal prices actually declining in real terms compared to prices in the 1970s (EIA 1997a) (see Figure 2-3). After 1990, when carbon dioxide emissions from fossil fuel combustion were 1,331.4 MMTCE (4,881.9 Tg), there was a slight decline

Figure 2-3

Fossil Fuel Production Prices



Source: DOE/EIA-0384(96), Annual Energy Review 1996, July, 1997, Table 3.1

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

Table 2-3: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and End-Use Sector (MMTCE)

Fuel/End-Use Sector	1990	1991	1992	1993	1994	1995	1996
Coal	**481.6**	**475.8**	**478.3**	**494.7**	**496.7**	**498.5**	**524.0**
Residential	1.6	1.4	1.5	1.5	1.4	1.4	1.4
Commercial	2.4	2.2	2.2	2.2	2.1	2.1	2.1
Industrial	68.5	64.8	62.6	62.2	62.7	62.1	59.4
Transportation	-	-	-	-	-	-	-
Utilities	409.0	407.2	411.8	428.7	430.2	432.7	460.9
U.S. Territories	0.1	0.2	0.2	0.2	0.3	0.3	0.3
Natural Gas	**273.1**	**277.9**	**286.2**	**296.3**	**302.1**	**314.8**	**318.6**
Residential	65.1	67.5	69.4	73.4	71.8	71.7	77.4
Commercial	38.8	40.4	41.5	43.1	42.9	45.9	47.4
Industrial	118.2	120.0	125.8	131.0	133.3	139.7	143.0
Transportation	9.8	8.9	8.8	9.3	10.2	10.4	10.5
Utilities	41.2	41.1	40.7	39.5	44.0	47.2	40.3
U.S. Territories	-	-	-	-	-	-	-
Petroleum	**576.7**	**562.6**	**572.0**	**576.4**	**593.5**	**587.7**	**609.0**
Residential	23.9	24.4	24.8	26.2	25.3	25.7	27.2
Commercial	18.0	17.1	16.1	14.9	14.9	15.0	15.3
Industrial	100.2	94.5	104.3	98.3	102.2	97.9	104.6
Transportation	399.0	391.1	397.3	404.1	416.6	421.7	434.3
Utilities	26.6	25.1	19.9	22.5	20.6	14.0	15.6
U.S. Territories	9.0	10.5	9.6	10.4	11.2	10.9	10.6
Geothermal*	**0.1**	**0.1**	**0.1**	**0.1**	**+**	**+**	**+**
Total	**1,331.4**	**1,316.4**	**1,336.6**	**1,367.5**	**1,389.6**	**1,398.7**	**1,450.3**

- Not applicable
+ Does not exceed 0.05 MMTCE
* Although not technically a fossil fuel, geothermal energy related CO_2 emissions are included for reporting purposes.
Note: Totals may not sum due to independent rounding.

of emissions in 1991, followed by an increase to 1,450.3 MMTCE (5,317.8 Tg) in 1996 (see Table 2-3 and Table 2-4). 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.

Consumption of all fossil fuels increased, with about 38 percent of the increase in CO_2 emissions from fossil fuel combustion since 1990 coming from natural gas consumption, 36 percent from coal, and 26 percent from petroleum. 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 6.5 percent from 1995 to 1996.

In 1996, the U.S. coal industry produced the largest amount of coal ever. Preliminary data (EIA 1997b) show that annual U.S. coal consumption totaled 892 teragrams (Tg) in 1996, a 4.5 percent increase from 1995, the combustion of which accounted for roughly half of the total increase in emissions during the same period.

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 higher fuel consumption for transportation activities.

Table 2-4: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and End-Use Sector (Tg)

Fuel/End-Use Sector	1990	1991	1992	1993	1994	1995	1996
Coal	**1,765.7**	**1,744.7**	**1,753.8**	**1,813.9**	**1,821.3**	**1,827.8**	**1,921.4**
Residential	5.8	5.3	5.4	5.3	5.2	5.1	5.1
Commercial	8.7	8.0	8.1	8.1	7.9	7.6	7.6
Industrial	251.0	237.6	229.5	228.0	229.9	227.7	217.8
Transportation	-	-	-	-	-	-	-
Utilities	1,499.7	1,493.2	1,510.0	1,571.7	1,577.4	1,586.4	1,689.9
U.S. Territories	0.4	0.6	0.8	0.7	0.9	0.9	0.9
Natural Gas	**1,001.3**	**1,019.1**	**1,049.5**	**1,086.5**	**1,107.7**	**1,154.3**	**1,168.1**
Residential	238.5	247.3	254.5	269.1	263.3	263.0	283.8
Commercial	142.4	148.2	152.3	158.2	157.4	168.2	173.7
Industrial	433.2	440.1	461.2	480.4	488.6	512.1	524.2
Transportation	36.0	32.8	32.1	33.9	37.2	38.1	38.6
Utilities	151.1	150.6	149.3	144.9	161.2	173.0	147.9
U.S. Territories	-	-	-	-	-	-	-
Petroleum	**2,114.6**	**2,062.9**	**2,097.3**	**2,113.6**	**2,166.0**	**2,146.2**	**2,228.2**
Residential	87.7	89.4	90.9	96.1	92.8	94.4	99.8
Commercial	66.1	62.6	59.1	54.7	54.7	54.9	56.2
Industrial	367.2	346.3	382.3	360.5	374.6	359.1	383.7
Transportation	1,463.1	1,434.1	1,456.8	1,481.8	1,527.4	1,546.3	1,592.5
Utilities	97.6	91.9	73.1	82.5	75.6	51.3	57.2
U.S. Territories	32.8	38.5	35.1	38.0	40.9	40.1	38.8
Geothermal*	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.1**	**0.1**
Total	**4,881.9**	**4,826.9**	**4,900.7**	**5,014.1**	**5,095.2**	**5,128.5**	**5,317.8**

- Not applicable
+ Does not exceed 0.05 Tg
* Although not technically a fossil fuel, geothermal energy related CO_2 emissions are included for reporting purposes.
Note: Totals may not sum due to independent rounding.

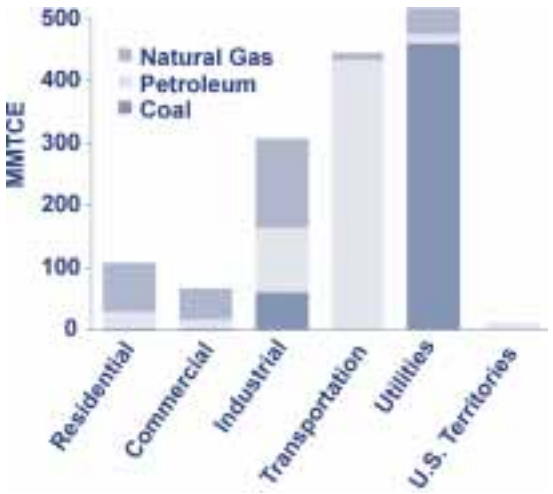
From 1995 to 1996, emissions from natural gas rose only 1.2 percent, largely due to higher natural gas prices in 1996 that reversed a 10 year long trend of declining prices. The U.S. Department of Energy's Energy Information Administration cited low levels of storage and unusually cold weather as the two main reasons for this price increase (EIA 1997e). 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 1997e). Increased consumption of natural gas accounted for only 7.5 percent of the increase in fossil fuel CO_2 emissions from 1995 to 1996.

End-Use Sector Contributions

The four end-use sectors contributing to CO_2 emissions from fossil fuel combustion include: industrial, transportation, residential, and commercial. Electric utilities also emit CO_2, although these emissions are produced as they consume fossil fuel to provide electricity to one of the four end-use sectors. For the discussion below, utility emissions have been distributed to each end-use sector based upon their aggregate electricity consumption. Emissions from utilities are addressed separately after the end-use sectors have been discussed. Emissions from U.S. territories are also calculated separately due to a lack of end-use specific consumption data. Table 2-5 and Figure 2-4 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Figure 2-4

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

Industrial End-Use Sector

The industrial end-use sector accounted for approximately one-third of CO_2 emissions from fossil fuel combustion. On average, nearly 64 percent of these emissions resulted from the direct consumption of fossil fuels in order to meet industrial demand for steam and process heat. The remaining 36 percent of industrial energy needs was met by electricity for uses such as motors, electric furnaces, ovens, and lighting.

Coal consumption by industry declined in 1996 from the previous year's levels. At coke plants, consumption dropped by 3.9 percent. Consumption by other industries declined by 2.9 percent (EIA 1997b). Industrial use of natural gas and petroleum were up in 1996 by 2.4 percent and 5.0 percent, respectively, from 1995 levels.

The industrial end-use sector was also the largest user of fossil fuels for non-energy applications. Fossil fuels used for producing fertilizers, plastics, asphalt, or lubricants can sequester or store carbon in products for long periods of time. Asphalt used in road construction, for example, stores carbon essentially indefinitely. Similarly, fossil fuels used in the manufacture of materials like plastics also store carbon, releasing it if the material is burned. Carbon stored by industrial or transportation non-fuel uses of fossil fuels rose 18 percent between 1990 and 1996 (69.2 MMTCE and 81.7 MMTCE, respectively).

Transportation End-Use Sector

The transportation sector accounted for slightly over 30 percent of U.S. CO_2 emissions from fossil fuel combustion. Virtually all of the energy consumed in this sector came from petroleum-based products, with nearly two-thirds resulting from gasoline consumption in automobiles and other on-road vehicles. Other uses, including diesel fuel for the trucking industry and jet fuel for aircraft, accounted for the remainder.

Following the overall trend in U.S. energy consumption, fossil fuel combustion for transportation grew steadily after declining in 1991, resulting in an increase in CO_2 emissions from 409.6 MMTCE (1,501.7 Tg) in 1990 to 445.5 MMTCE (1,633.5 Tg) in 1996. During this seven year period, petroleum consumption—mainly motor gasoline, distillate fuel oil (e.g., diesel), and jet fuel—in the transportation end-use sector increased 8.5 percent. This increase was slightly offset by decreases in the consumption of avia-

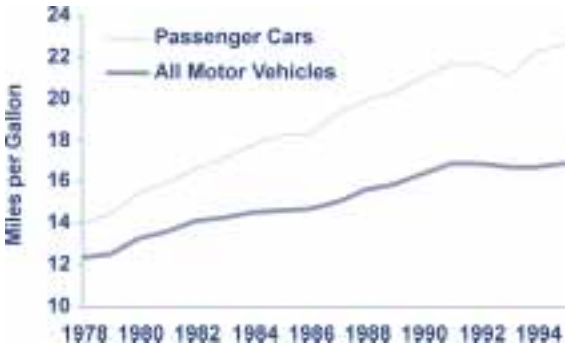
Table 2-5: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMTCE)*

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.

Figure 2-5

Motor Vehicle Fuel Efficiency



Source: DOE/EIA-0384(96), Annual Energy Review 1996, July, 1997, Table 3.13

tion gasoline and residual fuel. Overall, motor vehicle fuel efficiency stabilized in the 1990s after increasing steadily since 1977 (EIA 1997a). This trend is due, in part, to new motor vehicle sales being increasingly dominated by less fuel-efficient light-duty trucks and sport-utility vehicles (see Figure 2-5). Moreover, declining petroleum prices during these years—with the exception of 1996, when the average price increased—combined with a stronger economy, were largely responsible for an overall increase in vehicle miles traveled by on-road vehicles (see Figure 2-6).

Table 2-6 provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. On average 60 percent of the emissions from this end-use sector were the result of the combustion of motor gasoline in passenger cars and light-duty trucks. Diesel highway vehicles and jet aircraft were also significant contributors, each accounting for, on average, 13 percent of CO_2 emissions from the transportation end-use sector. It should be noted that the U.S. Department of Transportation's Federal Highway Administration altered its definition of light-duty trucks in 1995 to include sport utility vehicles and minivans; previously these vehicles were included under the passenger cars category. As a consequence of this reclassification, a discontinuity exists in the time series in Table 2-6 for both passenger cars and light-duty trucks.

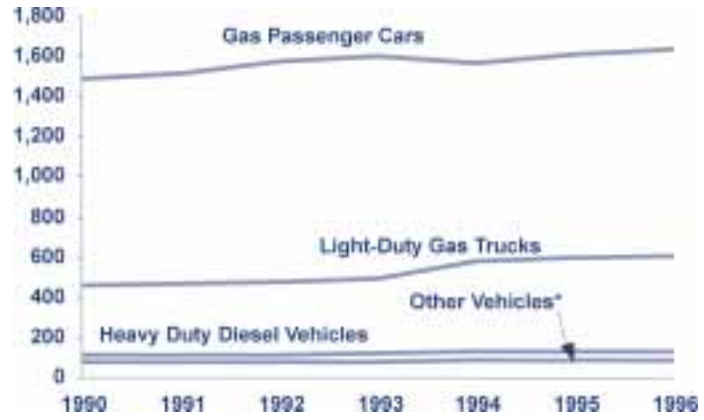
Residential and Commercial End-Use Sectors

From 1990 to 1996, the residential and commercial end-use sectors, on average, accounted for 19 and 16 percent, respectively, of CO_2 emissions from fossil fuel combustion. Unlike in other major end-use sectors, emissions from the residential end-use sector did not decline in 1991, but they did decrease in 1992 and 1994, then grew steadily through 1996. Both end-use sectors were heavily reliant on electricity for meeting energy needs, with about two-thirds of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs.

Natural gas consumption in the residential and commercial end-use sectors increased in 1996 by 7.6 and 3.3 percent, respectively. This increase is attributed to record low temperatures at the start of 1996 and new consumers in the natural gas market (EIA 1997e). Petroleum consumption increased about 6 and 2 percent from 1995

Figure 2-6

U.S. Vehicle Miles Traveled



* "Other Vehicles" includes heavy duty gas vehicles, diesel passenger cars, light duty diesel trucks, and motorcycles
Source: EPA/OAQPS

Important Note: There is a discontinuity in the VMT data starting in 1994. Before 1994, vans, minivans, and sport utility vehicles were included in the passenger car category. Beginning in 1994, all three vehicle types (passenger or cargo) were included in the light duty truck category.

Table 2-6: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMTCE)

Fuel/Vehicle Type	1990	1991	1992	1993	1994	1995	1996
Motor Gasoline	**260.9**	**259.5**	**263.4**	**269.3**	**273.7**	**279.9**	**285.5**
Passenger Cars*	167.3	165.9	170.0	171.5	170.5	158.1	161.3
Light-Duty Trucks*	74.9	74.7	74.6	77.8	84.2	101.3	103.4
Other Trucks	11.3	11.2	11.2	11.7	10.4	10.9	11.2
Motorcycles	0.4	0.4	0.4	0.5	0.5	0.5	0.5
Buses	0.6	0.6	0.6	0.7	0.9	0.8	0.8
Construction Equipment	0.6	0.6	0.6	0.6	0.6	0.7	0.7
Agricultural Machinery	1.2	1.2	1.2	2.0	2.1	2.2	2.2
Boats (Recreational)	4.6	4.8	4.7	4.6	4.5	5.3	5.4
Distillate Fuel Oil (Diesel)	**73.4**	**70.5**	**73.4**	**75.2**	**80.4**	**81.8**	**86.1**
Passenger Cars*	2.0	1.9	2.0	2.0	2.0	1.8	1.9
Light-Duty Trucks*	2.5	2.4	2.5	2.6	2.8	3.3	3.4
Other Trucks	45.3	43.3	45.1	47.7	51.7	52.7	55.5
Buses	2.2	2.2	2.3	2.3	2.3	2.7	2.8
Construction Equipment	2.9	2.9	2.9	2.9	2.9	2.8	3.0
Agricultural Machinery	6.4	6.3	6.4	6.4	6.3	6.2	6.5
Boats (Freight)	5.0	4.8	5.1	4.6	4.6	4.3	4.6
Locomotives	7.3	6.7	7.3	6.6	7.8	8.0	8.4
Jet Fuel	**55.0**	**53.0**	**52.3**	**52.7**	**54.9**	**54.2**	**56.7**
General Aviation	1.7	1.5	1.3	1.3	1.2	1.4	1.5
Domestic Carriers	32.0	29.6	30.5	30.9	32.0	32.8	34.2
International Carriers	5.1	5.1	5.3	5.3	5.5	5.7	6.0
Military Aircraft	16.3	16.9	15.2	15.2	16.1	14.3	15.0
Aviation Gasoline	**0.8**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**	**0.7**
General Aviation	0.8	0.8	0.8	0.7	0.7	0.7	0.7
Residual Fuel Oil	**6.7**	**5.5**	**5.5**	**4.2**	**4.6**	**2.9**	**3.1**
Boats (Freight)	6.7	5.5	5.5	4.2	4.6	2.9	3.1
Natural Gas	**9.8**	**8.9**	**8.8**	**9.3**	**10.2**	**10.4**	**10.5**
Passenger Cars*	+	+	+	+	+	+	+
Light-Duty Trucks*	+	+	+	+	+	+	+
Buses	+	+	+	+	+	+	+
Pipeline	9.8	8.9	8.8	9.2	10.1	10.4	10.5
LPG	**0.4**	**0.3**	**0.3**	**0.3**	**0.5**	**0.5**	**0.6**
Light-Duty Trucks*	0.1	0.1	0.1	0.1	0.2	0.3	0.3
Other Trucks	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Buses	+	+	+	+	+	+	+
Electricity	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Buses	+	+	+	+	+	+	+
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pipeline	0.6	0.5	0.5	0.5	0.5	0.5	0.5
Lubricants	**1.8**	**1.6**	**1.6**	**1.6**	**1.7**	**1.7**	**1.6**
Total	**409.6**	**400.8**	**406.7**	**414.1**	**427.4**	**432.8**	**445.5**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMTCE
*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 emissions for passenger cars from 1994 to 1995 was observed. This gap, however, was offset by an equivalent rise in emissions from light-duty trucks.

to 1996 in the residential and commercial end-use sectors, respectively. Coal consumption was a small component of energy use in these end-use sectors.

Electric Utilities

As one of the largest consumers of fossil fuels in the United States (averaging 28 percent of national fossil fuel consumption and 88 percent of coal consumption on an energy content basis), electric utilities were collectively the largest producers of U.S. CO_2 emissions, accounting for 35 percent. The United States relies on electricity to meet a significant portion of its energy requirements for uses such as lighting, heating, electric motors, and air conditioning. Because electric utilities

consume such a substantial portion of U.S. fossil fuels to generate this electricity, the type of fuel they use has a significant effect national CO_2 emissions. Some of this electricity was generated with the lowest CO_2 emitting energy technologies, particularly non-fossil options such as hydropower or nuclear energy; however, electric utilities still 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.

The combustion of coal was used to generate 57 percent of the electricity consumed in the United States in 1996, up from 55 percent in 1995 (EIA 1997f). From 1990 to 1996, coal emissions from utilities increased 12.7 percent. This increase in coal-related emissions from utilities was alone responsible for 56 percent of the overall rise in CO_2 emissions from fossil fuel combustion.

Balancing the increased consumption of coal by utilities, their consumption of natural gas declined in 1996 due to rising gas prices relative to coal and petroleum (EIA 1997a). Utility natural gas use increased significantly in 1994 and 1995, as the natural gas industry stabilized following a series of cold winters and a period of industry restructuring. However, in 1996 utility gas prices increased by a dramatic 33 percent (EIA 1997a), making gas-based electricity generation less economical. Consequently, natural gas consumption by electric utilities declined by 15 percent in 1996. Utilities compensated primarily by burning more coal, emissions from which increased by 6.5 percent from 1995 to 1996. Petroleum constitutes only a small portion of utility fossil fuel consumption (3.4 percent in 1996**,** occurring mostly in the eastern United States).

Methodology

The methodology used by the United States for estimating CO_2 emissions from fossil fuel combustion is conceptually similar to the approach recommended by the IPCC for countries that intend to develop detailed, sectoral-based emission estimates (IPCC/UNEP/OECD/IEA 1997). A detailed description of the U.S. methodology is presented in Annex A, and is characterized by the following five steps:

1. *Determine fuel consumption by fuel type and end-use sector*. By aggregating consumption data by end-use sector (e.g., commercial, industrial, etc.), primary fuel type (e.g., coal, oil, gas), and secondary fuel category (e.g., gasoline, distillate fuel, etc.), estimates of total U.S. energy consumption for a particular year were made.[2]
2. *Determine the total carbon content of fuels consumed*. Total carbon was estimated by multiplying the amount of fuel consumed by the amount of carbon in each fuel. This total carbon estimate defines the maximum amount of carbon that could potentially be released to the atmosphere if all of the carbon were converted to CO_2. The carbon emission coefficients used by the United States are presented in Annex A.
3. *Subtract the amount of carbon stored in products.* Non-fuel uses of fossil fuels can result in storage of some or all of the carbon contained in the fuel for some period of time, depending on the end-use. For example, asphalt made from petroleum can sequester up to 100 percent of the carbon for extended periods of time, while other products, such as lubricants or plastics, lose or emit some carbon when they are used and/or burned as waste. The amount of carbon sequestered or stored in non-energy uses of fossil fuels was based on the best available data on the end-uses and ultimate fate of the various energy products. These non-energy uses occurred in the industrial and transportation end-use sectors. Carbon sequestered by these uses was 69 MMTCE in 1990, rising to 82 MMTCE in 1996.
4. *Adjust for carbon that does not oxidize during combustion*. Because combustion processes are not 100 percent efficient, some of the carbon contained in fuels is not emitted to the atmosphere. Rather, it remains behind as soot or other by-products of inefficient combustion. The estimated amount of carbon not oxidized due to inefficiencies during the combustion process ranged from 1 percent for petroleum and coal to 0.5 percent for natural gas (see Annex A).

[2] Fuel consumption by U.S. territories (i.e. American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed about 11 MMTCE of emissions in 1995 and 1996.

5. *Subtract emissions from international bunker fuels.* According to the IPCC guidelines (IPCC/UNEP/OECD/IEA 1997) emissions from international transport activities, or bunker fuels, should not be included in national totals. Because U.S. energy consumption statistics include these bunker fuels—primarily residual oil—as part of consumption by the transportation end-use sector, emissions from this source were calculated separately and subtracted. The calculations for emissions from bunker fuels follows the same procedures used for emissions from consumption of all fossil fuels (i.e., estimation of consumption, determination of carbon content, and adjustment for the fraction of carbon not oxidized). Carbon dioxide emissions from international bunkers were 22.7 MMTCE (83.4 Tg) in 1990, rising to 24.9 MMTCE (91.3 Tg) in 1992 and then declining to 22.5 MMTCE (82.4 Tg) in 1996.
6. *Allocate transportation emissions by vehicle type.* Because the transportation end-use sector was the largest direct consumer of fossil fuels in the United States, a more detailed accounting of carbon dioxide emissions is provided. Fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Specific data by vehicle type were not available for 1996; therefore, the 1995 percentage allocations were applied to 1996 fuel consumption data in order to estimate emissions in 1996. Military aircraft jet fuel consumption was assumed to account for the difference between total U.S. jet fuel consumption (as reported by DOE/EIA) and civilian airline consumption (as reported by DOT/BTS).

Data Sources

Fuel consumption, carbon content of fuels, and percent of carbon sequestered in non-fuel uses data were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE). Fuel consumption data were obtained primarily from the *Monthly Energy Review* (EIA 1997d). IPCC (IPCC/UNEP/OECD/IEA 1997) provided combustion efficiency rates for petroleum and natural gas. Bechtel (1993) provided the combustion efficiency rates for coal. Vehicle type fuel consumption data was taken from the *Transportation Energy Databook* prepared by the Center for Transportation Analysis at Oak Ridge National Laboratory (DOE 1993, 1994, 1995, 1996, 1997).

For consistency of reporting, the IPCC has recommended that national inventories report energy data (and emissions from energy) using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA, and used in this inventory, are, instead, "bottom up" in nature. In other words, they are collected through surveys at the point of delivery or use and aggregated to determine national totals.

Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted, in principle is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and consumption of products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

There are uncertainties, however, concerning the consumption data sources, carbon content of fuels and products, and combustion efficiencies. For example, given the same primary fuel type (e.g., coal), the amount of carbon contained in the fuel per unit of useful energy can vary. Non-energy uses of the fuel can also create situations where the carbon is not emitted to the atmosphere (e.g., plastics, asphalt, etc.) or is emitted at a much delayed rate. The proportions of fuels used in these non-fuel production processes that result in the sequestration of carbon have been assumed. Additionally, inefficiencies in the combustion process, which can result in ash

or soot remaining unoxidized for long periods, were also assumed. These factors all contribute to the uncertainty in the CO_2 estimates. For the United States, however, these uncertainties are believed to be relatively small. U.S. CO_2 emission estimates from fossil fuel combustion are considered accurate within one or two percent. See, for example, Marland and Pippin (1990).

Stationary Source Fossil Fuel Combustion (excluding CO_2)

Stationary sources encompass all fossil fuel combustion activities except transportation (i.e., mobile combustion). Other than carbon dioxide (CO_2), which was addressed in the previous section, gases from stationary combustion include the greenhouse gases methane (CH_4) and nitrous oxide (N_2O) and the criteria pollutants nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs). Emissions of these gases from stationary sources depend upon fuel characteristics, technology type, usage of pollution control equipment, and ambient environmental conditions. Emissions also vary with the size and vintage of the combustion technology as well as maintenance and operational practices.

Stationary combustion is a small source of CH_4 and N_2O in the United States. Methane emissions from stationary combustion in 1996 accounted for less than 2 percent of total U.S. CH_4 emissions, while N_2O emissions from stationary combustion accounted for just under 4 percent of all N_2O emissions. Emissions of CH_4 increased slightly (from 2.3 to 2.5 MMTCE) over the period 1990 to 1996, due mainly to an increase in residential wood use. Nitrous oxide emissions rose 9 percent from 3.7 MMTCE in 1990 to 4.0 MMTCE in 1996. The largest source of N_2O emissions was coal combustion by electric utilities, which alone accounted for 55 percent of total N_2O emissions from stationary combustion in 1996.

Nitrous oxide and NO_x emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. Carbon monoxide emissions from stationary combustion are generally a function of the efficiency of combustion and the use of emission controls; they are highest when less oxygen is present in the air-fuel mixture than is necessary for complete combustion. These conditions are most likely to occur during start-up and shut-down and during fuel switching (e.g., the switching of coal grades at a coal-burning electric utility plant). Methane and NMVOC emissions from stationary combustion are believed to be a function of the CH_4 content of the fuel and post-combustion controls.

In general, stationary combustion was a significant source of NO_x and CO emissions, and a smaller source of NMVOCs. In 1996, emissions of NO_x from stationary combustion represented 45 percent of national NO_x emissions, while CO and NMVOC emissions from stationary combustion contributed approximately 7 and 6 percent, respectively, to the national totals for the same year. From 1990 to 1996, emissions of NO_x decreased by 4 percent, while emissions of CO and NMVOCs increased by 8 and 7 percent, respectively.

The increase in CO and NMVOC emissions from 1990 to 1996 can largely be attributed to increased residential wood consumption, which is the most significant source of these pollutants in the Energy sector. A combination of technological advances and more stringent emissions requirements dampened the rate of increase in these emissions. Overall, NO_x emissions from energy varied due to fluctuations in emissions from electric utilities, which constituted 58 percent of stationary NO_x emissions in 1996. Table 2-7, Table 2-8, Table 2-9, and Table 2-10 provide CH_4 and N_2O emission estimates from mobile sources by vehicle type, fuel type, and transport activity. Estimates of NO_x, CO, and NMVOC emissions in 1996 are given in Table 2-11.[3]

Methodology

Methane and nitrous oxide emissions were estimated by multiplying emission factors (by sector and fuel type) by fossil fuel and wood consumption data. Greenhouse gas emissions from stationary combustion activi-

[3] See Annex B for a complete time series of criteria pollutant emission estimates for 1990 through 1996.

Table 2-7: CH_4 Emissions from Stationary Sources (MMTCE)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996
Electric Utilities	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	+	+	+	+	+	+	+
Natural gas	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+
Industrial	**0.7**	**0.7**	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**
Coal	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural gas	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Wood	0.3	0.2	0.3	0.3	0.3	0.3	0.3
Commercial/Institutional	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.1	+	+	+	+	+	+
Natural gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	+	+	+	0.1	0.1	0.1	0.1
Residential	**1.3**	**1.3**	**1.4**	**1.2**	**1.2**	**1.3**	**1.3**
Coal	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.9	1.0	1.1	0.9	0.9	1.0	1.0
Total	**2.3**	**2.3**	**2.4**	**2.3**	**2.3**	**2.4**	**2.5**

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

Table 2-8: N_2O Emissions from Stationary Sources (MMTCE)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996
Electric Utilities	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**	**2.1**	**2.2**
Coal	1.9	1.9	1.9	2.0	2.0	2.0	2.1
Fuel Oil	0.1	0.1	+	0.1	+	+	+
Natural gas	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+
Industrial	**1.3**	**1.3**	**1.3**	**1.3**	**1.4**	**1.4**	**1.4**
Coal	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel Oil	0.4	0.4	0.4	0.4	0.5	0.4	0.5
Natural gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.5	0.5	0.5	0.5	0.5	0.5	0.6
Commercial/Institutional	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	+	+	+	+	+	+
Natural gas	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+
Residential	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	+	+	+	+	+	+	+
Wood	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**3.7**	**3.7**	**3.7**	**3.8**	**3.8**	**3.8**	**4.0**

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

Table 2-9: CH_4 Emissions from Stationary Sources (Gg)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996
Electric Utilities	**23**	**23**	**22**	**23**	**23**	**22**	**23**
Coal	16	16	16	17	17	17	18
Fuel Oil	4	4	3	3	3	2	2
Natural gas	3	3	3	3	3	3	3
Wood	+	+	+	+	+	+	+
Industrial	**129**	**126**	**130**	**132**	**136**	**138**	**142**
Coal	27	26	25	25	25	24	23
Fuel Oil	17	16	17	17	18	17	18
Natural gas	40	41	43	45	46	48	49
Wood	44	44	45	46	48	48	51
Commercial/Institutional	**31**	**31**	**31**	**35**	**35**	**36**	**38**
Coal	1	1	1	1	1	1	1
Fuel Oil	9	9	8	8	8	8	8
Natural gas	13	13	14	14	14	15	16
Wood	9	9	9	13	13	13	14
Residential	**218**	**227**	**237**	**211**	**207**	**223**	**226**
Coal	19	17	17	17	17	16	16
Fuel Oil	13	13	13	14	13	14	14
Natural Gas	21	22	23	24	24	24	26
Wood	166	175	184	156	153	170	170
Total	**401**	**407**	**420**	**402**	**401**	**420**	**429**

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

Table 2-10: N_2O Emissions from Stationary Sources (Gg)

Sector/Fuel Type	1990	1991	1992	1993	1994	1995	1996
Electric Utilities	**24**	**23**	**24**	**25**	**25**	**25**	**26**
Coal	23	22	23	24	24	24	25
Fuel Oil	1	1	1	1	1	+	+
Natural gas	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+
Industrial	**16**	**15**	**16**	**16**	**16**	**16**	**17**
Coal	4	4	3	3	3	3	3
Fuel Oil	5	5	5	5	5	5	6
Natural gas	1	1	1	1	1	1	1
Wood	6	6	6	6	6	6	7
Commercial/Institutional	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Coal	+	+	+	+	+	+	+
Fuel Oil	1	1	+	+	+	+	+
Natural gas	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+
Residential	**3**	**4**	**4**	**3**	**3**	**4**	**4**
Coal	+	+	+	+	+	+	+
Fuel Oil	1	1	1	1	1	1	1
Natural Gas	+	+	+	+	+	+	1
Wood	2	2	2	2	2	2	2
Total	**44**	**43**	**44**	**45**	**45**	**45**	**47**

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

Table 2-11: 1996 Emissions of NO_x, CO, and NMVOC from Stationary Sources (Gg)

Sector/Fuel Type	NO_x	CO	NMVOCs
Electric Utilities	**5,473**	**341**	**41**
Coal	5,004	238	28
Fuel Oil	87	10	3
Natural gas	244	40	2
Wood	NA	NA	NA
Internal Combustion	137	53	9
Industrial	**2,875**	**972**	**188**
Coal	543	90	5
Fuel Oil	223	65	11
Natural gas	1,212	316	66
Wood	NA	NA	NA
Other Fuels[a]	113	277	46
Internal Combustion	784	224	60
Commercial/Institutional	**366**	**227**	**21**
Coal	35	14	1
Fuel Oil	93	17	3
Natural gas	212	49	10
Wood	NA	NA	NA
Other Fuels[a]	26	148	8
Residential	**804**	**3,866**	**724**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	44	3,621	687
Other Fuels[a]	760	244	37
Total	**9,518**	**5,407**	**975**

NA (Not Available)
Note: Totals may not sum due to independent rounding. See Annex B for emissions in 1990 through 1995.
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1997).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1997).

ties were grouped into four sectors: industrial, commercial/institutional, residential, and electric utilities. For CH_4 and N_2O, estimates were based on consumption of coal, natural gas, fuel oil, and wood.

For NO_x, CO, and NMVOCs, the major source categories included in this section are those used in EPA (1997): coal, fuel oil, natural gas, wood, other fuels (including LPG, coke, coke oven gas, and others), and stationary internal combustion. The EPA also estimates emissions of NO_x, CO, and NMVOCs by sector and fuel source using a "bottom-up" estimating procedure. In other words, emissions were calculated either for individual sources (e.g., industrial boilers) or for multiple sources combined, using basic activity data as indicators of emissions. Depending on the source category, these basic activity data may include fuel consumption, fuel deliveries, tons of refuse burned, raw material processed, etc.

The EPA derived the overall emission control efficiency of a source category from published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of NO_x, CO, and NMVOCs from stationary source combustion, as described above, is similar to the methodology recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

More detailed information on the methodology for calculating emissions from stationary sources including emission factors and activity data is provided in Annex B.

Data Sources

Emissions estimates for NO_x, CO, and NMVOCs in this section were taken directly from the EPA's *National Air Pollutant Emissions Trends: 1900 - 1996* (EPA 1997). U.S. energy data were provided by the U.S. Energy Information Administration's *Monthly Energy Review* (EIA 1997). Emission factors were provided by *the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997).

Uncertainty

Methane emission estimates from stationary sources are highly uncertain, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control). The uncertainties associated with the emission estimates of these gases are greater than with estimates of CO_2 from fossil fuel combustion, which are mainly a function of the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O es-

timates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the criteria pollutants, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and projections of growth.

Mobile Source Fossil Fuel Combustion (excluding CO_2)

Mobile sources emit greenhouse gases other than CO_2, including methane (CH_4), nitrous oxide (N_2O), and the criteria pollutants carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs).

As with combustion in stationary sources, N_2O and NO_x emissions are closely related to fuel characteristics, air-fuel mixes, and combustion temperatures, as well as usage of pollution control equipment. Nitrous oxide, in particular, can be formed by the catalytic processes used to control NO_x and CO emissions. Carbon monoxide emissions from mobile source combustion are significantly affected by combustion efficiency and presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. This occurs especially in idle, low speed and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions, such as catalytic converters.

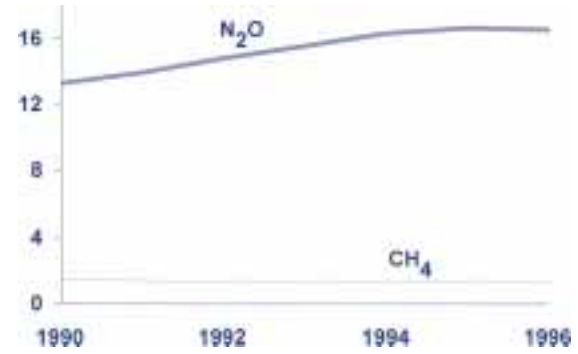
Emissions from mobile sources were estimated by transport mode (e.g., road, air, rail, and water) and fuel type—motor gasoline, diesel fuel, jet fuel, aviation gas, natural gas, liquefied petroleum gas (LPG), and residual fuel oil—and vehicle type. Road transport accounted for the majority of mobile source fuel consumption, and hence, the majority of mobile source emissions. Table 2-12, Table 2-13, Table 2-14, and Table 2-15 provide CH_4 and N_2O emission estimates from mobile sources by vehicle type, fuel type, and transport mode. Estimates of NO_x, CO, and NMVOC emissions in 1996 are given in Table 2-16.[4]

Mobile sources were responsible for a small portion of national CH_4 emissions but were the second largest source of N_2O in the United States. From 1990 to 1996, CH_4 emissions declined by 7 percent, to 1.4 MMTCE. Nitrous oxide emissions, however, rose from 13.2 to 16.5 MMTCE (a 25 percent increase). The reason for this conflicting trend was that the control technologies employed on highway vehicles in the United States lowered CO, NO_x, NMVOC, and CH_4 emissions, but resulted in higher N_2O emission rates. Fortunately, since 1994 improvements in the emission control technologies installed on new vehicles have reduced emission rates of both NO_x and N_2O per vehicle mile traveled. Overall, CH_4 and N_2O emissions were dominated by gasoline-fueled passenger cars and light-duty gasoline trucks. From 1995 to 1996, both CH_4 and N_2O emissions were almost constant (see Figure 2-7).

Emissions of criteria pollutants as a whole increased from 1990 through 1994, after which there was a slight decrease through 1996. A drop in gasoline prices combined with a strengthening U.S. economy caused the initial increase. These factors pushed the vehicle miles traveled (VMT) by road sources up, resulting in increased fuel consumption and higher emissions. Some of this increased activity was offset by an increasing portion of the U.S. vehicle fleet meeting established emissions standards.

Figure 2-7

Mobile Source CH_4 and N_2O Emissions



[4] See Annex C for a complete time series of criteria pollutant emission estimates for 1990 through 1996.

Table 2-12: CH_4 Emissions from Mobile Sources (MMTCE)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996
Gasoline Highway	**1.3**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
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
Heavy-Duty Vehicles	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+	+
Diesel Highway	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Heavy-Duty Vehicles	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Non-Highway	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Boats and Vessels	0.1	0.1	0.1	+	+	+	+
Locomotives	+	+	+	+	+	+	+
Farm Equipment	+	+	+	+	+	+	+
Construction Equipment	+	+	+	+	+	+	+
Aircraft	+	+	+	+	+	+	+
Other*	+	+	+	+	+	+	+
Total	**1.5**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**

+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding.
* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-13: N_2O Emissions from Mobile Sources (MMTCE)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996
Gasoline Highway	**12.3**	**12.9**	**13.8**	**14.6**	**15.3**	**15.6**	**15.5**
Passenger Cars	8.6	9.0	9.7	10.1	9.9	10.1	10.0
Light-Duty Trucks	3.4	3.7	3.9	4.2	5.1	5.2	5.1
Heavy-Duty Vehicles	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Motorcycles	+	+	+	+	+	+	+
Diesel Highway	**0.5**	**0.5**	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Heavy-Duty Vehicles	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Non-Highway	**0.5**	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**
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
Farm Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Construction Equipment	+	+	+	+	+	+	+
Aircraft[a]	+	+	+	+	+	+	+
Other[b]	+	+	+	+	+	+	+
Total	**13.2**	**13.9**	**14.8**	**15.6**	**16.3**	**16.6**	**16.5**

+ Does not exceed 0.05 MMTCE
Note: Totals may not sum due to independent rounding.
[a] Aircraft emissions include aviation gasoline combustion and exclude jet fuel combustion due to insufficient data availability.
[b] "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-14: CH_4 Emissions from Mobile Sources (Gg)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996
Gasoline Highway	**220**	**214**	**211**	**209**	**211**	**209**	**203**
Passenger Cars	133	128	127	123	115	114	111
Light-Duty Trucks	67	66	65	66	75	74	71
Heavy-Duty Vehicles	16	16	15	16	17	17	16
Motorcycles	4	4	4	4	4	4	4
Diesel Highway	**10**	**10**	**10**	**11**	**11**	**11**	**12**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Heavy-Duty Vehicles	10	10	10	10	11	11	11
Non-Highway	**25**	**25**	**26**	**23**	**24**	**24**	**24**
Boats and Vessels	9	10	10	8	8	9	8
Locomotives	3	2	3	2	2	3	3
Farm Equipment	6	5	6	5	6	6	6
Construction Equipment	1	1	1	1	1	1	1
Aircraft	6	6	6	5	5	5	6
Other*	1	1	1	1	1	1	1
Total	**255**	**250**	**248**	**244**	**246**	**244**	**238**

+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.
* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-15: N_2O Emissions from Mobile Sources (Gg)

Fuel Type/Vehicle Type	1990	1991	1992	1993	1994	1995	1996
Gasoline Highway	**145**	**153**	**164**	**173**	**181**	**184**	**183**
Passenger Cars	102	107	115	120	117	119	119
Light-Duty Trucks	41	44	46	50	60	61	61
Heavy-Duty Vehicles	2	3	3	3	3	4	4
Motorcycles	+	+	+	+	+	+	+
Diesel Highway	**6**	**6**	**6**	**6**	**7**	**7**	**7**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Heavy-Duty Vehicles	5	5	6	6	6	6	6
Non-Highway	**5**	**6**	**6**	**5**	**5**	**5**	**5**
Boats and Vessels	3	3	3	2	2	3	2
Locomotives	1	1	1	1	1	1	1
Farm Equipment	1	1	1	1	1	1	1
Construction Equipment	+	+	+	+	+	+	+
Aircraft[a]	+	+	+	+	+	+	+
Other[b]	1	+	+	+	1	+	+
Total	**157**	**165**	**175**	**184**	**193**	**196**	**195**

+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.
[a] Aircraft emissions includes aviation gasoline combustion and excludes jet fuel combustion due to insufficient data availability.
[b] "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

Table 2-16: 1996 Emissions of NO_x, CO, and NMVOC from Mobile Sources (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,752**	**46,712**	**4,709**
Passenger Cars	3,075	29,883	2,979
Light-Duty Trucks	1,370	13,377	1,435
Heavy-Duty Vehicles	295	3,267	259
Motorcycles	12	185	35
Diesel Highway	**1,753**	**1,318**	**283**
Passenger Cars	35	30	12
Light-Duty Trucks	9	7	4
Heavy-Duty Vehicles	1,709	1,280	267
Non-Highway	**4,183**	**15,424**	**2,201**
Boats and Vessels	244	1,684	460
Locomotives	836	102	44
Farm Equipment	1,012	901	207
Construction Equipment	1,262	1,066	184
Aircraft	151	861	161
Other*	678	10,810	1,144
Total	**10,688**	**63,455**	**7,192**

Note: Totals may not sum due to independent rounding. See Annex C for emissions in 1990 through 1995.
* "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.

Fossil-fueled motor vehicles comprise the single largest source of CO emissions in the United States and are a significant contributor to NO_x and NMVOC emissions. In 1996, CO emissions from mobile sources contributed 83 percent of all U.S. CO emissions and 50 and 42 percent of NO_x and NMVOC emissions, respectively. Since 1990, emissions of CO and NMVOCs from mobile sources decreased by 5 and 10 percent, respectively, while emissions of NO_x increased by 1 percent.

Methodology

Estimates for CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each category. Depending upon the category, activity data included such information as fuel consumption, fuel deliveries, and vehicle miles traveled (VMT). Emission estimates from highway vehicles were based on VMT and emission factors by vehicle type, fuel type, model year, and control technology. Fuel consumption data was employed as a measure of activity for non-highway vehicles and then fuel-specific emission factors were applied. A complete discussion of the methodology used to estimate emissions from mobile sources is provided in Annex C.

The EPA provided emissions estimates of NO_x, CO, and NMVOCs for eight categories of highway vehicles[5], aircraft, and seven categories of off-highway vehicles[6].

Data Sources

Emission factors used in the calculations of CH_4 and N_2O emissions are presented in Annex C. The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provided emission factors for CH_4, and were developed using MOBILE5a, a model used by the Environmental Protection Agency (EPA) to estimate exhaust and running loss emissions from highway vehicles. The MOBILE5a model uses information on ambient temperature, vehicle speeds, national vehicle registration distributions, gasoline volatility, and other variables in order to produce these factors (EPA 1997b).

Emission factors for N_2O from gasoline highway vehicles came from a recent EPA report (1998). This report developed emission factors for older passenger cars (roughly pre-1992 in California and pre-1994 in the rest of the United States), from published references, and for newer cars from a recent testing program at EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL). These emission factors for gasoline highway vehicles are lower than the U.S. default values in the *Revised 1996 IPCC Guidelines*, but are higher than the European de-

[5] These categories included: gasoline passenger cars, diesel passenger cars, light-duty gasoline trucks less than 6,000 pounds in weight, light-duty gasoline trucks between 6,000 and 8,500 pounds in weight, light-duty diesel trucks, heavy-duty gasoline trucks and buses, heavy-duty diesel trucks and buses, and motorcycles.

[6] These categories included: gasoline and diesel farm tractors, other gasoline and diesel farm machinery, gasoline and diesel construction equipment, snowmobiles, small gasoline utility engines, and heavy-duty gasoline and diesel general utility engines.

fault values, both of which were published before the more recent tests and literature review conducted by the NVFEL. The U.S. default values in the *Revised 1996 IPCC Guidelines* were based on three studies that tested a total of five cars using European rather than U.S. test protocols. More details may be found in EPA (1998).

Emission factors for gasoline vehicles other than passenger cars were scaled from those for passenger cars with the same control technology, based on their relative fuel economy. This scaling was supported by limited data showing that light-duty trucks emit more N_2O than passenger cars with equivalent control technology. The use of fuel-consumption ratios to determine emission factors is considered a temporary measure only, to be replaced as soon as additional testing data are available. For more details, see U.S. EPA (1998). Nitrous oxide emission factors for diesel highway vehicles were taken from the European default values found in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). There is little data addressing N_2O emissions from U.S. diesel-fueled vehicles, and in general, European countries have had more experience with diesel-fueled vehicles. U.S. default values in the *Revised 1996 IPCC Guidelines* were used for non-highway vehicles.

Activity data were gathered from several U.S. government sources including EIA (1997), FHWA (1997), and FAA (1997). Control technology data for highway vehicles were obtained from the EPA's Office of Mobile Sources. Annual VMT data for 1990 through 1996 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database, as noted in EPA (1997a).

Emissions estimates for NO_x, CO, NMVOCs were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900 - 1996* (EPA 1997a).

Uncertainty

Mobile source emission estimates can vary significantly due to assumptions concerning fuel type and composition, technology type, average speeds, type of emission control equipment, equipment age, and operating and maintenance practices. Fortunately, detailed activity data for mobile sources were available, including VMT by vehicle type for highway vehicles. The allocation of this VMT to individual model years was done using the profile of U.S. vehicle usage by vehicle age in 1990 as specified in MOBILE 5a. Data to develop a temporally variable profile of vehicle usage by model year instead of age was not available.

Average emission factors were developed based on numerous assumptions concerning the age and model of vehicle; percent driving in cold start, warm start, and cruise conditions; average driving speed; ambient temperature; and maintenance practices. The factors for regulated emissions from mobile sources—CO, NO_x, and hydrocarbons—have been extensively researched, and so involve lower uncertainty than emissions of unregulated gases. Although methane has not been singled out for regulation in the United States, overall hydrocarbon emissions from mobile sources—a component of which is methane—are regulated.

Compared to methane, CO, NO_x, and NMVOCs, there is relatively little data available to estimate emission factors for nitrous oxide. Nitrous oxide is not a criteria pollutant, and measurements of it in automobile exhaust have not been routinely collected. Research data has shown that N_2O emissions from vehicles with catalytic converters are greater than those without emission controls, and that vehicles with aged catalysts emit more than new ones. The emission factors used were, therefore, derived from aged cars (EPA 1998). The emission factors used for Tier 0 and older cars were based on tests of 28 vehicles; those for newer vehicles were based on tests of 22 vehicles. This sample is small considering that it is being used to characterize the entire U.S. fleet, and the associated uncertainty is therefore large. Currently, N_2O gasoline highway emission factors for vehicles other than passenger cars are scaled based on those for passenger cars and their relative fuel economy. Actual measurements should be substituted for this procedure when they become available. Further testing is needed to reduce the uncertainty in emission factors for all classes of vehicles, using realistic driving regimes, environmental conditions, and fuels.

Emissions of N_2O from the combustion of jet fuel in aircraft were not estimated due to insufficient data availability on the number of landing and take-off cycles executed and cruising fuel consumption by specific type

of aircraft. The estimates presented for N_2O emissions from aircraft include only the combustion of aviation gasoline. Complete N_2O emission estimates from aircraft will be included in future inventories.

Overall, uncertainty for N_2O emissions estimates is considerably higher than for CH_4, CO, NO_x, or NMVOC; however, all these gases involve far more uncertainty than CO_2 emissions from fossil fuel combustion.

Coal Mining

All underground and surface coal mining liberates (i.e., releases) methane as part of normal operations. The amount of methane liberated during mining is primarily dependent upon the amount of methane stored in the coal and the surrounding strata. This *in situ* methane content is a function of the quantity of methane generated during the coal formation process and its ability to migrate through the surrounding strata over time. The degree of coalification—defined by the rank or quality of the coal formed—determines the amount of methane generated during the coal formation process; higher ranked coals generate more methane. The amount of methane that remains in the coal and surrounding strata also depends upon geologic characteristics such as pressure and temperature within a coal seam. Deeper coal deposits tend to retain more of the methane generated during coalification. Accordingly, deep underground coal seams generally have higher methane contents than shallow coal seams or surface deposits.

Underground, versus surface, coal mines contribute the largest share of methane emissions. All underground coal mines employ ventilation systems to ensure that methane levels remain within safe concentrations. These systems exhaust significant amounts of methane to the atmosphere in low concentrations. Additionally, over twenty gassy U.S. coal mines supplement ventilation with degasification systems. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large volumes of methane before or after mining. Currently, twelve coal mines collect methane from degasification systems and sell this gas to a pipeline, thus reducing emissions to the atmosphere. Surface coal mines also release methane as the overburden is removed and the coal is exposed. Additionally, after coal has been mined, small amounts of methane retained in the coal are released during processing, storage, and transport.

Total methane emissions in 1996 were estimated to be 18.9 MMTCE (3.3 Tg), declining from 24.0 MMTCE (4.2 Tg) in 1990 (see Table 2-17 and Table 2-18). Of this amount, underground mines accounted for 67 percent, surface mines accounted for 13 percent, and post-mining emissions accounted for 20 percent. With the exception of 1995, total methane emissions declined every year during this period. In 1993, emissions from underground mining dropped to a low of 2.8 Tg, primarily due to labor strikes at many of the large underground mines. In 1995, there was an increase in methane emissions from underground mining (3.1 Tg) due to particularly high emissions at the gassiest coal mine in the country. While methane liberated from underground mines fluctuated from 1990 to 1996, the amount of methane recovered and used increased. As a result, with the exception of 1995, total methane emitted from underground mines declined in each year. Surface mine emissions

Table 2-17: Methane Emissions from Coal Mining (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996
Underground Mining	17.1	16.4	15.6	13.3	13.1	14.2	12.6
Liberated	18.8	18.1	17.8	16.0	16.3	17.7	16.5
Recovered & Used	(1.6)	(1.7)	(2.1)	(2.7)	(3.2)	(3.4)	(3.8)
Surface Mining	2.8	2.6	2.6	2.5	2.6	2.4	2.5
Post- Mining (Underground)	3.6	3.4	3.3	3.0	3.3	3.3	3.4
Post-Mining (Surface)	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Total	**24.0**	**22.8**	**22.0**	**19.2**	**19.4**	**20.3**	**18.9**

Note: Totals may not sum due to independent rounding.

Table 2-18: Methane Emissions from Coal Mining (Tg)

Activity	1990	1991	1992	1993	1994	1995	1996
Underground Mining	3.0	2.9	2.7	2.3	2.3	2.5	2.2
Liberated	3.3	3.2	3.1	2.8	2.8	3.1	2.9
Recovered & Used	(0.3)	(0.3)	(0.4)	(0.5)	(0.6)	(0.6)	(0.7)
Surface Mining	0.5	0.4	0.4	0.4	0.5	0.4	0.4
Post- Mining (Underground)	0.6	0.6	0.6	0.5	0.6	0.6	0.6
Post-Mining (Surface)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**4.2**	**4.0**	**3.8**	**3.4**	**3.4**	**3.6**	**3.3**

Note: Totals may not sum due to independent rounding.

and post-mining emissions remained relatively constant from 1990 to 1996.

In 1994, EPA's Coalbed Methane Outreach Program (CMOP) began working with the coal industry and other stakeholders to identify and remove obstacles to investments in coal mine methane recovery and use projects. Reductions attributed to CMOP were estimated to be 0.7, 0.8, and 1.0 MMTCE in 1994, 1995, and 1996, respectively.

Methodology

The methodology for estimating methane emissions from coal mining consists of two main steps. The first step involved estimating methane emissions from underground mines. Because of the availability of ventilation system measurements, underground mine emissions can be estimated on a mine-by-mine basis and then summed to determine total emissions. The second step involved estimating emissions from surface mines and post-mining activities by multiplying basin-specific coal production by basin specific emissions factors.

Underground mines. Total methane emitted from underground mines was estimated as the quantity of methane liberated from ventilation systems, plus methane liberated from degasification systems, minus methane recovered and used. The Mine Safety and Heath Administration (MSHA) measures methane emissions from ventilation systems for all mines with detectable[7] methane concentrations. These mine-by-mine measurements were used to estimate methane emissions from ventilation systems.

Some of the gassier underground mines also use degasification systems (e.g., wells or boreholes) that remove methane before or after mining . This methane can then be collected for use or vented to the atmosphere. Various approaches were employed to estimate the quantity of methane collected by each of the more than twenty mines using these systems, depending on available data. For example, some mines have reported to EPA the amounts of methane liberated from their degasification systems. For mines that sell recovered methane to a pipeline, pipeline sales data was used to estimate degasification emissions. Finally, for those mines for which no other data was available, default recovery efficiency values were developed, depending on the type of degasification system employed.

Finally, the amount of methane recovered by degasification systems and then used (i.e., not vented) was estimated. This calculation was complicated by the fact that methane is rarely recovered and used during the same year in which the particular coal seam is mined. In 1996, twelve coal mines sold recovered methane to a pipeline operator. Emissions avoided for these projects were estimated using gas sales data reported by various state agencies, and information supplied by coal mine operators regarding the number of years in advance of mining that gas recovery occurred. Additionally, some of the state agencies provided individual well production information, which was used to assign gas sales to a particular year.

Surface Mines and Post-Mining Emissions. Surface mining and post-mining methane emissions were estimated by multiplying basin-specific coal production by basin-specific emissions factors. For surface mining, emissions factors were developed by assuming that surface mines emit

[7] MSHA records coal mine methane readings with concentrations of greater than 50 ppm (parts per million) methane. Readings below this threshold are considered non-detectable.

from one to three times as much methane as the average *in situ* methane content of the coal. This accounts for methane released from the strata surrounding the coal seam. For post-mining emissions, the emission factor was assumed to be from 25 to 40 percent of the average *in situ* methane content of coals mined in the basin.

Data Sources

The Mine Safety and Health Administration provided mine-specific information on methane liberated from ventilation systems at underground mines. EPA developed estimates of methane liberated from degasification systems at underground mines based on available data for each of the mines employing these systems. The primary sources of data for estimating emissions avoided at underground mines were gas sales data published by state petroleum and natural gas agencies and information supplied by mine operators regarding the number of years in advance of mining that gas recovery occurred. Annual coal production data was taken from the Energy Information Agency's *Coal Industry Annual* (see Table 2-19) (EIA 1991, 1992, 1993, 1994, 1995, 1996, 1997). Data on *in situ* methane content and emissions factors were taken from EPA (1993).

Uncertainty

Table 2-19: Coal Production (Thousand Metric Tons)

Year	Underground	Surface	Total
1990	384,247	546,814	931,061
1991	368,633	532,653	901,285
1992	368,625	534,286	902,911
1993	318,476	539,211	857,687
1994	362,063	575,525	937,588
1995	359,475	577,634	937,109
1996	371,813	593,311	965,125

The emission estimates from underground ventilation systems were based upon actual measurement data for mines with detectable methane emissions. Accordingly, the uncertainty associated with these measurements is estimated to be low. Estimates of methane liberated from degasification systems are less certain because EPA assigns default recovery efficiencies for a subset of U.S. mines. Compared to underground mines, there is considerably more uncertainty associated with surface mining and post-mining emissions because of the difficulty in developing accurate emissions factors from field measurements. Because underground emissions comprise the majority of total coal mining emissions, the overall uncertainty is estimated to be only ±15 percent.[8]

Natural Gas Systems

Methane emissions from natural gas systems are generally process related, with normal operations, routine maintenance, and system upsets being the primary contributors. Emissions from normal operations include: natural gas combusting engine and turbine exhaust, bleed and discharge emissions from pneumatic devices, and fugitive emissions from system components. Routine maintenance emissions originate from pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions.

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, hundreds of thousands of miles of transmission pipelines, and over a million miles of distribution pipeline. The system, though, can be divided into four stages, each with different factors affecting methane emissions, as follows:

Field Production. In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, treatment facilities, gathering pipelines, and process units such as dehydrators and separators. Fugitive emissions and emissions from pneumatic devices accounted for the majority of emissions. Emissions from field production have increased absolutely and as a proportion of total emissions from natural gas systems—approximately 27 percent between 1990 and 1996—due to an increased number of producing gas wells and related equipment.

[8] Preliminary estimate

Processing. In this stage, processing plants remove various constituents from the raw gas before it is injected into the transmission system. Fugitive emissions from compressors, including compressor seals, were the primary contributor from this stage. Processing plants accounted for about 12 percent of methane emissions from natural gas systems during the period of 1990 through 1996.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production areas to distribution centers or large volume customers. From 1990 to 1996, the reported length of the gas utility transmission pipeline varied, with an overall decline from about 280,000 miles to about 265,000 miles. Throughout the transmission system, compressor stations pressurize the gas to move it through the pipeline. Fugitive emissions from compressor stations and metering and regulating stations accounted for the majority of the emissions from transmission. Pneumatic devices and engine exhaust were smaller sources of emissions from transmission facilities. Methane emissions from the transmission stage accounted for approximately 35 percent of the emissions from natural gas systems. Natural gas is also injected and stored in underground formations during periods of low demand, and withdrawn, processed, and distributed during periods of high demand. Compressors and dehydrators were the primary contributors from these storage facilities. Less than one percent of total emissions from natural gas systems can be attributed to these facilities.

Distribution. The distribution of natural gas requires the use of low-pressure pipelines to deliver gas to customers. The distribution network consisted of nearly 1.5 million miles of pipeline in 1996, increasing from a 1990 figure of just over 1.3 million miles (AGA 1996). Distribution system emissions, which accounted for approximately 27 percent of emissions from natural gas systems, resulted mainly from fugitive emissions from gate stations and non-plastic piping. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced the growth in emissions from this stage.

Overall, natural gas systems emitted 34.1 MMTCE (6.0 Tg) of methane in 1996 or 19 percent of total methane emissions (see Table 2-20 and Table 2-21). Emissions rose slightly from 1990 to 1996, reflecting an increase in the number of producing gas wells and miles of distribution pipeline. Initiated in 1993, EPA's Natural Gas STAR program is working with the gas industry to promote profitable

Table 2-20: Methane Emissions from Natural Gas Systems (MMTCE)

Stage	1990	1991	1992	1993	1994	1995	1996
Field Production	8.0	8.1	8.5	8.7	8.8	9.1	9.5
Processing	4.0	4.0	4.0	4.0	4.2	4.1	4.1
Transmission and Storage	12.6	12.7	12.9	12.6	12.5	13.2	12.4
Distribution	8.3	8.4	8.6	8.8	8.7	8.7	9.1
Total	**32.9**	**33.3**	**33.9**	**34.1**	**33.9**	**34.6**	**34.1**

Note: 1994 through 1996 totals include reductions from Natural Gas STAR program. Totals may not sum due to independent rounding.

Table 2-21: Methane Emissions from Natural Gas Systems (Tg)

Stage	1990	1991	1992	1993	1994	1995	1996
Field Production	1.4	1.4	1.5	1.5	1.5	1.5	1.5
Processing	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Transmission and Storage	2.2	2.2	2.3	2.2	2.2	2.3	2.2
Distribution	1.4	1.5	1.5	1.5	1.5	1.5	1.6
Total	**5.7**	**5.8**	**5.9**	**5.9**	**5.9**	**6.0**	**6.0**

Note: 1994 through 1996 totals include reductions from Natural Gas STAR program. Totals may not sum due to independent rounding.

practices that reduce methane emissions. The program was estimated to have reduced emissions by 0.3, 0.5, and 0.9 MMTCE in 1994, 1995, and 1996, respectively.

Methodology

The foundation for the estimate of methane emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute and EPA (GRI/EPA 1995). The GRI/EPA study developed over 100 detailed emission factors and activity levels through site visits to selected gas facilities, and arrived at a national point estimate for 1992. Since publication of this study, EPA conducted additional analysis to update the activity data for some of the components of the system, particularly field production equipment. Summing emissions across individual sources in the natural gas system provided a 1992 baseline emissions estimate from which the emissions for the period 1990 through 1996 were derived.

Apart from the year 1992, detailed statistics on each of the over 100 activity levels were not available for the time series 1990 through 1996. To estimate these activity levels, aggregate annual statistics were obtained on the main driving variables, including: number of producing wells, number of gas plants, miles of transmission pipeline, miles of distribution pipeline, and miles of distribution services. By assuming that the relationships among these variables remained constant (e.g., the number of heaters per well remained the same), the statistics on these variables formed the basis for estimating other activity levels.

For the period 1990 through 1995, the emission factors were held constant. A gradual improvement in technology and practices is expected to reduce the emission factors slightly over time. To reflect this trend, the emission factors for 1996 were reduced by about 0.2 percent, a rate that, if continued, would lower the emission factors by 5 percent in 2020. See Annex E for more detailed information on the methodology and data used to calculate methane emissions from natural gas systems.

Data Sources

Activity data were taken from the American Gas Association (AGA 1991, 1992, 1993, 1994, 1995, 1996, 1997), the Energy Information Administration's *Annual Energy Outlook* (EIA 1997a) and *Natural Gas Annual* (EIA 1997b), and the Independent Petroleum Association of America (IPAA 1997). The U.S. Department of Interior (DOI 1997) supplied offshore platform data. All emission factors were taken from GRI/EPA (1995).

Uncertainty

The heterogeneous nature of the natural gas industry makes it difficult to sample facilities that are completely representative of the entire industry. Because of this, scaling up from model facilities introduces a degree of uncertainty. Additionally, highly variable emission rates were measured among many system components, making the calculated average emission rates uncertain. Despite the difficulties associated with estimating emissions from this source, the uncertainty in the total estimated emissions are believed to be on the order of ±40 percent.

Petroleum Systems

One of the gases emitted from the production and refining of petroleum products is methane. The activities that lead to methane emissions include: production field treatment and separation, routine maintenance of production field equipment, crude oil storage, refinery processes, crude oil tanker loading and unloading, and venting and flaring. Each stage is described below:

Production Field Operations. Fugitive emissions from oil wells and related production field treatment and separation equipment are the primary source of emissions from production fields. From 1990 to 1996, these emissions accounted for about 10 percent of total emissions from petroleum systems. Routine maintenance, which includes the repair and maintenance of valves, piping, and other equipment, accounted for less than 1 percent of total emissions from petroleum systems. Emissions from production fields are expected to decline in the future as the number of oil wells decreases.

Crude Oil Storage. Crude oil storage tanks emit methane during two processes. "Breathing losses" from roof seals and joints occur when the tank is in use, and while tanks are being drained or filled, "working losses" occur as the methane in the air space above the liquid is displaced. Piping and other equipment at storage facilities

can also produce fugitive emissions. Between 1990 and 1996, crude oil storage emissions accounted for less than 1 percent of total emissions from petroleum systems.

Refining. Waste gas streams from refineries are a source of methane emissions. Based on Tilkicioglu and Winters (1989), who extrapolated waste gas stream emissions to national refinery capacity, emissions estimates from this source accounted for approximately 4 percent of total methane emissions from the production and refining of petroleum.

Tanker Operations. The loading and unloading of crude oil tankers releases methane. From 1990 to 1996, emissions from crude oil transportation on tankers accounted for roughly 2 percent of total emissions from petroleum systems.

Venting and Flaring. Gas produced during oil production that cannot be contained or otherwise used is released into the atmosphere or flared. Vented gas typically has a high methane content; however, it is assumed that flaring destroys the majority of the methane in the gas (about 98 percent depending upon the moisture content of the gas). Venting and flaring may account for up to 85 percent of emissions from petroleum systems. There is considerable uncertainty in the estimate of emissions from this activity.

From 1990 to 1996, methane emissions from petroleum systems remained relatively constant at approximately 1.6 MMTCE (0.3 Tg), accounting for about 1 percent of total methane emissions in 1996. Emission estimates are provided below in Table 2-22 and Table 2-23.

Methodology

The methodology used for estimating emissions from each activity is described below:

Production Field Operations. Emission estimates were calculated by multiplying emission factors (i.e., emissions per oil well) with their corresponding activity data (i.e., number of oil wells). To estimate emissions for 1990 to 1996, emission factors developed to estimate 1990 emissions were multiplied by updated activity data for 1990 through 1996. Emissions estimates from petroleum systems excluded associated natural gas wells to prevent double counting with the estimates for natural gas systems.

Crude Oil Storage. Tilkicioglu and Winters (1989) estimated crude oil storage emissions on a model tank farm facility with fixed and floating roof tanks. Emission factors developed for the model facility were applied to published crude oil storage data to estimate emissions.

Table 2-22: Methane Emissions from Petroleum Systems (MMTCE)

Stage	1990	1991	1992	1993	1994	1995	1996
Production Field Operations	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Crude Oil Storage	+	+	+	+	+	+	+
Refining	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Tanker Operations	+	+	+	+	+	+	+
Venting and Flaring	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Total	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.5**

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

Table 2-23: Methane Emissions from Petroleum Systems (Gg)

Stage	1990	1991	1992	1993	1994	1995	1996
Production Field Operations	24	25	24	24	24	23	23
Crude Oil Storage	2	2	2	2	2	2	2
Refining	10	10	10	10	10	10	9
Tanker Operations	6	6	5	5	5	5	5
Venting and Flaring	231	231	231	231	231	231	231
Total	**272**	**273**	**272**	**272**	**272**	**271**	**271**

Note: Totals may not sum due to independent rounding.

Refining. Tilkicioglu and Winters (1989) also estimated methane emissions from waste gas streams based on measurements at ten refineries. These data were extrapolated to total U.S. refinery capacity to estimate emissions from refinery waste gas streams for 1990. To estimate emissions for 1991 through 1996, the emissions estimates for 1990 were scaled using updated data on U.S. refinery capacity.

Tanker Operations. Methane emissions from tanker operations are associated with the loading and unloading of domestically-produced crude oil transported by tanker, and the unloading of foreign-produced crude transported by tanker. The quantity of domestic crude transported by tanker was estimated as Alaskan crude oil production less Alaskan refinery crude utilization, plus 10 percent of non-Alaskan crude oil production. Crude oil imports by tanker were estimated as total imports less imports from Canada. An emission factor based on the methane content of hydrocarbon vapors emitted from crude oil was employed (Tilkicioglu and Winters 1989). This emission factor was multiplied by updated activity data to estimate total emissions for 1990 through 1996.

Venting and Flaring. Although venting and flaring data indicate that the amount of venting and flaring activity has changed over time, there is currently insufficient data to assess the change in methane emissions associated with these changes. Given the considerable uncertainty in the emissions estimate for this stage, and the inability to discern a trend in actual emissions, the 1990 emissions estimate was held constant for the years 1991 through 1996.

See Annex F for more detailed information on the methodology and data used to calculate methane emissions from petroleum systems.

Data Sources

Data on the number of oil wells in production fields were taken from the American Petroleum Institute (API 1997) as were the number of oil wells that do not produce natural gas. Crude oil storage, U.S. refinery capacity, crude oil stocks, crude oil production, utilization, and import data were obtained from the U.S. Department of Energy (EIA 1991, 1992, 1993, 1994, 1995, 1996, 1997). Emission factors were taken from Tilkicioglu and Winters (1989) and EPA (1993).

Uncertainty

There are significant uncertainties associated with all aspects of the methane emissions estimates from petroleum systems. Published statistics are inadequate for estimating activity data at the level of detail required. Similarly, emission factors for each stage remain uncertain. In particular, there is insufficient information to estimate annual venting and flaring emissions using published statistics. EPA is currently undertaking more detailed analyses of emissions from this source and anticipates that new information will be available for the 1997 inventory. Preliminary work suggests that emissions will increase. Table 2-24 provides emission estimate ranges given the uncertainty in the venting and flaring estimates.

Natural Gas Flaring and Criteria Pollutant Emissions from Oil and Gas Activities

The flaring of natural gas from petroleum wells is a small source of carbon dioxide (CO_2). In addition, oil and gas activities also release small amounts of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane

Table 2-24: Uncertainty in Methane Emissions from Petroleum Systems (Gg)

Stage	1990	1991	1992	1993	1994	1995	1996
Venting and Flaring (point estimate)	**231**	**231**	**231**	**231**	**231**	**231**	**231**
Low	93	93	93	93	93	93	93
High	462	462	462	462	462	462	462
Total (point estimate)	**272**	**273**	**272**	**272**	**272**	**271**	**271**
Low	103	103	103	103	103	102	102
High	627	631	628	627	625	621	620

volatile organic compounds (NMVOCs). Each of these sources is a small portion of overall emissions. Emissions of CO_2, NO_x, and CO from petroleum and natural gas production activities are all less than 1 percent of national totals, while NMVOC emissions are roughly 3 percent of national totals.

Carbon dioxide emissions from petroleum production result from natural gas that is flared (i.e., combusted) at the production site. Barns and Edmonds (1990) noted that of total reported U.S. venting and flaring, approximately 20 percent is actually vented, with the remaining 80 percent flared. For 1996, these emissions were estimated to be approximately 3.5 MMTCE (12.7 Tg), an increase of 75 percent from 1990 (see Table 2-25).

Criteria pollutant emissions from oil and gas production, transportation, and storage, constitute a relatively small and stable portion of the total emissions of these gases for the 1990 to 1996 period (see Table 2-26).

Methodology

The estimates for CO_2 emissions were prepared using an emission factor of 14.92 MMTCE/QBtu of flared gas, and an assumed flaring efficiency of 100 percent. The quantity of flared gas (i.e., 80 percent of total vented and flared gas) for each year was multiplied by this factor to calculate emissions.

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

Data Sources

Activity data for estimating CO_2 emissions from natural gas flaring were provided in EIA's *Natural Gas Annual* (EIA 1997). The emission factor was also provided by EIA.

EPA (1997) provided emission estimates for NO_x, CO, and NMVOCs from petroleum refining, petroleum product storage and transfer, and petroleum marketing operations. Included are gasoline, crude oil and distillate fuel oil storage and transfer operations, gasoline bulk terminal and bulk plants operations, and retail gasoline service stations operations.

Table 2-25: CO_2 Emissions from Natural Gas Flaring

Year	MMTCE	Tg
1990	2.0	7.3
1991	2.2	8.2
1992	2.2	8.1
1993	3.0	11.0
1994	3.0	11.1
1995	3.7	13.7
1996	3.5	12.7

Table 2-26: NO_x, NMVOCs, and CO Emissions from Oil and Gas Activities (Gg)

Year	NO_x	CO	NMVOCs
1990	139	302	555
1991	110	313	581
1992	134	337	574
1993	111	337	588
1994	106	307	587
1995	100	316	582
1996	100	316	469

Uncertainty

Uncertainties in CO_2 emission estimates primarily arise from assumptions concerning what proportion of natural gas is flared and the flaring efficiency. The 20 percent vented as methane is accounted for in the section on methane emissions from petroleum production, refining, transportation, and storage activities. Uncertainties in criteria pollutant emission estimates are partly due to the accuracy of the emission factors used and projections of growth.

Wood Biomass and Ethanol Consumption

The combustion of biomass fuels—such as wood, charcoal, and wood waste—and biomass-based fuels—such as ethanol from corn and woody crops—generates carbon dioxide (CO_2). However, in the long run the carbon dioxide emitted from biomass consumption does not increase atmospheric carbon dioxide concentrations, assuming the biogenic carbon emitted is offset by the growth of new biomass. As a result, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel-based emissions and are not included in the

Table 2-27: CO_2 Emissions from Wood Consumption by End-Use Sector (MMTCE)

End-Use Sector	1990	1991	1992	1993	1994	1995	1996
Electric Utility	0.3	0.2	0.2	0.2	0.2	0.2	0.3
Industrial	34.0	33.3	34.7	35.4	36.5	37.0	38.9
Residential	12.7	13.4	14.1	11.9	11.7	13.0	13.0
Commercial	0.7	0.7	0.7	1.0	1.0	1.0	1.1
Total	**47.6**	**47.5**	**49.7**	**48.6**	**49.4**	**51.2**	**53.2**

Note: Totals may not sum due to independent rounding.

Table 2-28: CO_2 Emissions from Wood Consumption by End-Use Sector (Tg)

End-Use Sector	1990	1991	1992	1993	1994	1995	1996
Electric Utility	1.0	0.8	0.9	0.9	0.9	0.9	1.0
Industrial	124.8	122.1	127.3	129.8	133.7	135.7	142.6
Residential	46.4	49.0	51.5	43.8	42.9	47.6	47.5
Commercial	2.4	2.4	2.4	3.5	3.6	3.6	3.9
Total	**174.6**	**174.3**	**182.1**	**178.0**	**181.1**	**187.8**	**195.0**

Note: Totals may not sum due to independent rounding.

U.S. totals. 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.

In 1996, CO_2 emissions due to burning of woody biomass within the industrial, residential and commercial end-use sectors and by electric utilities were about 53.2 MMTCE (195.0 Tg) (see Table 2-27 and Table 2-28). As the largest consumer of biomass fuels, the industrial end-use sector was responsible for 73 percent of the CO_2 emissions from biomass-based fuels. The residential end-use sector was the second largest emitter, making up 24 percent of total emissions from woody biomass. The commercial end-use sector and electric utilities accounted for the remainder.

Between 1990 and 1996, total emissions of CO_2 from biomass burning increased 12 percent. This increase in emissions was mainly due to a 14 percent rise in industrial biomass fuel consumption between 1990 and 1996. Consumption of biomass fuels within the commercial end-use sector and by electric utilities remained relatively stable and thus had little impact on changes in overall CO_2 emissions from biomass combustion.

Biomass-derived fuel consumption in the United States consisted mainly of ethanol use in the transportation end-use sector. Ethanol is primarily produced from corn grown in the Midwest, and was used primarily in the Midwest and South. Pure ethanol can be combusted, or it can be mixed with gasoline as a supplement or octane-enhancing agent. The most common mixture is a 90 percent gasoline, 10 percent ethanol blend known as gasohol. Ethanol and ethanol blends are often used to fuel public transport vehicles such as buses, or centrally fueled fleet vehicles. Ethanol and ethanol blends are believed to burn "cleaner" than gasoline (i.e., lower in NO_x and hydrocarbon emissions), and have been employed in urban areas with poor air quality. However, because ethanol is a hydrocarbon fuel, its combustion emits CO_2.

In 1996, the United States consumed an estimated 74 trillion Btus of ethanol (1.0 billion gallons), mostly in the transportation end-use sector. Emissions of CO_2 in 1996 due to ethanol fuel burning were estimated to be approximately 1.4 MMTCE (5.1 Tg) (see Table 2-29). Between 1990 and 1991, emissions of CO_2 due to ethanol fuel consumption fell by 21 percent. Since this de-

Table 2-29: CO_2 Emissions from Ethanol Consumption

Year	MMTCE	Tg
1990	1.6	5.7
1991	1.2	4.5
1992	1.5	5.5
1993	1.7	6.1
1994	1.8	6.7
1995	2.0	7.2
1996	1.4	5.1

cline, emissions from ethanol have steadily increased through 1995. From 1995 to 1996, however, ethanol consumption declined by 29 percent. Overall, from 1990 to 1996, emissions of CO_2 decreased by 9.8 percent. Again, emissions from ethanol consumption are not included under the Energy sector because the corn from which ethanol is derived is of biogenic origin.[9]

Ethanol production dropped sharply in the middle of 1996 because of short corn supplies and high prices. Plant output began to increase toward the end of the growing season, reaching close to normal levels at the end of the year. However, total 1996 ethanol production fell far short of the 1995 level (EIA 1997b).

Methodology

Woody biomass emissions were estimated by converting U.S. consumption data in energy units (17.2 million Btu per short ton) to megagrams (Mg) of dry matter using EIA assumptions. Once consumption data for each sector were converted to megagrams of dry matter, the carbon content of the dry fuel was estimated based on default values of 45 to 50 percent carbon in dry biomass. The amount of carbon released from combustion was estimated using 87 percent for the fraction oxidized (i.e., combustion efficiency). Ethanol consumption data in energy units were also multiplied by a carbon coefficient (18.96 mg C/Btu) to produce carbon emission estimates.

Data Sources

Woody biomass consumption data were provided by EIA (1997a) (see Table 2-30). The factor for converting energy units to mass was supplied by EIA (1994). Carbon content and combustion efficiency values were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Uncertainty

The combustion efficiency factor used is believed to under estimate the efficiency of wood combustion processes in the United States. The IPCC emission factor has been used because better data are not yet available. Increasing the combustion efficiency would increase emission estimates. In addition, according to EIA (1994) commercial wood energy use is typically not reported because there are no accurate data sources to provide reliable estimates. Emission estimates from ethanol production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Emissions from ethanol were estimated using consumption data from EIA (1997a) (see Table 2-31). The carbon coefficient used was provided by OTA (1991).

Table 2-30: Residential and Industrial Biomass Consumption (Trillion Btu)

Year	Industrial	Residential
1990	1,562	581
1991	1,528	613
1992	1,593	645
1993	1,625	548
1994	1,673	537
1995	1,698	596
1996	1,784	595

Table 2-31: Ethanol Consumption

Year	Trillion Btu
1990	82
1991	65
1992	79
1993	88
1994	97
1995	104
1996	74

9 Emissions and sinks of biogenic carbon are accounted for under the Land-Use Change and Forestry sector.

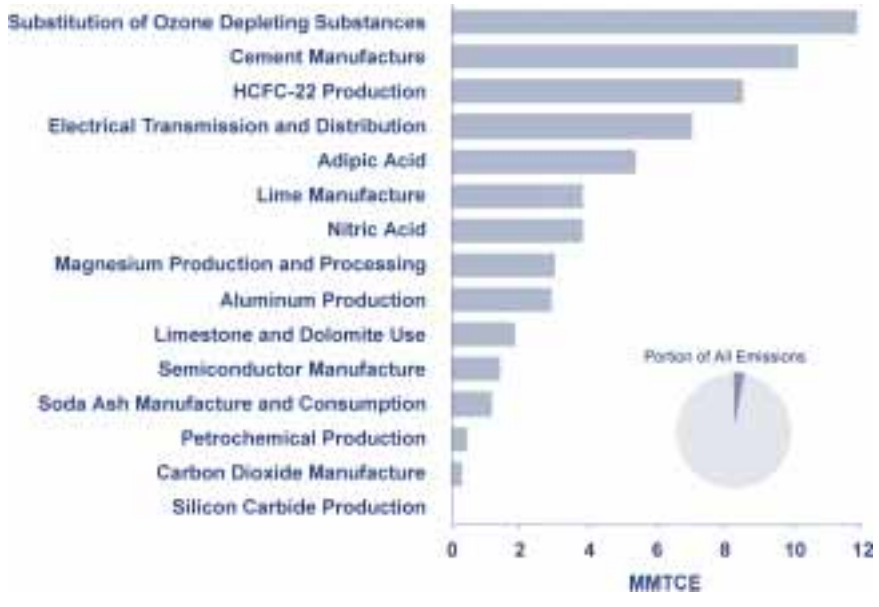
3. Industrial Processes

Greenhouse gas emissions are produced as a by-product of various non-energy related industrial activities. That is, these emissions are produced directly from an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically transformed from one state to another. This transformation often results in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The processes addressed in this chapter include cement production, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and use, CO_2 manufacture, iron and steel production, ammonia manufacture, ferroalloy production, aluminum production, petrochemical production (including carbon black, ethylene, dicholoroethylene, styrene, and methanol), silicon carbide production, adipic acid production, and nitric acid production (see Figure 3-1).[1]

In addition to the three greenhouse gases listed above, there are also industrial sources of several classes of man-made fluorinated compounds called hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The present contribution of these gases to the radiative forcing effect of all anthropogenic greenhouse gases is

Figure 3-1

1996 Industrial Processes Sector GHG Sources



[1] Carbon dioxide emissions from iron and steel production, ammonia manufacture, ferroalloy production, and aluminum production are included under the Energy sector as part of fossil fuel combustion of industrial coking coal, natural gas, and petroleum coke.

small; however, because of their extremely long lifetimes, they will continue to accumulate in the atmosphere as long as emissions continue. Sulfur hexafluoride, itself, is the most potent greenhouse gas the IPCC has ever evaluated. Usage of these gases, especially HFCs, is growing rapidly as they are the primary substitutes for ozone depleting substances (ODS), which are being phased-out under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. In addition to ODS substitutes, HFCs, PFCs, and other fluorinated compounds are employed and emitted by a number of other industrial sources in the United States. These industries include aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing.

Total CO_2 emissions from industrial processes were approximately 17.3 MMTCE (63.3 Tg) in 1996. This amount accounted for only 1 percent of total U.S. CO_2 emissions. Methane emissions from petrochemical and silicon carbide production resulted in emissions of approximately 0.4 MMTCE (0.1 Tg) in 1996, which was less than 1 percent of U.S. CH_4 emissions. Nitrous oxide emissions from adipic acid and nitric acid production were 9.2 MMTCE (0.1 Tg) in 1996, or 9 percent of total U.S. N_2O emissions. In the same year, combined emissions of HFCs, PFCs and SF_6 totaled 34.7 MMTCE. Overall, emissions from the Industrial Processes sector increased by 35 percent from 1990 to 1996, and 8 percent in the last year alone.

Emission estimates are presented under this sector for several industrial processes that are actually accounted for within the Energy sector. Although CO_2 emissions from iron and steel production, ammonia manufacture, ferroalloy production, and aluminum production are not the result of the combustion of fossil fuels for energy, their associated emissions are captured in the fuel data for industrial coking coal, natural gas, industrial coking coal, and petroleum coke, respectively. Consequently, if all emissions were attributed to their appropriate sector, then emissions from energy would decrease by roughly 30 MMTCE in 1996, and industrial process emissions would increase by the same amount.

Greenhouse gases are also emitted from a number of industrial processes not addressed in this section. For example, caprolactam—a chemical feedstock for the manufacture of nylon 6,6—and urea production are believed to be industrial sources of N_2O emissions. However, emissions for these and other sources have not been estimated at this time due to a lack of information on the emission processes, manufacturing data, or both. As more information becomes available, emission estimates for these processes will be calculated and included in future greenhouse gas emission inventories, although their contribution is expected to be small.[2]

The general method employed to estimate emissions for industrial processes, as recommended by the Intergovernmental Panel on Climate Change (IPCC), generally involved multiplying production data for each process by an emission factor per unit of production. The emission factors used were either derived using calculations that assume precise and efficient chemical reactions or were based upon empirical data in published references. As a result, uncertainties in the emission coefficients can be attributed to, among other things, inefficiencies in the chemical reactions associated with each production process or to the use of empirically derived emission factors that are biased and, therefore, may not represent U.S. national averages. Additional sources of uncertainty specific to an individual source category are discussed in each section.

Table 3-1 summarizes emissions from the Industrial Processes sector in units of million metric tons of carbon equivalents (MMTCE), while unweighted gas emissions in teragrams (Tg) are provided in Table 3-2.

Cement Manufacture

Cement production is an energy and raw material intensive process resulting in the generation of substantial amounts of carbon dioxide (CO_2) from both the energy consumed in making the cement and the chemical process itself. Cement production accounts for about 2.4 percent of total global industrial and energy related CO_2 emissions (IPCC 1996). The United States is the world's third largest cement producer. Cement is pro-

Table 3-1: Emissions from Industrial Processes (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO_2	14.9	14.5	14.6	15.1	15.9	16.8	17.3
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
Iron and Steel Production*	23.9	19.2	20.7	21.0	21.6	22.2	21.6
Ammonia Manufacture*	6.3	6.4	6.7	6.4	6.6	6.5	6.6
Ferroalloy Production*	0.5	0.4	0.4	0.4	0.4	0.4	0.5
Aluminum Production*	1.6	1.7	1.6	1.5	1.3	1.4	1.4
CH_4	**0.3**	**0.3**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**
Petrochemical Production	0.3	0.3	0.3	0.4	0.4	0.4	0.4
Silicon Carbide Production	+	+	+	+	+	+	+
N_2O	**8.1**	**8.3**	**8.0**	**8.4**	**8.9**	**9.0**	**9.2**
Adipic Acid Production	4.7	4.9	4.6	4.9	5.2	5.2	5.4
Nitric Acid Production	3.4	3.3	3.4	3.5	3.7	3.7	3.8
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	**45.5**	**44.7**	**45.9**	**47.2**	**51.2**	**56.9**	**61.5**

+ Does not exceed 0.05 MMTCE
* Emissions from these sources are accounted for in the Energy sector and are not included in the Industrial Processes totals.
Note: Totals may not sum due to independent rounding.

duced in almost every state and is used in all of them. Carbon dioxide, emitted from the chemical process of cement production, represents one of the most significant sources of industrial CO_2 emissions in the United States.

During cement production, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature of 1,930°C (3,500°F) to form lime (i.e., calcium oxide or CaO) and CO_2. This process is known as calcination or calcining. Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the by-product CO_2 being released to the atmosphere. The clinker is then allowed to cool, mixed with a small amount of gypsum, and used to make Portland and masonry cement. The production of masonry cement requires additional lime and, thus, results in additional CO_2 emissions. However, this additional lime is already accounted for in the Lime Manufacture section of this chapter; therefore, the additional emission from making masonry cement from clinker are not counted in this source's total. They are presented here for informational purposes only.

In 1996, U.S. clinker production—including Puerto Rico—totaled 73.1 teragrams (Tg), and U.S. masonry cement production reached 3.4 Tg (USGS 1997). The resulting emissions of CO_2 from clinker production were estimated to be 10.1 MMTCE (37.1 Tg), or less than 1 percent of total U.S. CO_2 emissions (Table 3-3). Emissions from masonry production from clinker raw material were estimated to be 0.02 MMTCE (0.08 Tg) in 1996, but are accounted for under Lime Manufacture.

After falling in 1991 by 2 percent from 1990 levels, cement production emissions have grown every year since. Overall, from 1990 to 1996 emissions increased by 14 percent. In 1996, output by cement plants increased 3 percent over 1995, to 73 Tg. In both the near and in-

[2] See Annex Q for a discussion of emission sources excluded.

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

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO_2	**54.6**	**53.3**	**53.7**	**55.3**	**58.4**	**61.5**	**63.3**
Cement Manufacture	32.6	31.9	32.1	33.9	35.4	36.1	37.1
Lime Manufacture	11.9	11.7	12.1	12.4	12.8	13.6	14.1
Limestone and Dolomite Use	5.1	4.9	4.5	4.1	5.3	6.5	6.7
Soda Ash Manufacture and Consumption	4.1	4.0	4.1	4.0	4.0	4.3	4.3
Carbon Dioxide Manufacture	0.8	0.8	0.9	0.9	0.9	1.0	1.1
Iron and Steel Production[a]	87.6	70.6	75.8	77.1	79.0	81.4	79.0
Ammonia Manufacture[a]	23.1	23.4	24.4	23.4	24.3	23.7	24.2
Ferroalloy Production[a]	1.8	1.6	1.6	1.5	1.6	1.6	1.7
Aluminum Production[a]	6.0	6.1	5.9	5.4	4.9	5.0	5.3
CH_4	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Petrochemical Production	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Silicon Carbide Production	+	+	+	+	+	+	+
N_2O	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Adipic Acid Production	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Nitric Acid Production	+	+	+	+	+	+	+
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
HCFC-22 Production[b]	+	+	+	+	+	+	+
Semiconductor Manufacture	M	M	M	M	M	M	M
Electrical Transmission and Distribution[c]	+	+	+	+	+	+	+
Magnesium Production and Processing[c]	+	+	+	+	+	+	+

+ Does not exceed 0.05 Tg
M (Mixture of gases)
[a] Emissions from these sources are accounted for in the Energy sector and are not included in the Industrial Processes totals.
[b] HFC-23 emitted
[c] SF_6 emitted
Note: Totals may not sum due to independent rounding.

Table 3-3: CO_2 Emissions from Cement Production*

Year	MMTCE	Tg
1990	8.9	32.6
1991	8.7	31.9
1992	8.8	32.1
1993	9.3	33.9
1994	9.7	35.4
1995	9.9	36.1
1996	10.1	37.1

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

termediate terms, cement production in the United States is anticipated to grow only modestly (USGS 1996). Cement is a critical component of the construction industry; therefore, the availability of public construction funding, as well as overall economic growth, will have considerable influence on cement production in the future.

Methodology

Carbon dioxide emissions from cement production are created by the chemical reaction of carbon-containing minerals (i.e., calcining limestone). While in the kiln, limestone is broken down into CO_2 and lime with the CO_2 released to the atmosphere. The quantity of the CO_2 emitted during cement production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ (i.e., limestone) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

Carbon dioxide emissions were estimated by applying an emission factor, in tons of CO_2 released per ton of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis is the product of the average lime fraction for clinker of

64.6 percent (IPCC/UNEP/OECD/IEA 1997) and a constant reflecting the mass of CO_2 released per unit of lime. This yields an emission factor of 0.507 metric tons of CO_2 per metric ton of clinker produced. The emission factor was calculated as follows:

$$EF_{Clinker} = 0.646 \left[\frac{CaO \times 44.01 \text{ g/mole } CO_2}{56.08 \text{ g/mole CaO}} \right] = 0.507 \text{ tons/ } CO_2\text{/ton clinker}$$

Masonry cement requires additional lime over and above the lime used in clinker production. In particular, non-plasticizer additives such as lime, slag, and shale are added to the cement, increasing its weight by approximately 5 percent. Lime accounts for approximately 60 percent of this added weight. Thus, the additional lime is equivalent to roughly 2.86 percent of the starting amount of the product, since:

$$0.6 \times 0.05/(1 + 0.05) = 2.86\%$$

An emission factor for this added lime can then be calculated by multiplying this percentage (2.86 percent) by the molecular weight ratio of CO_2 to CaO (0.785) to yield 0.0224 metric tons of additional CO_2 emitted for every metric ton of masonry cement produced.

As previously mentioned, the CO_2 emissions from the additional lime added during masonry cement production were accounted for in the section on CO_2 emissions from Lime Manufacture. Thus, these emissions were estimated in this chapter for informational purposes only, and are not included in the cement emission totals.

Data Sources

The activity data for cement and clinker production (see Table 3-4) were taken from U.S. Geological Survey (USGS 1992, 1995, 1996, 1997); the 1996 figure was adjusted, as stated below, from USGS, *Mineral Industry Surveys: Cement in December 1996.* The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants. For 1996, clinker figures were not yet available. Thus, as recommended by the USGS, clinker production was estimated for 1996 by subtracting 5 percent from Portland cement production (Portland cement is a mixture of clinker and approximately 5 percent gypsum).

Table 3-4: Cement Production (Thousand Metric Tons)

Year	Clinker	Masonry
1990	64,355	3,209
1991	62,918	2,856
1992	63,415	3,093
1993	66,957	2,975
1994	69,786	3,283
1995	71,257	3,603
1996	73,103	3,420

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the amount of lime added to masonry cement. For example, the lime content of clinker varies from 64 to 66 percent. Also, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Since the amount of CO_2 reabsorbed is thought to be minimal, it is not considered in this analysis. In addition, estimating emissions based on finished cement production for 1996 ignores the consideration that some domestic cement may be made from imported clinker.

Lime Manufacture

Lime, or calcium oxide (CaO), is an important manufactured product with many industrial, chemical, and environmental applications. Lime has historically ranked fifth in total production of all chemicals in the United States. Its major uses are in steel making, flue gas desulfurization (FGD), construction, pulp and paper manufacturing, and water purification. Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce CaO and CO_2. Some of the CO_2 generated during the production process, however, is recovered for use in sugar refining and precipitated calcium carbonate (PCC) production. The CO_2 is driven off as a gas and is normally emitted to the atmosphere.

Table 3-5: Net CO_2 Emissions from Lime Manufacture

Year	MMTCE
1990	3.3
1991	3.2
1992	3.3
1993	3.4
1994	3.5
1995	3.7
1996	3.8

Table 3-6: CO_2 Emissions from Lime Manufacture (Tg)

Year	Production	Recovered*	Net Emissions
1990	12.5	(0.5)	11.9
1991	12.3	(0.6)	11.7
1992	12.7	(0.6)	12.1
1993	13.2	(0.8)	12.4
1994	13.7	(0.9)	12.8
1995	14.5	(0.9)	13.6
1996	15.0	(0.9)	14.1

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

Lime production in the United States—including Puerto Rico—was reported to be 19.1 teragrams (Tg) in 1996 (USGS 1997). This resulted in CO_2 emissions of 3.8 MMTCE (14.1 Tg), or 0.2 percent of U.S. CO_2 emissions (see Table 3-5 and Table 3-6).

Domestic lime manufacture has increased every year since 1991, when it declined by 1 percent from 1990 levels. Production in 1996 increased 3 percent over that in 1995 to about 19 Tg. Commercial sales increased by 500,000 metric tons to a record high of 16.9 Tg (USGS 1997).

Overall, from 1990 to 1996, CO_2 emissions increased by 18 percent. This incresase is attributed in part to growth in demand for environmental applications. In 1993, the U.S. Environmental Protection Agency (EPA) completed regulations under the Clean Air Act capping sulfur dioxide (SO_2) emissions from electric utilities. This action resulted in greater lime consumption for flue gas desulfurization systems, which increased by 16 percent in 1993 (USGS 1994b). At the turn of the century, over 80 percent of lime consumed in the United States went for construction uses, but currently over 90 percent is consumed for chemical and industrial purposes, of which 28 percent are environmental uses (USGS 1997).

Methodology

During the calcination stage of lime manufacture, CO_2 is driven off as a gas and normally exits the system with the stack gas. The mass of CO_2 released per unit of lime produced can be calculated based on stoichiometry: (44.01 g/mole CO_2) ÷ (56.08 g/mole CaO) = 0.785 g CO_2/g CaO

Lime production in the United States was 19,100 thousand metric tons in 1996 (USGS 1997), resulting in potential CO_2 emissions of 15.0 Tg. Some of the CO_2 generated during the production process, however, was recovered for use in sugar refining and precipitated calcium carbonate (PCC) production. Combined lime manufacture by these producers was 1,428 thousand metric tons in 1996, generating 1.1 Tg of CO_2. Approximately 80 percent of this CO_2 was recovered.

Table 3-7: Lime Manufacture and Lime Use for Sugar Refining and PCC (Thousand Metric Tons)

Year	Production	Use
1990	15,859	826
1991	15,694	964
1992	16,227	1,023
1993	16,800	1,310
1994	17,400	1,377
1995	18,500	1,504
1996	19,100	1,428

Data Sources

The activity data for lime manufacture and lime consumption by sugar refining and precipitated calcium carbonate (PCC) for 1990 through 1992 (see Table 3-7) were taken from USGS (1991, 1992); for 1993 through 1994 from Michael Miller (1995); and for 1995 through 1996 from USGS (1997).

Uncertainty

The term “lime” is actually a general term that includes various chemical and physical forms of this commodity. Uncertainties in the emission estimate can be attributed to slight differences in the chemical composition of these products. For example, although much care is taken

to avoid contamination during the production process, lime typically contains trace amounts of impurities such as iron oxide, alumina and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants manufacture lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime manufacture will actually be reabsorbed when the lime is consumed. In most processes that use lime (e.g., water softening), CO_2 reacts with the lime to create calcium carbonate. This is not necessarily true about lime consumption in the steel industry, however, which is the largest consumer of lime. A detailed accounting of lime use in the United States and further research into the associated processes are required to quantify the amount of CO_2 that is reabsorbed. As more information becomes available, this emission estimate will be adjusted accordingly.

In some cases, lime is generated from calcium carbonate by-products at paper mills and water treatment plants.[3] The lime generated by these processes is not included in the USGS data for commercial lime consumption. In the paper industry, mills which employ the sulfate process (i.e., Kraft) consume lime in order to causticize a waste sodium carbonate solution (i.e., black liquor). Most sulfate mills recover the waste calcium carbonate after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. However, some of these mills capture the CO_2 released in this process to be used as precipitated calcium carbonate (PCC). Further research is necessary to determine to what extent CO_2 is released to the atmosphere through generation of lime by paper mills.

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Limestone and Dolomite Use

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[4] are basic raw materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass manufacture, and environmental pollution control. Limestone is widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for commercial use. For example, limestone can be used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, or as a raw material in glass manufacturing. Limestone is heated during these processes, generating CO_2 as a by-product.

In 1996, approximately 11.8 Tg of limestone and 3.2 Tg of dolomite were used as flux stone in the chemical and metallurgical industries, in FGD systems, and for glass manufacturing (see Table 3-10). Overall, both limestone and dolomite usage resulted in aggregate CO_2 emissions of 1.8 MMTCE (6.7 Tg), or 0.1 percent of U.S. CO_2 emissions (see Table 3-8 and Table 3-9).

Emissions in 1996 increased 4 percent from the previous year. Though slightly decreasing in 1991, 1992, and 1993, CO_2 emissions from this source have since increased 33 percent from the 1990 baseline. In the near future, gradual increases in demand for crushed stone are anticipated based on the volume of work on highway and other infrastructure projects that are being financed by the Intermodal Surface Transportation Efficiency Act of 1991, the National Highway System Designation Act of 1995, and the overall growth in the U.S. economy (USGS 1996). The increases will be influenced, however, by construction activity for both publicly and privately funded projects.

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3 Some carbide producers may also regenerate lime from their calcium hydroxide by-products, nevertheless this process is not a source of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + \text{heat} \rightarrow CaO + H_2O$] and no CO_2 is released to the atmosphere.

4 Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Table 3-8: CO_2 Emissions from Limestone & Dolomite Use (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996
Flux Stone	0.8	0.7	0.6	0.5	0.8	1.1	1.1
Glass Making	0.1	+	0.1	0.1	0.1	0.1	0.2
FGD	0.5	0.6	0.5	0.5	0.6	0.6	0.6
Total	**1.4**	**1.3**	**1.2**	**1.1**	**1.5**	**1.8**	**1.8**

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

Table 3-9: CO_2 Emissions from Limestone & Dolomite Use (Tg)

Activity	1990	1991	1992	1993	1994	1995	1996
Flux Stone							
Limestone	2.6	2.3	2.0	1.6	2.1	2.5	2.7
Dolomite	0.4	0.4	0.3	0.3	0.8	1.4	1.5
Glass Making							
Limestone	0.2	0.2	0.2	0.3	0.4	0.4	0.4
Dolomite	NA	NA	NA	NA	NA	0.1	0.1
FGD	**1.9**	**2.0**	**2.0**	**1.9**	**2.0**	**2.0**	**2.1**
Total	**5.1**	**4.9**	**4.5**	**4.1**	**5.3**	**6.5**	**6.7**

NA (Not Available)
Note: Totals may not sum due to independent rounding.

Table 3-10: Limestone & Dolomite Consumption (Thousand Metric Tons)

Activity	1990	1991	1992	1993	1994	1995	1996
Flux Stone							
Limestone	5,797	5,213	4,447	3,631	4,792	5,734	6,052
Dolomite	932	838	737	632	1,739	2,852	3,010
Glass Making							
Limestone	430	386	495	622	809	958	1,011
Dolomite	NA	NA	NA	NA	NA	216	228
FGD	**4,369**	**4,606**	**4,479**	**4,274**	**4,639**	**4,650**	**4,700**

NA (Not Available)

Methodology

Carbon dioxide emissions were calculated by multiplying the amount of limestone consumed by an average carbon content for limestone, approximately 12.0 percent for limestone and 13.2 percent for dolomite (based on stoichiometry). Assuming that all of the carbon was released into the atmosphere, the appropriate emission factor was multiplied by the annual level of consumption for flux stone, glass manufacturing, and FGD systems to determine emissions.

Data Sources

Consumption data for 1990 through 1995 of limestone and dolomite used as flux stone and in glass manufacturing (see Table 3-10) were obtained from the USGS (1991, 1993, 1996). Data for 1996 were taken from USGS (1997). Consumption data for limestone used in FGD were taken from unpublished survey data in the Energy Information Administration's Form EI-767, "Steam Electric Plant Operation and Design Report," (EIA 1997).

The USGS reports production of total crushed stone annually, however, the breakdown of limestone and dolo-

mite production is only provided for odd years. Consumption figures for even years were estimated by assuming that limestone and dolomite account for the same percentage of total crushed stone for the given even year as the average of the percentages for the years before and after (exception: 1990 and 1996 consumption were estimated using the percentages for only 1991 and 1995, respectively).

It should be noted that there is a large quantity of crushed stone reported to the USGS under the category "unspecified uses". A portion of this consumption is believed to be limestone or dolomite used as flux stone and for glass manufacture. The quantity listed for "unspecified uses" was, therefore, allocated to each reported end-use according to each end-uses fraction of total consumption in that year.[5]

Uncertainty

Uncertainties in this estimate are due to variations in the chemical composition of limestone. In addition to calcite, limestone may contain smaller amounts of magnesia, silica, and sulfur. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process, the kind of ore processed, and the final use of the slag. Similarly, the quality of the limestone used for glass manufacturing will depend on the type of glass being manufactured. Uncertainties also exist in the activity data. Much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. Furthermore, some of the limestone reported as "limestone" is believed to be dolomite, which has a higher carbon content than limestone.

Soda Ash Manufacture and Consumption

Soda ash (sodium carbonate, Na_2CO_3) is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. It is used primarily as an alkali, either in glass manufacturing or simply as a material that reacts with and neutralizes acids or acidic substances. Internationally, two types of soda ash are produced—natural and synthetic. The United States produces only natural soda ash and is the largest soda ash-producing country in the world. Trona is the principal ore from which natural soda ash is made.

Only two states produce natural soda ash: Wyoming and California. Of these two states, only Wyoming has net emissions of CO_2. This difference is a result of the production processes employed in each state.[6] During the production process used in Wyoming, natural sources of sodium carbonate are heated and transformed into a crude soda ash that requires further refining. Carbon dioxide (CO_2) is generated as a by-product of this reaction, and is eventually emitted into the atmosphere. In addition, CO_2 is also released when soda ash is consumed.

In 1996, CO_2 emissions from trona production were approximately 0.4 MMTCE (1.6 Tg). Soda ash consumption in the United States also generated about 0.7 MMTCE (2.7 Tg) of CO_2 in 1996. Total emissions from this source in 1996 were 1.2 MMTCE (4.3 Tg), or less than 0.1 percent of U.S. CO_2 emissions (see Table 3-11 and Table 3-12). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 1996 decreased by 1 percent from the previous year, but have increased 3 percent since 1990.

The United States has the world's largest deposits of trona and represents about one-third of total world soda ash output. The distribution of soda ash by end-use in 1996 was glass making, 48 percent; chemical production, 27 percent; soap and detergent manufacturing, 12 percent; distributors, 5 percent; pulp and paper production, 3 percent;

5 This approach was recommended by USGS.

6 In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which will precipitate under these conditions. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a by-product, the CO_2 is recovered and recycled for use in the carbonation stage and is never actually released.

Table 3-11: CO_2 Emissions from Soda Ash Manufacture and Consumption

Year	MMTCE
1990	1.1
1991	1.1
1992	1.1
1993	1.1
1994	1.1
1995	1.2
1996	1.2

Table 3-12: CO_2 Emissions from Soda Ash Manufacture and Consumption (Tg)

Year	Trona Production	Soda Ash Consumption	Total
1990	1.4	2.7	4.1
1991	1.4	2.6	4.0
1992	1.5	2.6	4.1
1993	1.4	2.6	4.1
1994	1.4	2.6	4.0
1995	1.6	2.7	4.3
1996	1.6	2.7	4.3

Note: Totals may not sum due to independent rounding.

flue gas desulfurization and miscellaneous, 2 percent each; and water treatment, 1 percent (USGS 1997).

Exports are a driving force behind increasing U.S. soda ash production capacity (USGS 1997). For example, the automotive manufacturing industry in South America is expanding considerably. This expansion will require additional quantities of flat glass for automotive windows in the estimated 2 million vehicles that are planned to be built by the end of the century (USGS 1997). Domestic soda ash consumption is also expected to rise in 1997.

Methodology

During the production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as a by-product of the calcination process. Carbon dioxide emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$2(Na_3H(CO_3)_2\ 2H_2O) \rightarrow 3Na_2CO_3 + 5H_2O + CO_2$$
[trona] [soda ash]

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2. Thus, the 16.3 million metric tons of trona mined in 1996 for soda ash production (USGS 1997) resulted in CO_2 emissions of approximately 0.4 MMTCE (1.6 Tg).

Once manufactured, most soda ash is consumed in glass and chemical production, with minor amounts in soap and detergents, pulp and paper, flue gas desulfurization and water treatment. As soda ash is processed for these purposes, additional CO_2 is usually emitted. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed.

Table 3-13: Soda Ash Manufacture and Consumption (Thousand Metric Tons)

Year	Trona Production	Soda Ash Consumption
1990	14,734	6,527
1991	14,674	6,287
1992	14,900	6,360
1993	14,500	6,350
1994	14,600	6,240
1995	16,500	6,510
1996	16,300	6,410

Data Sources

The activity data for trona production and soda ash consumption (see Table 3-13) were taken from USGS (1993, 1994, 1995, 1997). Soda ash production and inventory data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. All six of the soda ash operations in the United States completed surveys to provide production and consumption data to the USGS.

[7] It is unclear to what extent the CO_2 used for EOR will be re-released. For example, the CO_2 used for EOR is likely to show up at the wellhead after a few years of injection (Hangebrauk et al. 1992). This CO_2, however, is typically recovered and re-injected into the well. More research is required to determine the amount of CO_2 that in fact escapes. For the purposes of this analysis, it is assumed that all of the CO_2 remains sequestered.

Uncertainty

Emissions from soda ash consumption are dependent upon the type of processing employed by each end-use; however, specific information characterizing the emissions from each end-use is limited. Therefore, uncertainty exists as to the accuracy of the emission factors.

Carbon Dioxide Manufacture

Carbon dioxide (CO_2) is used for a variety of applications, including food processing, chemical production, carbonated beverages, and enhanced oil recovery (EOR). Carbon dioxide used for EOR is injected into the ground to increase reservoir pressure, and is therefore considered sequestered.[7] For the most part, however, CO_2 used in non-EOR applications will eventually enter the atmosphere.

Carbon dioxide is produced from a small number of natural wells, as a by-product from the production of chemicals (e.g., ammonia), or separated from crude oil and natural gas. Depending on the raw materials that are used, the by-product CO_2 generated during these production processes may already be accounted for in the CO_2 emission estimates from fossil fuel consumption (either during combustion or from non-fuel uses). For example, ammonia is manufactured using primarily natural gas as a feedstock. Carbon dioxide emissions from this process are accounted for in the Energy sector under Fossil Fuel Combustion and therefore are not included here.

In 1996, CO_2 emissions from this source were approximately 0.3 MMTCE (1.1 Tg), or less than 0.1 percent of U.S. CO_2 emissions (see Table 3-14). This amount represents an increase of 18 percent from the previous year and is 43 percent higher than CO_2 emissions in 1990, which totaled 0.2 MMTCE. Carbon dioxide demand in the merchant market is expected to expand 4.2 percent annually through 1998 (Freedonia Group 1994).

Methodology

Carbon dioxide emission estimates were based on CO_2 consumption with the assumption that the end-use applications, except enhanced oil recovery, eventually release 100 percent of the CO_2 into the atmosphere. Carbon dioxide consumption for uses other than enhanced oil recovery was about 5.7 teragrams in 1996 (Ita 1997). The Freedonia Group estimates that, in the United States, there is a 80 to 20 percent split between CO_2 produced as a by-product and CO_2 produced from natural wells. Thus, emissions are equal to 20 percent of CO_2 consumption. The remaining 80 percent was assumed to already be accounted for in the CO_2 emission estimates from other categories (the most important being Fossil Fuel Combustion).

Table 3-14: CO_2 Emissions from Carbon Dioxide Manufacture

Year	MMTCE	Tg
1990	0.2	0.8
1991	0.2	0.8
1992	0.2	0.9
1993	0.2	0.9
1994	0.2	0.9
1995	0.3	1.0
1996	0.3	1.1

Data Sources

Carbon dioxide consumption data (see Table 3-15) were obtained from Freedonia Group Inc. (1994, 1996). Data for 1996 were obtained by personal communication with Paul Ita of the Freedonia Group Inc. (1997). Percent of carbon dioxide produced from natural wells was obtained from Freedonia Group Inc. (1991).

Table 3-15: Carbon Dioxide Consumption

Year	Thousand Metric Tons
1990	4,000
1991	4,200
1992	4,410
1993	4,559
1994	4,488
1995	4,842
1996	5,702

Uncertainty

Uncertainty exists in the assumed allocation of carbon dioxide manufactured from fossil fuel by-products (80 percent) and carbon dioxide produced from wells (20 percent). In addition, it is possible that CO_2 recovery exists in particular end-use sectors. Contact with

several organizations did not provide any information regarding recovery. More research is required to determine the quantity, if any, that may be recovered.

Iron and Steel Production

The production of iron and steel emits CO_2. Iron is produced by first reducing iron oxide (ore) with metallurgical coke in a blast furnace to produce pig iron (impure iron of about 4 to 4.5 percent carbon by weight). Carbon dioxide is produced as the coke used in the process is oxidized. Steel (less than 2 percent carbon by weight) is produced from pig iron in a variety of specialized steel furnaces. The majority of CO_2 emissions come from the production of iron, with smaller amounts evolving from the removal of carbon from pig iron to produce steel.

Additional CO_2 emissions also occur from the use of limestone or dolomite flux; however, these emissions are accounted for under Limestone and Dolomite Use.

Emissions of CO_2 from iron and steel production in 1996 were 21.6 MMTCE (79.0 Tg), falling from a high of 23.9 MMTCE (87.6 Tg) in 1990. Emissions fluctuated significantly in this period. CO_2 emissions from this source are not included in totals for the Industrial Processes sector because these emissions are accounted for with Fossil Fuel Combustion emissions from industrial coking coal in the Energy sector.[8] Emissions estimates are presented here for informational purposes only (see Table 3-16).

Table 3-16: CO_2 Emissions from Iron and Steel Production

Year	MMTCE	Tg
1990	23.9	87.6
1991	19.2	70.6
1992	20.6	75.8
1993	21.0	77.1
1994	21.6	79.0
1995	22.2	81.4
1996	21.6	79.0

Methodology

Carbon dioxide emissions were calculated by multiplying annual estimates of pig iron production by the ratio of CO_2 emitted per unit of iron produced (1.6 metric ton CO_2/ton iron). The emission factor employed was applied to both pig iron production and integrated pig iron plus steel production; therefore, emissions were estimated using total U.S. pig iron production for all uses including making steel.

Data Sources

The emission factor was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Production data for 1990 through 1996 (see Table 3-17) came from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Volume I-Metals and Minerals* (USGS 1994, 1996).

Table 3-17: Pig Iron Production

Year	Thousand Metric Tons
1990	54,750
1991	44,100
1992	47,400
1993	48,200
1994	49,400
1995	50,900
1996	49,400

Uncertainty

The emission factor employed was assumed to be applicable to both pig iron production and integrated pig iron plus steel production. This assumption was made because the uncertainty in the factor is greater than the additional emissions generated when steel is produced from pig iron. Using plant-specific emission factors would yield a more accurate estimate, but these factors were not available. The most accurate alternative would be to calculate emissions based on the amount of reducing agent used, rather than on the amount of iron or steel produced; however, these data were also not available.

[8] Although the CO_2 emissions from the use of industrial coking coal as a reducing agent should be included in the Industrial Processes sector, information to distinguish individual non-fuel uses of fossil fuels is unfortunately not available in DOE/EIA fuel statistics.

Ammonia Manufacture

Emissions of CO_2 occur during the production of ammonia. In the United States, roughly 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas, and the remainder is produced using naphtha (a petroleum fraction) or the electrolysis of brine at chlorine plants (EPA 1997). The former two fossil fuel-based reactions produce carbon monoxide and hydrogen gas. (The latter reaction does not lead to CO_2 emissions.) Carbon monoxide (CO) is transformed into CO_2 in the presence of a catalyst (usually a metallic oxide) during the process. The hydrogen gas is diverted and combined with nitrogen gas to produce ammonia. The CO_2, included in a gas stream with other process impurities, is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released.

$$CH_4 + H_2O \xrightarrow{\text{(catalyst)}} 4H_2 + CO_2$$

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

Emissions of CO_2 from ammonia production in 1996 were 6.6 MMTCE (24.2 Tg). For the 1990 through 1996 period, emissions fluctuated within a range of 6.3 to 6.7 MMTCE (23.1 to 24.4 Tg). Carbon dioxide emissions from this source are not included in totals for the Industrial Processes sector because these emissions are accounted for with Fossil Fuel Combustion of natural gas in the Energy sector.[9] Emissions estimates are presented here for informational purposes only (see Table 3-18).

Table 3-18: CO_2 Emissions from Ammonia Manufacture

Year	MMTCE	Tg
1990	6.3	23.1
1991	6.4	23.4
1992	6.7	24.4
1993	6.4	23.4
1994	6.6	24.3
1995	6.5	23.7
1996	6.6	24.2

Methodology

Emissions of CO_2 were calculated by multiplying annual estimates of ammonia production by an emission factor (1.5 ton CO_2/ton ammonia). It was assumed that all ammonia was produced using catalytic steam reformation, although small amounts may have been produced using chlorine brines. The actual amount produced using this latter method is not known, but assumed to be small.

Data Sources

The emission factor was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Production data (see Table 3-19) came from the Census Bureau of the U.S. Department of Commerce (Census Bureau 1997).

Table 3-19: Ammonia Manufacture

Year	Metric tons
1990	15,425,394
1991	15,573,812
1992	16,260,834
1993	15,599,485
1994	16,210,848
1995	15,787,276
1996	16,113,777

Uncertainty

It is uncertain how accurately the emission factor used represents an average across all ammonia plants. By using an alternative method of estimating emissions from ammonia production that requires data on the consumption of natural gas at each ammonia plant, more accurate estimates could be calculated. However, these consumption data are often considered confidential and are difficult to acquire. All ammonia production in this analysis was assumed to be from the same process; however, actual emissions could differ because processes other than catalytic steam reformation may have been used.

[9] Although the CO_2 emissions from the use of natural gas as a feedstock should be included in the Industrial Processes sector, information to distinguish individual non-fuel uses of fossil fuels is unfortunately not available in DOE/EIA fuel statistics.

Ferroalloy Production

Carbon dioxide is emitted from the production of several ferroalloys. Ferroalloys are composites of iron and other elements often including silicon, manganese, and chromium. When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel. Estimates from two types of ferrosilicon (50 and 75 percent silicon) and silicon metal (about 98 percent silicon) have been calculated. Emissions from the production of ferrochromium and ferromanganese are not included here because of the small number of manufacturers of these materials. As a result, government information disclosure rules prevent the publication of production data for them. Similar to emissions from the production of iron and steel, CO_2 is emitted when coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing environment, CO is initially produced. The CO is eventually oxidized, becoming CO_2. A representative reaction equation for the production of 50 percent ferrosilicon is given below:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

Emissions of CO_2 from ferroalloy production in 1996 were 0.5 MMTCE (1.7 Tg). From 1990 through 1996, emissions fluctuated within a range of 0.4 to 0.5 MMTCE (1.5 to 1.8 Tg). Carbon dioxide emissions from this source are not included totals for the Industrial Processes sector because these emissions are accounted for in the calculations of industrial coking coal combustion under the Energy sector.[10] Emission estimates are presented here for informational purposes only (see Table 3-20).

Table 3-20: CO_2 Emissions from Ferroalloy Production

Year	MMTCE	Tg
1990	0.5	1.8
1991	0.4	1.6
1992	0.4	1.6
1993	0.4	1.5
1994	0.4	1.6
1995	0.4	1.6
1996	0.5	1.7

Methodology

Emissions of CO_2 were calculated by multiplying annual estimates of ferroalloy production by material-specific emission factors. Emission factors were applied to production data for ferrosilicon 50 and 75 percent (2.35 and 3.9 metric ton CO_2/metric ton, respectively) and silicon metal (4.3 metric ton CO_2/metric ton). It was assumed that all ferroalloy production was produced using coking coal, although some ferroalloys may have been produced with wood, biomass, or graphite carbon inputs.

Data Sources

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Production data for 1990 through 1996 (see Table 3-21) came from the *Minerals Yearbook: Volume I—Metals and Minerals* published in USGS (1991, 1992, 1993, 1994, 1995, 1996, 1997).

Table 3-21: Production of Ferroalloys (Metric Tons)

	Ferrosilicon		Silicon
Year	50%	75%	Metal
1990	321,385	109,566	145,744
1991	230,019	101,549	149,570
1992	238,562	79,976	164,326
1993	199,275	94,437	158,000
1994	198,000	112,000	164,000
1995	181,000	128,000	163,000
1996	182,000	132,000	175,000

Uncertainty

Although some ferroalloys may be produced using wood or biomass as a carbon source, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood would not be counted under this source because wood-based carbon is of biogenic origin.[11] Emissions from ferroalloys produced with graphite inputs would be counted in national totals, but may generate differing amounts of CO_2 per unit of ferroalloy produced compared to the use of coking coal. As with emissions from iron and steel production, the most accurate method for these estimates would be basing calculations on the amount of reducing

[10] Although the CO_2 emissions from the use of industrial coking coal as a reducing agent should be included in the Industrial Processes sector, information to distinguish individual non-fuel uses of fossil fuels is unfortunately not available in DOE/EIA fuel statistics.

[11] Emissions and sinks of biogenic carbon are accounted for under the Land-Use Change and Forestry sector.

agent used in the process, rather than on the amount of ferroalloys produced. Again, these data were unavailable.

Petrochemical Production

Small amounts of methane (CH_4) are released during the production of petrochemicals. Emissions are calculated here from the production of five chemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol. Emissions of CH_4 from petrochemical production in 1996 were 0.4 MMTCE (73 Gg), or 0.2 percent of U.S. CH_4 emissions (see Table 3-22). Production levels of all five chemicals increased from 1990 to 1996.

Table 3-22: CH_4 Emissions from Petrochemical Production

Year	MMTCE	Gg
1990	0.3	55
1991	0.3	57
1992	0.3	60
1993	0.4	65
1994	0.4	70
1995	0.4	70
1996	0.4	73

Methodology

Emissions of CH_4 were calculated by multiplying annual estimates of chemical production by an emission factor. The following factors were used: 11 kg CH_4/metric ton carbon black, 1 kg CH_4/metric ton ethylene, 0.4 kg CH_4/metric ton ethylene dichloride, 4 kg CH_4/metric ton styrene, and 2 kg CH_4/metric ton methanol. These emission factors were based upon measured material balances. Although the production of other chemicals may also result in methane emissions, there were not sufficient data to estimate their emissions.

Data Sources

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Annual production data (see Table 3-23) came from the Chemical Manufacturers Association *Statistical Handbook* (CMA 1997).

Uncertainty

The emission factors used here were based on a limited number of studies. Using plant-specific factors instead of average factors would increase the accuracy of the emissions estimates, however, such data were not available. There may also be other significant sources of methane arising from chemical production activities which have not been included in these estimates.

Silicon Carbide Production

Methane is emitted from the production of silicon carbide, a material used as an industrial abrasive. To make silicon carbide (SiC), quartz (SiO_2) is reacted with carbon in the form of petroleum coke. Methane is produced during this reaction from volatile compounds in the petroleum coke. Although CO_2 is also emitted from this production process, the requisite data were unavailable for these calculations. Regardless, they are already accounted for under CO_2 from Fossil Fuel Combustion in the Energy sector. Emissions of CH_4 from silicon carbide production in 1996 (see Table 3-24) were less than 0.1 MMTCE (1 Gg).

Methodology

Emissions of CH_4 were calculated by multiplying annual estimates of silicon carbide production by an emission factor (11.6 kg CH_4/metric ton silicon carbide). This emission factor was derived empirically from measure-

Table 3-23: Production of Selected Petrochemicals (Metric Tons)

Chemical	1990	1991	1992	1993	1994	1995	1996
Carbon Black	1,306,368	1,224,720	1,365,336	1,451,520	1,492,344	1,524,096	1,560,384
Ethylene	16,541,885	18,124,042	18,563,126	18,382,594	20,200,622	19,470,326	20,343,960
Ethylene Dichloride	6,282,360	6,220,670	6,872,040	8,141,213	8,482,320	7,830,950	8,595,720
Styrene	3,636,965	3,680,510	4,082,400	4,565,030	5,112,072	5,166,504	5,386,954
Methanol	3,784,838	3,948,134	3,665,995	4,781,851	4,904,323	5,122,958	5,261,760

Table 3-24: CH_4 Emissions from Silicon Carbide Production

Year	MMTCE	Gg
1990	+	1
1991	+	1
1992	+	1
1993	+	1
1994	+	1
1995	+	1
1996	+	1

+ Does not exceed 0.05 MMTCE

ments taken at Norwegian silicon carbide plants (IPCC/UNEP/OECD/IEA 1997).

Data Sources

The emission factor was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Production data for 1990 through 1996 (see Table 3-25) came from the *Minerals Yearbook: Volume I-Metals and Minerals* published in USGS (1991, 1992, 1993, 1994, 1995, 1996, 1997).

Table 3-25: Production of Silicon Carbide

Year	Metric Tons
1990	105,000
1991	78,900
1992	84,300
1993	74,900
1994	84,700
1995	75,400
1996	73,600

Uncertainty

The emission factor used here was based on one study of Norwegian plants. The applicability of this factor to average U.S. practices at silicon carbide plants is uncertain. The most accurate alternative would be to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced. Again, these data were unavailable.

Adipic Acid Production

Adipic acid production has been identified as a significant anthropogenic source of nitrous oxide (N_2O) emissions. Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Ninety percent of all adipic acid produced in the United States is used in the production of nylon 6,6. It is also used to provide some foods with a "tangy" flavor.

Adipic acid is produced through a two-stage process during which N_2O is generated in the second stage. This second stage involves the oxidation of ketone-alcohol with nitric acid. Nitrous oxide is generated as a by-product of this reaction and is emitted in the waste gas stream. In the United States, this waste gas is treated to remove nitrogen oxides (NO_x), other regulated pollutants, and in some cases N_2O. There are currently four plants in the United States that produce adipic acid. Since 1990, two of these plants have employed emission control measures destroying roughly 98 percent of the N_2O in their waste gas stream before it is released to the atmosphere (Radian 1992). It is expected that all adipic acid production plants will have N_2O emission controls in place and operating by the end of 1997, as a result of a voluntary agreement among producers.

Adipic acid production for 1996 was estimated to be 835 thousand metric tons. Nitrous oxide emissions from this source were estimated to be 5.4 MMTCE for 1996, or 5 percent of U.S. N_2O emissions (see Table 3-26).

Adipic acid production reached its highest level in twelve years in 1996, growing about 2 percent from the previous year. Though production may continue to increase in the future, emissions should follow a significantly different path by the end of 1997, due to the widespread installation of pollution control measures mentioned above.

Table 3-26: N_2O Emissions from Adipic Acid Manufacture

Year	MMTCE	Gg
1990	4.7	56
1991	4.9	58
1992	4.6	54
1993	4.9	58
1994	5.2	62
1995	5.2	62
1996	5.4	63

Methodology

Nitrous oxide emissions were calculated by multiplying adipic acid production by the ratio of N_2O emitted per unit of adipic acid produced and adjusting for the actual percentage of N_2O released as a result of plant specific emission controls. Because emissions of N_2O in the United States are not regulated, emissions have not been well characterized. However, on the basis of experiments (Thiemens and Trogler 1991), the overall reaction stoichiometry for N_2O production in the preparation of adipic acid was estimated at approximately 0.3 kg of N_2O per kilogram of product.

Data Sources

Adipic acid production data for 1990 through 1995 (see Table 3-27) were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992, 1993, 1994, 1995, 1996). The 1996 data were projected from the 1995 manufactured total based upon suggestions of industry contacts. The emission factor was taken from Thiemens, M.H. and W.C. Trogler (1991).

Table 3-27: Adipic Acid Manufacture

Year	Thousand Metric Tons
1990	735
1991	771
1992	708
1993	765
1994	815
1995	816
1996	835

Uncertainty

Because N_2O emissions are controlled in some adipic acid production facilities, the amount of N_2O that is actually released will depend on the level of controls in place at a specific production plant. Thus, in order to calculate accurate emission estimates, it is necessary to have production data on a plant-specific basis. In most cases, however, these data are confidential. As a result, plant-specific production figures were estimated by allocating total adipic acid production using existing plant capacities. This creates a degree of uncertainty in the adipic acid production data used to derive the emission estimates as it is necessary to assume that all plants operate at equivalent utilization levels.

The emission factor was based on experiments (Thiemens and Trogler 1991) that attempt to replicate the industrial process and, thereby, measure the reaction stoichiometry for N_2O production in the preparation of adipic acid. However, the extent to which the lab results are representative of actual industrial emission rates is not known.

Nitric Acid Production

Nitric acid (HNO_3) is an inorganic compound used primarily to make synthetic commercial fertilizer. It is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. Virtually all of the nitric acid produced in the United States is manufactured by the catalytic oxidation of ammonia (EPA 1997). During this reaction, N_2O is formed as a by-product and is released from reactor vents into the atmosphere. While the waste gas stream may be cleaned of other pollutants such as nitrogen dioxide, there are currently no control measures aimed at eliminating N_2O.

Nitric acid production reached 8,252 thousand metric tons in 1996 (C&EN 1997). Nitrous oxide emissions from this source were estimated at 3.8 MMTCE, accounting for approximately 4 percent of U.S. N_2O emissions (see Table 3-28). Nitric acid production for 1996 increased 3 percent from the previous year, or 12 percent since 1990.

Table 3-28: N_2O Emissions from Nitric Acid Manufacture

Year	MMTCE	Gg
1990	3.4	40
1991	3.3	40
1992	3.4	40
1993	3.5	41
1994	3.7	44
1995	3.7	44
1996	3.8	45

Methodology

Nitrous oxide emissions were calculated by multiplying nitric acid production by the amount of N_2O emitted per unit of nitric acid produced. Off-gas measurements at one nitric acid production facility showed N_2O emission rates to be approximately 2 to 9 g N_2O per kg of nitric acid produced (Reimer et al. 1992). In calculating emissions, the midpoint of this range was used (5.5 kg N_2O/metric ton HNO_3).

Data Sources

Nitric acid production data for 1990 through 1996 (see Table 3-29) were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992, 1993, 1994, 1995, 1996). The emission factor range was taken from Reimer, R.A., Parrett, R.A., and Slaten, C.S. (1992).

Table 3-29: Nitric Acid Manufacture

Year	Thousand Metric Tons
1990	7,257
1991	7,189
1992	7,298
1993	7,488
1994	8,005
1995	8,023
1996	8,252

Uncertainty

These emission estimates are highly uncertain due to a lack of information on manufacturing processes and emission controls. Although no abatement techniques are specifically directed at removing N_2O at nitric acid plants, existing control measures for other pollutants may have some impact upon N_2O emissions. The emission factor range of 2 to 9 g N_2O per kg of nitric acid produced is significant, leading to further uncertainty when applying the midpoint value.

Substitution of Ozone Depleting Substances

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used primarily as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990[12]. Ozone depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs, unlike ODSs, are not harmful to the stratospheric ozone layer, they are powerful greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 3-30 and Table 3-31.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODS were relatively small amounts of HFC-152a—a component of the refrigerant blend R-500 used in chillers—and HFC-134a in refrigeration end-uses. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air conditioners and in refrigerant blends such as R-404[13]. In 1993, use of HFCs in foams and aerosols began, and in 1994 these compounds also found applications as solvents and sterilants. In 1995, ODS substitutes for halons entered widespread use in the United States as halon production was phased-out.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes 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. 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*.

12 [42 U.S.C § 7671, CAA § 601]

13 R-404 contains HFC-125, HFC-143a, and HFC-134a.

Table 3-30: Emissions of HFCs and PFCs from ODS Substitution (MMTCE)

Gas	1990	1991	1992	1993	1994	1995	1996
HFC-23	+	+	+	+	+	+	0.1
HFC-125	+	+	0.2	0.4	1.2	2.2	2.4
HFC-134a	0.2	0.2	0.2	1.0	1.9	3.4	4.8
HFC-143a	+	+	+	+	+	0.1	0.2
HFC-152a	0.1	+	+	+	+	+	+
HFC-227ea	+	+	+	+	0.7	1.5	1.6
HFC-236fa	+	+	+	+	+	+	0.1
HFC-4310mee	+	+	+	+	+	0.2	0.4
C_4F_{10}	+	+	+	+	+	+	0.1
C_6F_{14}	+	+	+	+	+	+	+
PFC/PFPEs*	+	+	+	+	0.1	2.0	2.0
Total	**0.3**	**0.2**	**0.4**	**1.4**	**4.0**	**9.5**	**11.9**

+ Does not exceed 0.05 MMTCE
* PFC/PFPEs are a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solventapplications. For estimating purposes, the GWP value used was based upon C_6F_{14}.
Note: Totals may not sum due to independent rounding.

Table 3-31: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	1991	1992	1993	1994	1995	1996
HFC-23	+	+	+	+	+	9	26
HFC-125	+	+	236	481	1,628	2,823	3,172
HFC-134a	564	564	626	2,885	5,410	9,553	13,605
HFC-143a	+	+	+	12	43	94	226
HFC-152a	1,500	750	313	694	833	981	1,085
HFC-227ea	+	+	+	+	894	1,895	2,063
HFC-236fa	+	+	+	+	+	+	79
HFC-4310mee	+	+	+	+	+	611	1,030
C_4F_{10}	+	+	+	+	+	22	64
C_6F_{14}	+	+	+	+	+	2	6
PFC/PFPEs*	+	+	+	+	33	990	990

+ Does not exceed 0.5 Mg
* PFC/PFPEs are a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

Methodology and Data Sources

The EPA used a detailed vintaging model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes, including HFCs and PFCs. The name of the model refers to the fact that the model tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. This vintaging model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles. By aggregating the data for more than 40 different end-uses, the model produces estimates of annual use and emissions of each compound.

The major end-use categories defined in the vintaging model to characterize ODS use in the United States were: refrigeration and air conditioning, aerosols, solvent cleaning, fire extinguishing equipment, sterilization, and foams.

The vintaging model estimates HFC and PFC use and emissions resulting from their use as replacements for ODS by undertaking the following steps:

Step 1: Estimate ODS Use in the United States Prior to Phase-out Regulations

The model begins by estimating chlorofluorocarbon (CFC), halon, methyl chloroform, and carbon tetrachloride use prior to the restrictions on the production of these compounds in the United States. For modeling purposes, total ODS use was divided into more than 40 separate end-uses. The methodology used to estimate baseline ODS use varied depending on the end-use under consideration. The next section describes the methodology used for estimating baseline ODS use in the refrigeration, air conditioning, and fire extinguishing (halon) sectors. The subsequent section details the methodology used for all other end-uses.

Step 1.1: Estimate Baseline ODS Use for Refrigeration, Air Conditioning, and Fire Extinguishing

For each equipment type, the model estimates the total stock of ODS-containing equipment during the period 1985 to 1996. The key data required to develop stock estimates for each end-use were as follows:

- Total stock of ODS-containing equipment in use in the United States in 1985
- The annual rate of growth in equipment consumption in each end-use
- The retirement function for equipment in each end-use

Historical production and consumption data were collected for each equipment type to develop estimates of total equipment stock in 1985. For some end-uses, the only data available were estimates of ODS usage. In these cases, the total 1985 stock was estimated by dividing total ODS use by the average charge of ODS in a typical piece of equipment.

Stocks of ODS-containing equipment change over time. In the vintaging model, the growth in equipment stocks in each end-use was simulated after 1985 using growth rates that define the total number of pieces of new equipment added to the stock each year. The model also uses a retirement function to calculate the length of time each piece of equipment is expected to remain in service. These retirement functions are a critical part of the vintaging model because they determine the speed at which the stock of equipment turns over and is replaced by new equipment. In this analysis, point estimates of the average lifetime of equipment in each end-use were used to develop retirement functions. These retirement functions assume 100 percent survival of equipment up to this average age and zero percent survival thereafter.

Given these data, the total equipment stock in service in a given year *t* was estimated as the equipment stock in the year (*t*-1), plus new equipment added to the stock in year *t*, minus retirements in year *t*.

Annual ODS use was then estimated for each equipment type during the period 1985 through 1996. Because control technologies can reduce particular kinds of ODS use, use estimates were broken down by type of use (e.g., use in new equipment at manufacture and use required to maintain existing equipment). Baseline estimates of ODS use were based on the following data collected for each equipment type:

- ODS charge size (Refers to the number of kilograms of ODS installed in new equipment during manufacture)
- ODS required to maintain existing equipment (In many end-uses, ODS must be regularly added to equipment to replace chemical emitted from the equipment. Such emissions result from normal leakage and from loss during servicing of the equipment.)

With these data, ODS usage for each refrigeration, air conditioning, and fire extinguishing end-use was calculated using the following equation:

(Total stock of existing equipment in use) X (ODS required to maintain each unit of existing equipment) + (New equipment additions) X (ODS charge size)

Step 1.2: Estimate Baseline ODS Use in Foams, Solvents, Sterilization, and Aerosol End-Uses

For end-uses other than refrigeration, air conditioning, and fire extinguishing, a simpler approach was used because these end-uses do not require partial re-filling of existing equipment each year. Instead, such equipment either does not require any ODS after initial production (e.g., foams and aerosols), or requires complete

re-filling or re-manufacturing of the equipment each year (e.g., solvents and sterilants). ODS use does not need to be differentiated between new and existing equipment for these end-uses. Thus, it is not necessary to track the stocks of new and existing equipment separately over time.

The approach used for these end-uses was to estimate total ODS use in 1985 based on available industry data. Future ODS use was estimated using growth rates that predict ODS consumption growth in these end-uses over time, based upon input from industry.

Step 2: Specification and Implementation of Control Technologies

Having established a baseline for ODS equipment in 1985, the vintaging model next defines controls that may be undertaken for purposes of reducing ODS use and emissions within each end-use. The following controls are implemented in the model:

- Replacement of ODS used in the manufacturing of new equipment or in the operation of existing equipment (i.e., retrofits) with alternative chemicals, such as HFCs and PFCs
- Replacement of ODS-based processes or products with alternative processes or products (e.g., the use of aqueous cleaning to replace solvent cleaning with CFC-113)
- Modification of the operation and servicing of equipment to reduce use and emission rates through the application of engineering and recycling controls

Assumptions addressing these types of controls in each end-use were used to develop "substitution scenarios" that simulate the phase-out of ODSs in the United States by end-use. These scenarios represent EPA's best estimates of the use of control technologies towards the phase-out ODS in the United States, and are periodically reviewed by industry experts.

In addition to the chemical substitution scenarios, the model also assumes that a portion of ODS substitutes are recycled during servicing and retirement of the equipment. Recycling is assumed to occur in the refrigeration and air conditioning, fire extinguishing, and solvent end-uses.

The substitution scenarios defined for each equipment type were applied to the relevant equipment stocks. The equipment life-cycle was then simulated after the imposition of controls. Substitute chemical use and emissions—including HFCs and PFCs—were calculated for each scenario using the methods described below.

Step 3: Estimate ODS Substitute Use and Emissions (HFCs and PFCs)

ODS substitute use (i.e., HFC and PFC use) was calculated using the same routine described above for refrigeration, air conditioning, and fire extinguishing equipment. In terms of chemical usage, a key question was whether implementation of a given ODS substitute in an end-use changed the quantity of chemical required to manufacture new equipment or service existing equipment. In this analysis, it was assumed that the use of ODS alternatives in new equipment—including HFCs and PFCs—did not change the total charge of initial chemical used in the equipment in each end-use. For certain refrigeration and air conditioning end-uses, however, it was assumed that new equipment manufactured with HFCs and PFCs would have lower leak rates than older equipment. Existing ODS-containing equipment that was retrofitted with HFCs or PFCs was assumed to have a higher leak rate than new HFC/PFC equipment.

The use of HFCs and PFCs in all other sectors was calculated by simply replacing ODS use with the chemical alternatives defined in the substitution scenarios. The use of HFCs and PFCs was not assumed to change the quantity of chemical used in new or existing equipment for these sectors.

The vintaging model estimates HFC and PFC emissions over the lifetime of equipment in each end-use. Emissions may occur at the following points in the lifetime of the equipment:

- Emissions upon manufacture of equipment
- Annual emissions from equipment (due to normal leakage, and if applicable, servicing of equipment)
- Emissions upon retirement of equipment

The emissions that occur upon manufacture of refrigeration and air conditioning equipment were assumed to be less than 0.1 percent. Annual emissions of HFCs and

PFCs from equipment—due to normal leakage and servicing—were assumed to be constant each year over the life of the equipment. The quantity of emissions at disposal is a function of the prevalence of recycling at disposal.

Emissions for open cell foam were assumed to be 100 percent in the year of manufacture. Closed cell foams were assumed to emit a portion of total HFC/PFC use upon manufacture, a portion at a constant rate over the lifetime of the foam, and the rest at disposal. There were no foam recycling technologies in use in the United States; therefore, HFCs and PFCs remaining in closed cell foam were assumed to be emitted by the end of the product lifetime.

Emissions were assumed to occur at manufacture, during normal operation, and upon retirement of fire extinguishing systems. Emissions at manufacture were assumed to be negligible and emissions upon disposal were assumed to be minimal because of the use of recovery technologies.

For solvent applications, 15 percent of the chemical used in equipment was assumed to be emitted in that year. The remainder of the used solvent was assumed to be disposed rather than emitted or recycled.

For sterilization applications, all chemicals that were used in the equipment were assumed to be emitted in that year.

All HFCs and PFCs used in aerosols were assumed to be emitted in the same year. No technologies were known to exist that recycle or recover aerosols.

Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the EPA vintaging model or the methods outlined in IPCC/UNEP/OECD/IEA (1997). Though EPA's model is more comprehensive than the IPCC methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

Aluminum Production

Aluminum is a light-weight, malleable, and corrosion resistant metal that is used in many manufactured products including aircraft, automobiles, bicycles, and kitchen utensils. The United States was the largest producer with 17 percent of the world total in 1996 (USGS 1997). The United States was also a major importer. The production of aluminum—in addition to consuming large quantities of electricity—results in emissions of several greenhouse gases including carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Occasionally, sulfur hexafluoride (SF_6) is also used by the aluminum industry as a degassing agent in specialized applications. In these cases it is mixed with argon and nitrogen and blown through molten aluminum as it cools; however, this practice is not know to be used by firms in the United States. Where it does occur in other countries, the concentration of SF_6 in the mixture is small and it is believed that nearly all the SF_6 is destroyed in the process.

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Heroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, some of this carbon is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated at 1.4 MMTCE (5.3 Tg) in 1996 (see Table 3-32). The CO_2 emissions from this source, however, are accounted for under the non-fuel use portion of CO_2 from Fossil Fuel Combustion of petroleum coke and tar pitch in the Energy sector. Thus, to avoid double counting, CO_2 emissions from aluminum production are not included in totals for the Industrial Processes sector. They are described here for informational purposes only.

Table 3-32: CO_2 Emissions from Aluminum Production

Year	MMTCE	Tg
1990	1.6	6.0
1991	1.7	6.1
1992	1.6	5.9
1993	1.5	5.4
1994	1.3	4.8
1995	1.4	5.0
1996	1.4	5.3

In addition to CO_2 emissions, the aluminum production industry was also the largest source of PFC emissions in the United States. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, termed "anode effects". These anode effects cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given level of production depends on the frequency and duration of these anode effects. The more frequent and long-lasting the anode effects, the greater the emissions.

Primary aluminum production related emissions of PFCs are estimated to have declined from 4.3 MMTCE of CF_4 (2,430 Mg) and 0.6 MMTCE of C_2F_6 (240 Mg) in 1990 to 2.5 MMTCE of CF_4 (1,430 Mg) and 0.4 MMTCE of C_2F_6 (140 Mg) in 1996, as shown in Table 3-33 and Table 3-34. The overall decline in PFC emissions is estimated to have been 40 percent. This decline was both due to reductions in domestic aluminum production and actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects under EPA's Voluntary Aluminum Industrial Partnership (VAIP).

Table 3-33: PFC Emissions from Aluminum Production (MMTCE)

Year	CF_4	C_2F_6	Total
1990	4.3	0.6	4.9
1991	4.1	0.6	4.7
1992	3.6	0.5	4.1
1993	3.1	0.4	3.5
1994	2.5	0.4	2.8
1995	2.4	0.3	2.7
1996	2.5	0.4	2.9

Note: Totals may not sum due to independent rounding.

Table 3-34: PFC Emissions from Aluminum Production (Mg)

Year	CF_4	C_2F_6
1990	2,430	240
1991	2,330	230
1992	2,020	200
1993	1,750	170
1994	1,400	140
1995	1,330	130
1996	1,430	140

U.S. primary aluminum production for 1996, totaling 3,577 thousand metric tons, increased by 6 percent from 1995 to 1996. Production fell to a seven-year low in 1994, continuing a decline which started in 1991. These declines were due in part to a continued increase in imports, primarily from the former Soviet Union. For example, in 1994 these countries exported 60 percent more ingots (metal cast for easy transformation) to the United States than in 1993. However, the U.S. Geological Survey (USGS) reported that this supply surplus would be temporary and that a more normal global supply and demand equilibrium should return beginning in 1995. Data for 1995 and 1996 appear to support this assessment. U.S. imports for consumption of aluminum materials decreased in 1996 compared with those of the previous year. Although imports from Russia continued to decline from their peak level in 1994, Russia remained the second largest source of imports (USGS 1997).

The transportation industry remained the largest domestic consumer of aluminum, accounting for about 28 percent (USGS 1997). The "big three" automakers have announced new automotive designs that will expand the use of aluminum materials in the near future. USGS believes that demand for and production of aluminum should continue to increase.

Methodology

Carbon dioxide is released to the atmosphere during alumina reduction to aluminum metal following the reaction below:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

The quantity of CO_2 released was estimated from

the production volume of primary aluminum metal and the carbon consumed by the process. During alumina reduction, approximately 1.5 to 2.2 metric tons of CO_2 are emitted for each metric ton of aluminum produced (Abrahamson 1992). In previous inventories, the midpoint (1.85) of this range was used for the emission factor. However, for this year's report—and adjusting earlier years—the emission factor was revised to 1.5 metric tons CO_2 per metric ton of aluminum smelted based on a mass balance for a "typical" aluminum smelter (Drexel University Project Team 1996). This value is at the low end of the Abrahamson (1992) range.

The CO_2 emissions from this source are already accounted for under CO_2 Emissions from Fossil Fuel Combustion in the Energy sector.[14] Thus, to avoid double counting, CO_2 emissions from aluminum production are not included in totals for the Industrial Processes sector.

PFC emissions from aluminum production were estimated using a per unit production emission factor for the base year 1990. The emission factor used is a function of several operating variables including average anode effect frequency and duration. Total annual emissions for 1990 were then calculated based on reported annual production levels. The five components of the per unit production emission factor are:

- Amount of CF_4 and C_2F_6 emitted during every minute of an anode effect, per ampere of current
- Average duration of anode effects
- Average frequency of anode effects
- Current efficiency for aluminum smelting
- Current required to produce a metric ton of aluminum, assuming 100 percent efficiency

Using available data for the United States, this methodology yields a range in the emission factor of 0.01 to 1.2 kg CF_4 per metric ton of aluminum produced in 1990 (Jacobs 1994). The emission factor for C_2F_6 was estimated to be approximately an order of magnitude lower. Emissions for 1991 through 1996 were estimated with emission factors that incorporated data on reductions in anode effects reported to the VAIP by aluminum companies.

Data Sources

Production data for 1990 through 1996 (see Table 3-35) were obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1997, 1995). The USGS requested data from the 13 domestic producers, all of whom responded. The CO_2 emission factor range was taken from Abrahamson (1992). The mass balance for a "typical" aluminum smelter was taken from Drexel University Project Team (1996).

PFC emission estimates were provided by the EPA's Atmospheric Pollution Prevention Division in cooperation with participants in the Voluntary Aluminum Industrial Partnership.

Table 3-35: Production of Primary Aluminum

Year	Thousand Metric Tons
1990	4,048
1991	4,121
1992	4,042
1993	3,695
1994	3,299
1995	3,375
1996	3,577

Uncertainty

Uncertainty exists as to the most accurate CO_2 emission factor for aluminum production. Emissions vary depending on the specific technology used by each plant. However, evidence suggests that there is little variation in CO_2 emissions from plants utilizing similar technologies (IPCC/UNEP/OECD/IEA 1997). A less uncertain method would be to calculate emissions based upon the amount of carbon—in the form of petroleum coke or tar pitch—consumed by the process; however, this type of information was not available.

[14] Although the carbon contained in the anode is considered a non-fuel use of petroleum coke or tar pitch and should be included in the Industrial Processes sector, information to distinguish individual non-fuel uses of fossil fuels is unfortunately not available in DOE/EIA fuel statistics.

For PFC emission estimates, the value for emissions per anode effect minute per ampere was based on a limited number of measurements that may not be representative of the industry as a whole (EPA 1993). For example, the emission factor may vary by smelter technology type, among other factors. The average frequency of anode effects and the current efficiency are well documented; however, insufficient measurement data existed to quantify a relationship between PFC emissions and anode effect minutes. Future inventories will incorporate additional data reported to VAIP by aluminum companies and ongoing research into PFC emissions from aluminum production.

HCFC-22 Production

Trifluoromethane (HFC-23 or CHF_3) is generated as a by-product during the manufacturing of chlorodifluoromethane (HCFC-22), which is currently used both as a substitute for ozone depleting substances—mainly in refrigeration and air conditioning systems—and as a chemical feedstock for manufacturing synthetic polymers. Although HCFC-22 production is scheduled to be phased out by 2020 under the U.S. Clean Air Act[15] because of its stratospheric ozone depleting properties, feedstock production is permitted to continue indefinitely.

Emissions of HFC-23 in 1996 were estimated to be 8.5 MMTCE (2,660 Mg). This represents over a 10 percent decline from emissions in 1990 (see Table 3-36).

In the future, production of HCFC-22 is expected to initially increase in the United States and then decline as non-feedstock HCFCs production is phased-out; feedstock production is anticipated to continue growing steadily, mainly for manufacturing Teflon® and other chemical products. All U.S. producers of HCFC-22 are participating in a voluntary program with the EPA to reduce HFC-23 emissions.

Table 36: HFC-23 Emissions from HCFC-22 Production

Year	MMTCE	Mg
1990	9.5	2,980
1991	8.4	2,630
1992	9.5	2,980
1993	8.7	2,730
1994	8.6	2,700
1995	7.4	2,320
1996	8.5	2,660

Methodology

EPA studied the conditions of HFC-23 generation, methods for measuring emissions, and technologies for emissions control. This effort was undertaken in cooperation with the manufacturers of HCFC-22.

Previous emission estimates assumed that HFC-23 emissions were between 2 and 4 percent of HCFC-22 production on a mass ratio basis. The methodology employed for this year's inventory was based upon measurements of critical feed components at individual HCFC-22 production plants. Individual producers also measured HFC-23 concentrations in the process stream by gas chromatography. Using measurements of feed components and HFC-23 concentrations in process streams, the amount of HFC-23 generated was estimated. HFC-23 concentrations were determined at the point the gas leaves the chemical reactor; therefore, estimates also include fugitive emissions.

Data Sources

Emission estimates were provided by the EPA's Atmospheric Pollution Prevention Division in cooperation with the U.S. manufacturers of HCFC-22.

Uncertainty

A high level of confidence has been attributed to the HFC-23 concentration data employed because measurements were conducted frequently and accounted for day-to-day and process variability. It is estimated that the emissions reported are within 20 percent of the true value. This methodology allowed for determination of reductions in HFC-23 emissions during a period of increasing HCFC-22 production. (Use of emission factors would not have allowed for such an assessment.) By

15 As construed, interpreted and applied in the terms and conditions of the *Montreal Protocol on Substances that Deplete the Ozone Layer*. [42 U.S.C. §7671m(b), CAA §614]

1996, the rate of HFC-23 generated as a percent of HCFC-22 produced dropped, on average, below 2 percent in the United States.

Semiconductor Manufacture

The semiconductor industry uses multiple long-lived fluorinated gases in plasma etching and chemical vapor deposition (CVD) processes. The gases most commonly employed are trifluoromethane (HFC-23), perfluoromethane (CF_4), perfluoroethane (C_2F_6), and sulfur hexafluoride (SF_6), although other compounds such as nitrogen trifluoride (NF_3) and perfluoropropane (C_3F_8) are also used. The exact combination of compounds is specific to the process employed.

For 1996, it was estimated that total weighted emissions of all greenhouse gases by the U.S. semiconductor industry was 1.3 MMTCE. These gases were not widely used in 1990, hence, emissions in 1990 were estimated to be only 0.2 MMTCE. Combined emissions of all gases are presented in Table 3-37 below. It is expected that the rapid growth of this industry and the increasing complexity of microchips will increase emissions in the future.

Table 3-37: PFC Emissions from Semiconductor Manufacture

Year	MMTCE*
1990	0.2
1991	0.4
1992	0.6
1993	0.8
1994	1.0
1995	1.2
1996	1.4

* Combined radiative forcing effect of all gases

Methodology

An estimate of emissions was developed based on the approximate sales of the four main gases (HFC-23, CF_4, C_2F_6, and SF_6) to semiconductor firms. Estimates were confirmed with data reported to the EPA by a subset of firms in the industry who have engaged in voluntary monitoring efforts. Further study of gas emission rates is also underway.

Data Sources

Emission estimates were provided by the EPA's Atmospheric Pollution Prevention Division in cooperation with the U.S. semiconductor industry.

Uncertainty

Emission estimates for this source are believed to be highly uncertain due to the lack of detailed gas consumption data and the complex chemical reactions involved in the processes used. For example, in the etching process the gas molecules are disrupted by a plasma into varied recombinant formulations specific to each tool and operation.

Because of the uncertainties surrounding its contribution to the greenhouse gas effect, NF_3 is not included in this inventory of greenhouse gas emissions. It has been estimated that the atmospheric lifetime of NF_3, before it undergoes photodissociation in the stratosphere, is about 700 years, resulting in a 100 year global warming potential (GWP) value of approximately 8,000 (Molina, Wooldridge, and Molina 1995). As the understanding of the emission characteristics of this gas improves, NF_3 will be included in future inventories.

Electrical Transmission and Distribution

The largest use for sulfur hexafluoride (SF_6), both domestically and internationally, is as an electrical insulator in equipment that transmits and distributes electricity. It has been estimated that eighty percent of the worldwide use of SF_6 is in electrical transmission and distribution systems (Ko et al. 1993). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. Sulfur hexafluoride has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas.

Fugitive emissions of SF_6 can escape from gas-insulated substations and gas-insulated circuit breakers through seals, especially from older equipment. It can also be released when equipment is opened for servic-

Table 3-38: SF_6 Emissions from Electrical Transmission and Distribution

Year	MMTCE	Mg
1990	5.6	859
1991	5.9	902
1992	6.2	945
1993	6.4	988
1994	6.7	1,031
1995	7.0	1,074
1996	7.0	1,074

ing, which typically occurs every few years. In the past, some utilities vented SF_6 to the atmosphere during servicing; however, it is believed that increased awareness and the relatively high cost of the gas have reduced this practice.

Emissions of SF_6 from electrical transmission and distribution systems was estimated to be 7.0 MMTCE (1,020 Mg) in 1996. This quantity amounts to a 25 percent increase over the estimate for 1990 (see Table 3-38).

Methodology

Manufacturers of circuit breakers and gas-insulated substations have claimed that new equipment leaks at rates of less than 1 percent annually. To explore emission rates from electrical equipment, the EPA examined atmospheric concentrations of SF_6. Assumptions were made to estimate historical worldwide SF_6 production. Based on measured concentrations, an atmospheric mass balance was then calculated. This mass balance provided an indication that most of the SF_6 produced worldwide since the early 1950s must have been emitted. Thus, it was concluded that emission rates from equipment must be higher than had been claimed. It was assumed that roughly three-quarters of SF_6 production was used in electrical equipment and that equipment leaked at a rate much higher than proposed by industry.

Data Sources

Emission estimates were provided by the EPA's Atmospheric Pollution Prevention Division in cooperation with the U.S. electric utilities.

Uncertainty

There is little verifiable data existing for estimating SF_6 emissions from electrical transmission and distribution systems. Neither gas consumption nor leakage monitoring data were available. An accurate inventory of the stock of SF_6 in existing equipment, in addition to improved assumptions of the leak rates from both new and old equipment, will be required to develop improved emission estimates.

Magnesium Production and Processing

The magnesium metal production and casting industries use sulfur hexafluoride (SF_6) as a covergas to prevent the violent oxidation of molten magnesium in the presence of air. Small concentrations of SF_6 in combinations with carbon dioxide and air are blown over the molten magnesium metal to induce the formation of a protective crust. The industry adopted the use of SF_6 to replace sulfur dioxide (SO_2). The SF_6 technique is used by producers of primary magnesium metal and most magnesium part casters. The recycling industry, for the most part, continues to employ sulfur dioxide as a covergas.

For 1996, a total of 3.0 MMTCE (460 Mg) of SF_6 was estimated to have been emitted by the magnesium industry, 76 percent more than was estimated for 1990 (see Table 3-39). There are no significant plans for expansion of primary production in the United States, but demand for magnesium metal for die casting has the potential to expand if auto manufacturers begin designing more magnesium parts into future vehicle models.

Methodology

Emissions were estimated based upon usage infor-

Table 3-39: SF_6 Emissions from Magnesium Production and Processing

Year	MMTCE	Mg
1990	1.7	260
1991	2.0	300
1992	2.2	340
1993	2.5	380
1994	2.7	420
1995	3.0	460
1996	3.0	460

mation supplied to the EPA by primary magnesium producers. Consumption was assumed to equal emissions in the same year. Although not directly employed, the Norwegian Institute for Air Research (NIAR 1993) has reported a range of emission factors for primary magnesium production as being from 1 to 5 kg of SF_6 per metric ton of magnesium. A survey of magnesium die casters has also reported an average emission factor of 4.1 kg of SF_6 per metric ton of magnesium parts die cast (Gjestland and Magers 1996).

Data Sources

Emission estimates were provided by the EPA's Atmospheric Pollution Prevention Division in cooperation with the U.S. primary magnesium metal producers and casting firms.

Uncertainty

There are a number of uncertainties in these estimates, including the assumption that SF_6 does not react nor decompose during use. In reality, it is possible that the high temperatures associated with molten magnesium would cause some gas degradation. Like other sources of SF_6 emissions, verifiable SF_6 consumption data were not available.

Industrial Sources of Criteria Pollutants

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of criteria air pollutants. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from non-energy industrial processes from 1990 to 1996 are reported by detailed source category in Table 3-40.

Methodology and Data Sources

The emission estimates for this source were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1996* (EPA 1997a). Emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997b). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

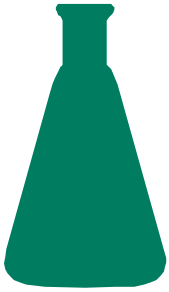
Uncertainty

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and accurate estimates of activity data.

Table 3-40: Emissions of NO_x, CO, and NMVOC from Industrial Processes (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
NO_x	**923**	**802**	**784**	**760**	**933**	**815**	**821**
Chemical & Allied Product Manufacturing	152	149	148	141	145	144	144
Metals Processing	88	69	74	75	82	89	89
Storage and Transport	3	5	4	4	5	5	5
Other Industrial Processes	343	319	328	336	353	362	366
Miscellaneous*	337	259	230	204	347	215	217
CO	**9,580**	**7,166**	**5,480**	**5,500**	**7,787**	**5,370**	**5,379**
Chemical & Allied Product Manufacturing	1,074	1,022	1,009	992	1,063	1,109	1,109
Metals Processing	2,395	2,333	2,264	2,301	2,245	2,159	2,157
Storage and Transport	69	25	15	46	22	22	22
Other Industrial Processes	487	497	494	538	544	566	576
Miscellaneous*	5,556	3,288	1,697	1,623	3,912	1,514	1,514
NMVOCs	**3,193**	**2,997**	**2,825**	**2,907**	**3,057**	**2,873**	**2,299**
Chemical & Allied Product Manufacturing	575	644	649	636	627	599	396
Metals Processing	111	112	113	112	114	113	64
Storage and Transport	1,356	1,390	1,436	1,451	1,478	1,499	1,190
Other Industrial Processes	364	355	376	401	397	409	398
Miscellaneous*	787	496	252	306	441	253	251

* Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, TSDFs (Transport, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act), cooling towers, and fugitive dust. It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Agricultural Burning source.
Note: Totals may not sum due to independent rounding.



4. Solvent Use

The use of solvents and other chemical products can result in emissions of various ozone precursors (i.e., criteria pollutants).[1] Nonmethane volatile organic compounds (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum based solvents, along with small amounts of carbon monoxide (CO) and oxides of nitrogen (NO_x) whose emissions are associated with control devices used to reduce NMVOC emissions. NMVOC emissions from solvent use increased 9 percent from 1990 to 1996. Surface coatings accounted for just under a majority of NMVOC emissions from solvent use (46 percent), while "non-industrial" uses accounted for about 33 percent and dry cleaning for 3 percent of NMVOC emissions in 1996. Overall, solvent use accounted for approximately 33 percent of total U.S. 1996 emissions of NMVOCs.

Although NMVOCs are not considered primary greenhouse gases, their role as precursors to the formation of ozone—which is a greenhouse gas—results in their inclusion in a greenhouse gas inventory. Emissions from solvent use have been reported separately by the United States to be consistent with the inventory reporting guidelines recommended by the IPCC. These guidelines identify solvent use as one of the major source categories for which countries should report emissions. In the United States, emissions from solvents are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The evaporation process varies depending on different solvent uses and solvent types. The major categories of solvents use include: degreasing, graphic arts, surface coating, other industrial uses of solvents (i.e., electronics, etc.), dry cleaning, and non-industrial uses (i.e., uses of paint thinner, etc.). Because many of these sources employ thermal incineration as a control technology, CO and NO_x combustion by-products are also reported with this source category.

Total emissions of nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), and carbon monoxide (CO) from non-energy industrial processes from 1990 to 1996 are reported by detailed source category in Table 4-1.

Methodology

Emissions were calculated by aggregating solvent use data based on information relating to solvent uses from different sectors such as degreasing, graphic arts, etc. Emission factors for each consumption category were then applied to the data to estimate emissions. For example, emissions from surface coatings were mostly due to solvent evaporation as the coatings solidify. By applying the appropriate solvent emission factors to the type of solvents used for surface coatings, an estimate of emissions was obtained. Emissions of CO and NO_x result primarily from thermal and catalytic incineration of solvent laden gas streams from painting booths, printing operations, and oven exhaust.

[1] Solvent usage in the United States also results in the emission of small amounts of hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances in the Industrial Processes sector.

Table 4-1: Emissions of NO_x, CO, and NMVOC from Solvent Use (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996
NO_x	**1**	**2**	**2**	**2**	**2**	**3**	**3**
Degreasing	+	+	+	+	+	+	+
Graphic Arts	+	+	1	1	1	1	1
Dry Cleaning	+	+	+	+	+	+	+
Surface Coating	1	1	2	2	2	2	2
Other Industrial Processes	+	+	+	+	+	+	+
Non-Industrial Processes	+	+	+	+	+	+	+
CO	**4**	**4**	**4**	**4**	**5**	**5**	**5**
Degreasing	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+
Dry Cleaning	+	+	+	+	1	1	1
Surface Coating	+	1	1	1	1	1	1
Other Industrial Processes	4	3	3	3	3	3	3
Non-Industrial Processes	+	+	+	+	+	+	+
NMVOCs	**5,217**	**5,245**	**5,353**	**5,458**	**5,590**	**5,609**	**5,691**
Degreasing	675	651	669	683	703	716	599
Graphic Arts	249	273	280	292	302	307	353
Dry Cleaning	195	198	203	204	207	209	172
Surface Coating	2,289	2,287	2,338	2,387	2,464	2,432	2,613
Other Industrial Processes	85	89	93	93	90	87	48
Non-Industrial Processes	1,724	1,746	1,771	1,798	1,825	1,858	1,905

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

Data Sources

The emission estimates for this source were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1996* (EPA 1997a). Emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of solvent purchased) as an indicator of emissions. National activity data were collected for individual source categories from various agencies.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997b). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA data bases.

Uncertainty

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and the reliability of correlations between activity data and actual emissions.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. The Agriculture sector includes the following sources: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil activities, and agricultural residue burning. Several other agricultural activities, such as irrigation and tillage practices, may also generate anthropogenic greenhouse gas emissions; however, the impacts of these practices are too uncertain to estimate emissions.[1] Agriculture related land-use activities, such as conversion of grassland to cultivated land, are discussed under the Land-Use Change and Forestry sector.

In 1996, agricultural activities were responsible for emissions of 125.4 MMTCE, or approximately 7 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent about 19 and 9 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of methane. Rice cultivation and agricultural crop waste burning were minor sources of methane. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of nitrous oxide emissions, accounting for 66 percent of total U.S. N_2O emissions. Manure management and agricultural residue burning were also smaller sources of N_2O emissions (see Figure 5-1).

Figure 5-1

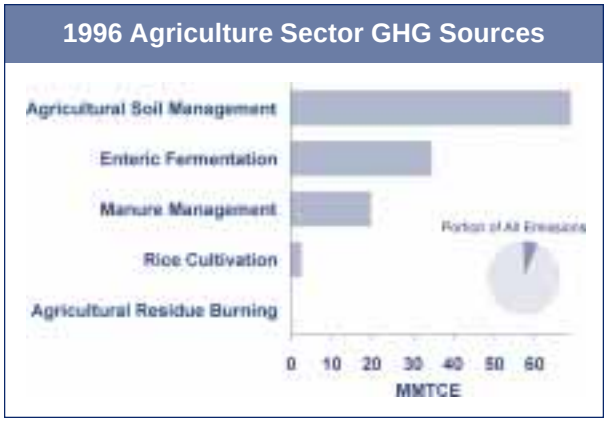


Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 1996, CH_4 emissions from the sector increased by 7 percent while N_2O emissions increased by 10 percent. In addition to CH_4 and N_2O, agricultural residue burning was also a minor source of the criteria pollutants carbon monoxide (CO) and nitrogen oxides (NO_x).

Enteric Fermentation

Methane (CH_4) is produced as part of the normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process,

[1] Irrigation associated with rice cultivation is included in this inventory.

Table 5-1: Emissions from the Agriculture Sector (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CH_4	**50.3**	**50.9**	**52.2**	**52.5**	**54.4**	**54.8**	**53.7**
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
N_2O	**65.2**	**66.3**	**68.1**	**67.1**	**73.5**	**70.2**	**71.7**
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
Total	**115.5**	**117.3**	**120.3**	**119.5**	**127.9**	**125.0**	**125.4**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from the Agriculture Sector (Tg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CH_4	**8.8**	**8.9**	**9.1**	**9.2**	**9.5**	**9.6**	**9.4**
Enteric Fermentation	5.7	5.7	5.8	5.9	6.0	6.1	6.0
Manure Management	2.6	2.7	2.8	2.8	2.9	2.9	2.9
Rice Cultivation	0.4	0.4	0.5	0.4	0.5	0.5	0.4
Agricultural Residue Burning	+	+	+	+	+	+	+
N_2O	**0.8**	**0.8**	**0.8**	**0.8**	**0.9**	**0.8**	**0.8**
Manure Management	+	+	+	+	+	+	+
Agricultural Soil Management	0.7	0.8	0.8	0.8	0.8	0.8	0.8
Agricultural Residue Burning	+	+	+	+	+	+	+

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

referred to as enteric fermentation, produces methane as a by-product, which can be exhaled, or eructated, by the animal. The amount of methane produced and excreted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Among domestic animal types, the ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of methane because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into soluble products that can be utilized by the animal. The microbial fermentation that occurs in the rumen enables ruminants to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest methane emissions among all animal types.

Non-ruminant domestic animals (e.g., pigs, horses, mules, rabbits, and guinea pigs) also produce methane through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants have significantly lower methane emissions than ruminants because the capacity of the large intestine to produce methane is lower.

In addition to the type of digestive system, an animal's feed intake also affects methane excretion. In general, a higher feed intake leads to higher methane emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types.

Methane emissions estimates for livestock are shown in Table 5-3 and Table 5-4. Total livestock emissions in 1996 were 34.5 MMTCE (6.0 Tg), or 19 percent of total U.S. methane emissions. Emissions from dairy cattle remained relatively constant from 1990 to 1996 despite a steady increase in milk production. During this time, emissions per cow increased due to a rise in milk production per dairy cow (see Table 5-5); however, this

Table 5-3: Methane Emissions from Enteric Fermentation (MMTCE)

Animal Type	1990	1991	1992	1993	1994	1995	1996
Dairy Cattle	8.4	8.4	8.4	8.4	8.4	8.4	8.3
Beef Cattle	22.6	22.8	23.1	23.6	24.5	24.9	24.6
Other	1.6	1.7	1.7	1.6	1.6	1.6	1.6
Sheep	0.5	0.5	0.5	0.5	0.4	0.4	0.4
Goats	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Hogs	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Total	**32.7**	**32.8**	**33.2**	**33.6**	**34.5**	**34.9**	**34.5**

Note: Totals may not sum due to independent rounding.

Table 5-4: Methane Emissions from Enteric Fermentation (Tg)

Animal Type	1990	1991	1992	1993	1994	1995	1996
Dairy Cattle	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Beef Cattle	4.0	4.0	4.0	4.1	4.3	4.3	4.3
Other	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Hogs	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**5.7**	**5.7**	**5.8**	**5.9**	**6.0**	**6.1**	**6.0**

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

trend was offset by a decline in the dairy cow population. Beef cattle emissions increased, reflecting the rise in the beef cow population, although, in 1996 the number of beef cows declined for the first time since 1990. Methane emissions from other animals have remained relatively constant during the period 1990 through 1996.

Methodology

Livestock emission estimates fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of methane emissions from livestock in the United States and are handled separately. Also, cattle production systems in the United States are well characterized in comparison with other livestock management systems. Overall, emissions estimates were derived using emission factors, which were multiplied by the appropriate animal population data.

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that describes the quantity of methane produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of feeding practices and production characteristics was used to estimate emissions from cattle populations.

To derive emission factors for the various types of cattle found in the United States, a mechanistic model of rumen digestion and animal production was applied to data on thirty-two different diets and nine different cattle types (Baldwin et al. 1987a and b).[2] The cattle types were defined to represent the different sizes, ages, feeding systems, and management systems that are typically found in the United States. Representative diets were defined for each category of animal, reflecting the feeds and forages consumed by cattle type and region. Using this model, emission factors were derived for each com-

[2] The basic model of Baldwin et al. (1987a and b) was revised somewhat to allow for evaluations of a greater range of animal types and diets. See EPA (1993).

bination of animal type and representative diet. Based upon the level of use of each diet in the five regions, average regional emission factors for each of the nine cattle types were derived.[3] These emission factors were then multiplied by the applicable animal populations from each region.

For dairy cows and beef cows and replacements, emission estimates for 1990 to 1996 were developed using regional emission factors. Dairy cow emission factors were modified to reflect changing (primarily increasing) milk production per cow over time in each region. All other emission factors were held constant over time. Emissions from other cattle types were estimated using national average emission factors.

Emissions estimates for other animal types were based upon average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total methane emissions from livestock in the United States. Also, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is smaller than for cattle.

See Annex G for more detailed information on the methodology and data used to calculate methane emissions from enteric fermentation.

Data Sources

The emission estimates for all domestic livestock were determined using a mechanistic model of rumen digestion and emission factors developed in EPA (1993). For dairy cows and beef cows and replacements, regional emission factors were used from EPA (1993). Emissions from other cattle types were estimated using national average emission factors from EPA (1993). Methane emissions from sheep, goats, pigs, and horses were estimated by using emission factors utilized in Crutzen et al. (1986) and annual population data from USDA statistical reports. These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology employed in EPA (1993) is the same as those recommended in IPCC (1997). All livestock population data were taken from USDA statistical reports. See the following section on manure management for a complete listing of reports cited. Table 5-5 below provides a summary of cattle population and milk production data.

Uncertainty

The diets analyzed using the rumen digestion model include broad representations of the types of feed consumed within each region. Therefore, the full diversity of feeding strategies employed in the United States is not represented and the emission factors used may be biased. The rumen digestion model, however, has been validated by experimental data. Animal population and production statistics, particularly for beef cows and other grazing cattle, are also uncertain. Overall, the uncertainty in the emission estimate is estimated to be roughly 20 percent (EPA 1993).

Manure Management

The management of livestock manure produces methane (CH_4) and nitrous oxide (N_2O) emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide is produced as part of the agricul-

Table 5-5: Cow Populations (thousands) and Milk Production (million kilograms)

Year	Milk Production	Dairy Cow Population	Beef Cow Population
1990	67,006	10,007	32,677
1991	66,995	9,883	32,960
1992	68,441	9,714	33,453
1993	68,304	9,679	34,132
1994	69,702	9,514	35,325
1995	70,500	9,494	35,628
1996	69,976	9,409	35,414

[3] Feed intake of bulls does not vary significantly by region, so only a national emission factor was derived for this cattle type.

tural nitrogen cycle through the denitrification of the organic nitrogen in livestock manure and urine.

When livestock and poultry manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid in lagoons, ponds, tanks, or pits), the decomposition of materials in manure tends to produce methane. When manure is handled as a solid (e.g., in stacks or pits) or deposited on pastures and range lands, it tends to decompose aerobically and produce little or no methane. Air temperature and moisture also affect the amount of methane produced because they influence the growth of the bacteria responsible for methane formation. Methane production generally increases with rising temperature. Also, for non-liquid based manure systems, moist conditions (which are a function of rainfall and humidity) favor methane production. Although the majority of manure is handled as a solid, producing little methane, the general trend in manure management, particularly for dairy and swine producers, is one of increasing usage of liquid systems.

The composition of the manure also affects the amount of methane produced. Manure composition depends upon the diet of the animals. The greater the energy content and digestibility of the feed, the greater the potential for methane emissions. For example, feedlot cattle fed a high energy grain diet generate manure with a high methane-producing capacity. Range cattle feeding on a low energy diet of forage material produce manure with only half the methane-producing capacity of feedlot cattle manure.

The amount of N_2O produced can also vary depending on the manure and urine composition, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. Nitrous oxide emissions result from livestock manure and urine that is managed using liquid and slurry systems, as well as manure and urine that is collected and stored. Nitrous oxide emissions from unmanaged livestock manure and urine on pastures, ranges, and paddocks, as well as from manure and urine that is spread daily onto fields is discussed under Agricultural Soil Management.

Table 5-6, Table 5-7, and Table 5-8 (note, Table 5-8 is in units of gigagrams) provide estimates of methane and nitrous oxide emissions from manure management. Emission quantities are broken down by animal categories representing the major methane producing groups. Estimates for methane emissions in 1996 were 16.6 MMTCE (2.9 Tg). Emissions have increased each year from 1990 through 1995; however, emissions decreased slightly in 1996 with a decline in animal popula-

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMTCE)

Animal Type	1990	1991	1992	1993	1994	1995	1996
CH_4	**14.9**	**15.4**	**16.0**	**16.1**	**16.7**	**16.9**	**16.6**
Dairy Cattle	4.3	4.3	4.4	4.4	4.5	4.5	4.5
Beef Cattle	1.1	1.2	1.2	1.2	1.2	1.3	1.3
Swine	7.8	8.2	8.6	8.6	9.1	9.2	8.8
Sheep	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Poultry	1.5	1.5	1.6	1.6	1.7	1.7	1.7
Horses	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**2.6**	**2.8**	**2.8**	**2.9**	**2.9**	**2.9**	**3.0**
Dairy Cattle	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Beef Cattle	1.1	1.2	1.2	1.2	1.2	1.2	1.2
Swine	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sheep	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Poultry	1.3	1.3	1.4	1.4	1.5	1.5	1.5
Horses	+	+	+	+	0.1	0.1	0.1
Total	**17.6**	**18.2**	**18.7**	**19.0**	**19.7**	**19.8**	**19.5**

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

Table 5-7: Methane Emissions from Manure Management (Tg)

Animal Type	1990	1991	1992	1993	1994	1995	1996
Dairy Cattle	0.7	0.8	0.8	0.8	0.8	0.8	0.8
Beef Cattle	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Swine	1.4	1.4	1.5	1.5	1.6	1.6	1.5
Sheep	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Poultry	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Horses	+	+	+	+	+	+	+
Total	**2.6**	**2.7**	**2.8**	**2.8**	**2.9**	**2.9**	**2.9**

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

Table 5-8: N_2O Emissions from Manure Management (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996
Dairy Cattle	1	1	1	1	1	1	1
Beef Cattle	13	15	14	15	15	14	14
Swine	1	1	1	1	1	1	1
Sheep	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Poultry	15	16	16	17	17	18	18
Horses	1	1	1	1	1	1	1
Total	**31**	**33**	**33**	**34**	**35**	**34**	**35**

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

tions, including swine. Under the AgSTAR Program of the U.S. Climate Change Action Plan, methane emissions from manure have been reduced through methane recovery efforts. The AgSTAR Program reported a reduction of 0.1 MMTCE of methane in 1996.

Total N_2O emissions from managed manure systems in 1996 were estimated to be 3.0 MMTCE (35 Gg). The 12 percent increase in emissions from 1990 to 1996 can be attributed to an increase in the proportion of beef cattle in feedlots, which are assumed to use managed manure management systems. Methane emissions were mostly unaffected by this shift in the beef cattle population because feedlot cattle use solid storage systems, which produce little methane.

In general, changes in the emission estimates over time reflect variations in animal populations. The estimates also reflect a regional redistribution of dairies to the southwestern states, which have larger average farm sizes, and an increase in feed consumption by dairy cows to accommodate increased milk production per cow. Regional shifts in the hog population were also addressed.

Methodology

The methods presented in EPA (1993) form the basis of the methane emissions estimates for each animal type. The calculation of emissions requires the following information:

- Amount of manure produced (amount per head times number of head)
- Portion of the manure that is volatile solids (by animal type)
- Methane producing potential of the volatile solids (by animal type)
- Extent to which the methane producing potential is realized for each type of manure management system (by state and manure management system)
- Portion of manure managed in each manure management system (by state and animal type)

For dairy cattle and swine—the two largest emitters of methane—estimates were developed using state-level animal population data. For other animal types, 1990 emission estimates from the detailed analysis presented in EPA (1993) were scaled at the national level

using the population of each livestock type. Nitrous oxide emissions were estimated by first determining manure management system usage. Manure system usage for dairy cows and swine were based on the farm size distribution. Total Kjeldahl nitrogen[4] production was calculated for all livestock using livestock population data and nitrogen excretion rates. The total amount of nitrogen from manure was reduced by 20 percent to account for the portion that volatilizes to NH_3 and NO_x (IPCC/UNEP/OECD/IEA 1997). Nitrous oxide emission factors were then applied to total nitrogen production to estimate N_2O emissions. Throughout the time series the estimates of the portion of manure and urine which is managed in each of the manure management systems in each state remained fixed.

See Annex H for more detailed information on the methodology and data used to calculate methane emissions from enteric fermentation. The same activity data was also used to calculate N_2O emissions.

Data Sources

Annual livestock population data for all livestock types except horses were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a, b; 1995a-j; 1996a-f; 1997a-f). Horse population data were obtained from the FAOSTAT database (FAO 1997). Data on farm size distribution for dairy cows and swine were taken from the U.S. Department of Commerce (DOC 1995, 1987). Manure management system usage data for other livestock were taken from EPA (1992). Nitrogen excretion rate data were developed by the American Society of Agricultural Engineers (ASAE 1995). Nitrous oxide emission factors were taken from IPCC/UNEP/OECD/IEA (1997). Manure management systems characterized as "Other" generally refers to deep pit and litter systems. The IPCC N_2O emission factor for "other" systems (0.005 kg N_2O/kg N excreted), was determined to be inconsistent with the characteristics of these management systems. Therefore, in its place the solid storage/drylot emission factor was used.

Uncertainty

The primary factors contributing to the uncertainty in emission estimates are a lack of information on the usage of various manure management systems in each state and the exact methane generating characteristics of each type of manure management system. Because of significant shifts in the dairy and swine sectors toward larger farms, it is believed that increasing amounts of manure are being managed in liquid manure management systems. The existing estimates capture a portion of these shifts as the dairy and swine populations move regionally toward states with larger average farm sizes. However, changes in farm size distribution within states since 1992 are not captured by the method. The methane generating characteristics of each manure management system type are based on relatively few laboratory and field measurements, and may not match the diversity of conditions under which manure is managed nationally.

The N_2O emission factors published in IPCC/UNEP/OECD/IEA (1997) were also derived using limited information. The IPCC factors are global averages; U.S.-specific emission factors may be significantly different. Manure and urine in anaerobic lagoons and liquid/slurry management systems produce methane at different rates, and would in all likelihood produce N_2O at different rates, although a single emission factor was used.

Rice Cultivation

Most of the world's rice, and all rice in the United States, is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soil and floodwater causing anaerobic conditions in the soil to develop. Under such conditions, methane is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. However, not all of the methane that is produced is released into the atmosphere. As much as 60 to 90 percent of the methane produced is oxidized by aerobic methanotrophic

[4] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

bacteria in the soil (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the methane is also leached away as dissolved methane in floodwater that percolates from the field. The remaining non-oxidized methane is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Some methane also escapes from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is one of the most important factors affecting methane emissions. Upland rice fields are not flooded, and therefore are not believed to produce methane. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), lower stems and roots of the rice plants are dead, and thus effectively block the primary methane transport pathway to the atmosphere. Therefore, while deepwater rice growing areas are believed to emit methane, the quantities released are likely to be significantly less than the quantities released from areas with more shallow flooding depths. Also, some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, methane emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil methane to oxidize but also inhibits further methane production in soils. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions.

Other factors that influence methane emissions from flooded rice fields include soil temperature, soil type, fertilization practices, cultivar selection, and other cultivation practices (e.g., tillage, seeding and weeding practices). Many studies have found, for example, that methane emissions increase as soil temperature increases. Several studies have also indicated that some types of synthetic nitrogen fertilizer inhibit methane generation, while organic fertilizers enhance methane emissions. However, while it is generally acknowledged that these factors influence methane emissions, the extent of their influence, individually or in combination, has not been well quantified.

Rice cultivation is a small source of methane in the United States. Only seven states grow rice: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Methane emissions from rice cultivation in 1996 were estimated to have been 2.5 MMTCE (431 Gg), accounting for just over 1 percent of total methane emissions from U.S. anthropogenic sources. Table 5-9 and Table 5-10 present annual emission estimates for each state. There was no apparent trend over the seven year period. Between 1994 and 1996, rice areas declined fairly steadily in almost all states, and the national total declined by about 8 percent each year (see Table 5-11).

The factors that affect the rice area harvested vary from state to state. In Florida, the state having the smallest harvested rice area, rice acreage is driven by sugarcane acreage. Sugarcane fields are flooded each year to control pests, and on this flooded land a rice crop is grown along with a ratoon crop of sugarcane (Schudeman 1997a). In Missouri, rice acreage is affected by weather (rain during the planting season may prevent the planting of rice), prices of soybeans relative to rice (if soybean prices are higher, then soybeans may be planted on

Table 5-9: Methane Emissions from Rice Cultivation (MMTCE)

State	1990	1991	1992	1993	1994	1995	1996
Arkansas	0.9	0.9	1.0	0.9	1.1	1.0	0.9
California	0.5	0.4	0.5	0.5	0.6	0.5	0.6
Florida	+	+	+	+	+	+	+
Louisiana	0.6	0.6	0.7	0.6	0.7	0.7	0.6
Mississippi	0.2	0.1	0.2	0.2	0.2	0.2	0.1
Missouri	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Texas	0.3	0.3	0.3	0.2	0.3	0.3	0.2
Total	**2.5**	**2.5**	**2.8**	**2.5**	**3.0**	**2.8**	**2.5**

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

Table 5-10: Methane Emissions from Rice Cultivation (Gg)

State	1990	1991	1992	1993	1994	1995	1996
Arkansas	156	164	180	160	185	175	152
California	79	70	79	88	98	94	101
Florida	3	5	5	5	5	5	4
Louisiana	111	104	126	108	126	116	99
Mississippi	27	24	30	27	34	32	23
Missouri	11	12	15	12	16	15	12
Texas	52	50	51	43	52	46	40
Total	**439**	**429**	**486**	**443**	**516**	**482**	**431**

Note: Totals may not sum due to independent rounding.

Table 5-11: Area Harvested for Rice-Producing States (hectares)

State/Crop	1990	1991	1992	1993	1994	1995	1996
Arkansas	485,633	509,915	558,478	497,774	574,666	542,291	473,493
California	159,854	141,643	159,450	176,851	196,277	188,183	202,347
Florida							
Primary	4,978	8,580	8,944	8,449	8,902	8,903	8,903
Ratoon	2,489	4,290	4,472	4,225	4,451	4,452	4,452
Louisiana							
Primary	220,558	206,394	250,911	214,488	250,911	230,676	215,702
Ratoon	66,168	61,918	75,273	64,346	75,273	69,203	64,711
Mississippi	101,174	89,033	111,291	99,150	126,669	116,552	84,176
Missouri	32,376	37,232	45,326	37,637	50,182	45,326	36,423
Texas							
Primary	142,857	138,810	142,048	120,599	143,262	128,693	120,599
Ratoon	57,143	55,524	56,819	48,240	57,305	51,477	48,240
Total	**1,273,229**	**1,253,339**	**1,413,011**	**1,271,759**	**1,487,897**	**1,385,755**	**1,259,045**

Note: Totals may not sum due to independent rounding.

some of the land which would otherwise have been planted in rice), and government support programs (which, beginning in 1996, were being phased-out) (Stevens 1997). In Mississippi, rice acreage is driven by both the price of rice and the price of soybeans. Rice in Mississippi is usually rotated with soybeans, but if soybean prices increase relative to rice prices, then some of the acreage that would have been planted in rice, is instead planted in soybeans (Street 1997). In Texas, rice production, and thus, harvested area, are driven by both government programs and the cost of production (Klosterboer 1997). California rice area is influenced by water availability as well as government programs and commodity prices. In recent years, California was able to grow more rice due to recovery from a drought, as well as price increases associated with gaining access to the Japanese market (Scardaci 1997). In Louisiana, rice area is influenced by government programs (which had less of an effect in 1996 than in other years because of the beginning of a phase-out of these programs), weather conditions (such as rainfall during the planting season), as well as the price of rice relative to that of corn and other crops (Saichuk 1997). Arkansas rice area has been influenced in the past by government programs. The phase-out of these programs began in 1996, and commodity prices in the spring had a greater effect on the amount of land planted in rice (Mayhew 1997).

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) recommend applying a seasonal emission factor to the annual harvested rice area to estimate annual CH_4 emissions. This methodology assumes that a seasonal emission factor is available for all growing conditions, including season lengths. Because season lengths are variable both within and among states in the United States, and because flux measurements have not been taken under all growing conditions in the United

States, the previous IPCC methodology (IPCC/UNEP/OECD/IEA 1995) has been applied here, using season lengths that vary slightly from the recommended approach. The 1995 *IPCC Guidelines* recommend multiplying a daily average emission factor by growing season length and annual harvested area. The *IPCC Guidelines* suggest that the "growing" season be used to calculate emissions based on the assumption that emission factors are derived from measurements over the whole growing season rather than just the flooding season. Applying this assumption to the United States, however, would result in an overestimate of emissions because the emission factors developed for the United States are based on measurements over the flooding, rather than the growing, season. Therefore, the method used here is based on the number of days of flooding during the growing season and a daily average emission factor, which is multiplied by the harvested area. Agricultural statisticians in each of the seven states in the United States that produce rice were contacted to determine water management practices and flooding season lengths in each state. Although all contacts reported that rice growing areas were continually flooded, flooding season lengths varied considerably among states; therefore, emissions were calculated separately for each state.

The climatic conditions of southwest Louisiana, Texas, and Florida also allow for a second, or ratoon, rice crop. This second rice crop is produced from regrowth on the stubble after the first crop has been harvested. The emission estimates presented here account for this additional harvested area.

Because the number of days that the rice fields remain permanently flooded varies considerably with planting system and cultivar type, a range for the flooding season length was adopted for each state. The harvested areas and flooding season lengths for each state are presented in Table 5-11 and Table 5-12, respectively.

Data Sources

Data on harvested rice area for all states except Florida were taken from U.S. Department of Agriculture's *Crop Production 1996 Summary* (USDA 1997). Harvested rice areas in Florida were obtained from Tom Schudeman (1997b), a Florida Agricultural Extension Agent. Acreages for the ratoon crops were estimated to account for about 30 percent of the primary crop in Louisiana, 40 percent in Texas (Lindau and Bollich 1993) and 50 percent in Florida (Schudeman 1995). Daily methane emission factors were taken from results of field studies performed in California (Cicerone et al. 1983), Texas (Sass et al. 1990, 1991a, 1991b, 1992) and Louisiana (Lindau et al. 1991, Lindau and Bollich 1993). Based on the maximal and minimal estimates of the emission rates measured in these studies, a range of 0.1065 to 0.5639 g/m^2/day was applied to the harvested areas and flooding season lengths in each state.[5] Since these measurements were taken in rice growing areas, they are representative of soil temperatures, and water and fertilizer management practices typical of the United States.

Uncertainty

There are three sources of uncertainty in the calculation of CH_4 emissions from rice cultivation. The largest uncertainty is associated with the emission factor. Daily average emissions, derived from field measurements in the United States, vary from state to state by as much as two orders of magnitude (IPCC/UNEP/OECD/IEA 1997). This variability is due to differences in cultivation practices, such as ratooning and fertilizer use, as well as differences in soil and climatic conditions. A range (0.3352 g/m^2/day ±68 percent) has been used in these calculations to reflect this variability. Based on this range, methane emissions from rice cultivation in 1996 were estimated to have been approximately 0.6 to 4.3 MMTCE (111 to 752 Gg).

[5] Two measurements from these studies were excluded when determining the emission coefficient range. A low seasonal average flux of 0.0595 g/m^2/day in Sass et al. (1990) was excluded because this site experienced a mid-season accidental drainage of floodwater, after which methane emissions declined substantially and did not recover for about two weeks. Also, the high seasonal average flux of 2.041 g/m^2/day in Lindau and Bollich (1993) was excluded since this emission rate is unusually high, compared to other flux measurements in the United States, as well as in Europe and Asia (see IPCC/UNEP/OECD/IEA 1997).

Table 5-12: Primary Cropping Flooding Season Length (days)

State	Low	High
Arkansas	75	100
California	123	153
Florida*	90	120
Louisiana*	90	120
Mississippi	75	82
Missouri	80	100
Texas*	60	80

* These states have a second, or "ratoon", cropping cycle which may have a shorter flooding season than the one listed in the table.

Another source of uncertainty is in the flooding season lengths used for each state. Flooding seasons in each state may fluctuate from year to year and thus a range has been used to reflect this uncertainty (see Table 5-13).

The last source of uncertainty centers around the ratoon, or second crop. Rice fields for the ratoon crop typically remain flooded for a shorter period of time than for the first crop. Studies indicate, however, that the methane emission rate of the ratoon crop may be significantly higher than that of the first crop. The rice straw produced during the first harvest has been shown to dramatically increase methane emissions during the ratoon cropping season (Lindau and Bollich 1993). It is not clear to what extent the shorter season length and higher emission rates offset each other. As scientific understanding improves, these emission estimates can be adjusted to better reflect these variables.

Agricultural Soil Management

Nitrous oxide (N_2O) is produced naturally in soils through the microbial processes of nitrification and denitrification.[6] A number of agricultural activities add nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities may add nitrogen to soils either directly or indirectly. Direct additions occur through various cropping practices (i.e., application of synthetic and organic fertilizers, daily spread of animal wastes, production of nitrogen-fixing crops, incorporation of crop residues, and cultivation of high organic content soils, called histosols), and through animal grazing (i.e., direct deposition of animal wastes on pastures, range, and paddocks by grazing animals[7]). Indirect additions occur through two mechanisms: 1) volatilization of applied nitrogen (i.e., fertilizer and animal waste) and subsequent atmospheric deposition of that nitrogen as ammonia (NH_3) and oxides of nitrogen (NO_x); and 2) surface runoff and leaching of applied nitrogen. Other agricultural soil management practices, such as irrigation, drainage, tillage practices, and fallowing of land, can affect fluxes of N_2O, as well as other greenhouse gases, to and from soils. However, because there are significant uncertainties as to the effects of these other practices, they have not been estimated.

Estimates of annual N_2O emissions from agricultural soils in previous U.S. inventories included only those that result directly from the application of commercial synthetic and organic fertilizer nitrogen, as was consis-

Table 5-13: N_2O Emissions from Agricultural Soil Management (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996
Direct							
Cropping Practices	33.5	34.0	35.4	33.6	39.0	35.9	37.4
Animal Production	10.1	10.1	10.4	10.5	10.8	11.0	10.8
Indirect	18.8	19.3	19.4	20.0	20.6	20.3	20.4
Total	**62.4**	**63.4**	**65.2**	**64.1**	**70.4**	**67.2**	**68.6**

Note: Totals may not sum do to independent rounding.

[6] Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to dinitrogen gas (IPCC/UNEP/OECD/IEA 1997). Nitrous oxide is a gaseous intermediate product in the reaction sequences of both processes, which leaks from microbial cells into the soil atmosphere.

[7] Nitrous oxide emissions from animal wastes that are managed in animal waste management systems are covered under Manure Management in the Agriculture sector.

Table 5-14: N_2O Emissions from Agricultural Soil Management (Gg N_2O)

Activity	1990	1991	1992	1993	1994	1995	1996
Direct Cropping Practices	396	403	418	398	461	424	442
Animal Production	119	120	123	125	128	131	128
Indirect	223	228	230	236	244	240	241
Total	**738**	**750**	**771**	**758**	**833**	**795**	**812**

Note: Totals may not sum do to independent rounding.

tent with earlier versions of the *IPCC Guidelines* (IPCC/OECD Joint Programme 1994, IPCC/UNEP/OECD/IEA 1995). The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) includes additional anthropogenic sources of soil nitrogen, and emissions from both direct and indirect pathways. As a consequence, the emission estimates provided below are significantly higher (by about 300 percent) than previous estimates.

The revised estimates of annual N_2O emissions from agricultural soil management range from 62.4 to 70.4 MMTCE (738 to 833 Gg N_2O) for the years 1990 to 1996 (Table 5-13 and Table 5-14). Emission levels increased fairly steadily from 1990 to 1996 except for the year 1993, when emissions declined slightly, and the year 1994, when emissions increased sharply. These fluctuations are largely a reflection of annual variations in synthetic nitrogen fertilizer consumption and crop production. The other agricultural sources of nitrogen (animal wastes, and histosol cultivation) generally increased steadily, or stayed flat, from year to year. Synthetic nitrogen fertilizer consumption, and production of corn and most beans and pulses, peaked in 1994 due to the 1993 flooding of the North Central region and the intensive cultivation that followed. Over the seven-year period, total emissions of N_2O increased by 10 percent.

Methodology and Data Sources

This N_2O source category is divided into three components: (1) direct emissions from agricultural soils due to cropping practices; (2) direct emissions from agricultural soils due to animal production; and (3) emissions from soils indirectly induced by agricultural applications of nitrogen. The emission estimates for all three components follow the methodologies in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Direct N_2O Emissions from Agricultural Cropping Practices

Estimates of N_2O emissions from this component are based on the total amount of nitrogen that is applied to soils through cropping practices. These practices are (1) the application of synthetic and organic fertilizers, (2) the application of animal waste through daily spread operations, (3) the production of nitrogen-fixing crops, (4) the incorporation of crop residues into the soil, and (5) the cultivation of histosols.

Annual fertilizer consumption data for the U.S. were taken from annual publications on commercial fertilizer statistics (AAPFCO 1995, 1996; TVA 1990, 1992a and b, 1994). These data are recorded in "fertilizer year" totals (July to June) which were converted to calendar year totals by assuming that approximately 35 percent of fertilizer usage occurred from July to December (TVA 1992b). Data for July to December of calendar year 1996 were based on preliminary estimates (Terry 1998). Data on the nitrogen content of synthetic fertilizers were available in published consumption reports; however, data on manure used as commercial fertilizer and other organic fertilizer consumption[8] did not include nitrogen content information. To convert to units of nitrogen, it was assumed that 1 percent of manure and 4.1 percent of other organic fertilizers (on a mass basis) was nitrogen (Terry 1997). Annual consumption of commercial fertilizers

[8] Organic fertilizers included in these publications are manure, compost, dried blood, sewage sludge, tankage, and other organics. Tankage is dried animal residue, usually freed from fat and gelatin.

(synthetic, manure, and other organics) in units of nitrogen are presented in Table 5-15. The total amount of nitrogen consumed from synthetic and organic fertilizers was reduced by 10 percent and 20 percent, respectively, to account for the portion that volatilizes to NH_3 and NO_x (IPCC/UNEP/OECD/IEA 1997).

To estimate the amount of animal waste applied annually through daily spread operations, it was assumed that only the wastes from dairy cattle on small farms were managed as daily spread (Safely et al. 1992). Dairy cow population data were obtained from the USDA National Agricultural Statistics Service (USDA 1995a,b,c,d, 1996a,b, 1997a,b). Farm size was reported by the Department of Commerce (DOC 1995). Population data for dairy cattle on small farms were multiplied by an average animal mass constant (ASAE 1995). Total Kjeldahl nitrogen[9] excreted per year (manure and urine) was then calculated using daily rates of N excretion per unit of animal mass (ASAE 1995) (Table 5-16). The total amount of nitrogen from manure was reduced by 20 percent to account for the portion that volatilizes to NH_3 and NO_x (IPCC/UNEP/OECD/IEA 1997).

Annual production statistics for nitrogen-fixing crops (beans, pulses, and alfalfa) were taken from U.S. Department of Agriculture reports (USDA 1994a, 1997c, 1998). These statistics are presented in Table 5-17. Crop product values for beans and pulses were expanded to total crop dry biomass, in mass units of dry matter, by applying residue to crop ratios and dry matter fractions for residue from Strehler and Stützle (1987). Crop product values for the alfalfa were converted to dry matter mass units by applying a dry matter fraction value estimated at 80 percent (Mosier 1998). To convert to units of nitrogen, it was assumed that 3 percent of the total crop dry mass for all crops was nitrogen (IPCC/UNEP/OECD/IEA 1997).

To estimate the amount of nitrogen applied to soils through crop residue incorporation, it was assumed that all residues from corn, wheat, bean, and pulse production, except the fractions that are burned in the field after harvest, are plowed under. Annual production statistics were taken from U.S. Department of Agriculture (USDA 1994a, 1997c, 1998). These statistics are presented in Table 5-17 and Table 5-18. Crop residue biomass, in dry matter mass units, was calculated from the production statistics by applying residue to crop mass ratios and dry matter fractions for residue from Strehler and Stützle (1987). For wheat and corn, nitrogen contents were taken from Barnard and Kristoferson (1985). For beans and pulses, it was assumed that 3 percent of the total crop residue was nitrogen (IPCC/UNEP/OECD/IEA 1997). The crops whose residues were burned in the field are corn, wheat, soybeans, and peanuts. For these crop types, the total residue nitrogen was reduced by 3 percent to subtract the fractions burned in the field (see the Agricultural Residue Burning section of this chapter).

Total crop nitrogen in the residues returned to soils was then added to the unvolatilized applied nitrogen from commercial fertilizers and animal wastes, and the nitrogen fixation from bean, pulse, and alfalfa cultivation. The sum was multiplied by the IPCC default emission factor (0.0125 kg N_2O-N/kg N applied) to estimate annual N_2O emissions from nitrogen applied to soils.

Statistics on the area of histosols cultivated annually were not available, so an estimate for the year 1982 (Mausbach and Spivey 1993) was used for all years in the 1990 to 1996 series (Table 5-19). The area estimate was derived from USDA land-use statistics. The histosol area cultivated was multiplied by the IPCC default emission factor (5 kg N_2O-N/ha cultivated) to estimate annual N_2O emissions from histosol cultivation.

Annual N_2O emissions from nitrogen applied to soils were then added to annual N_2O emissions from histosol cultivation to estimate total direct annual N_2O emissions from agricultural cropping practices (Table 5-20).

Direct N_2O Emissions from Animal Production

Estimates of N_2O emissions from this component were based on animal wastes that are not used as commercial fertilizers, or applied in daily spread applications, or managed in manure management systems, but instead are deposited directly on soils by animals in pastures, range, and paddocks.[10] It was assumed that all unmanaged wastes, except for dairy cow wastes, fall into

[9] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

this category (Safely et al. 1992). Estimates of nitrogen excretion by these animals were derived from animal population and weight statistics, information on manure management system usage in the United States, and nitrogen excretion values for each animal type.

Annual animal population data for all livestock types, except horses, were obtained from the USDA National Agricultural Statistics Service (USDA 1994b, c, 1995a-j, 1996a-i, 1997a, b, d-h). Horse population data were taken from U.S. Department of Commerce's Bureau of Census (DOC 1987) and FAO (1996). Manure management system usage for all livestock types, except swine, was taken from Safely et al. (1992). Because these data were not available for swine, the swine population values were allocated to manure management system types using information on farm size distribution reported by the U.S. Department of Commerce (DOC 1995). Swine populations in the larger farm categories were assumed to utilize manure collection and storage management systems; all the wastes from smaller farms were assumed to be managed as pasture, range, and paddock. Population data for animals whose wastes were managed in pasture, range, and paddock were multiplied by an average animal mass constant (ASAE 1995) to derive total animal mass for each animal type. Total Kjeldahl nitrogen excreted per year was then calculated for each animal type using daily rates of N excretion per unit of animal mass (ASAE 1995). Annual nitrogen excretion was then summed over all animal types (Table 5-16), and reduced by 20 percent to account for the portion that volatilizes to NH_3 and NO_x. The remainder was multiplied by the IPCC default emission factor (0.02 kg N_2O-N/kg N excreted) to estimate N_2O emissions (Table 5-21).

Indirect N_2O Emissions from Nitrogen Applied to Agricultural Soils

This component accounts for N_2O that is emitted indirectly from nitrogen applied as fertilizer and excreted by livestock. Through volatilization, some of this nitrogen enters the atmosphere as NH_3 and NO_x, and subsequently returns to soils through atmospheric deposition, thereby enhancing N_2O production. Additional nitrogen is lost from soils through leaching and runoff, and enters groundwater and surface water systems, from which a portion is emitted as N_2O. These two indirect emission pathways are treated separately, although the activity data used are identical.

Estimates of total nitrogen applied as fertilizer and excreted by all livestock (i.e., wastes from all unmanaged and managed systems) were derived using the same approach as was employed to estimate the direct soil emissions. Annual application rates for synthetic and non-manure organic fertilizer nitrogen[11] were derived as described above from commercial fertilizer statistics for the United States (AAPFCO 1995, 1996; TVA 1990, 1992a and b, 1994). Annual total nitrogen excretion data (by animal type) were derived, also as described above, using animal population statistics (USDA 1994b, c, 1995a-j, 1996a-i, 1997a, b, d-h; DOC 1987; and FAO 1996), average animal mass constants (ASAE 1995), and daily rates of N excretion per unit of animal mass (ASAE 1995). Annual nitrogen excretion was then summed over all animal types.

To estimate N_2O emissions from volatilization and subsequent atmospheric deposition, it was assumed that 10 percent of the synthetic fertilizer nitrogen applied, 20 percent of the non-manure organic fertilizer nitrogen ap-

10 The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) indicate that emissions from animal wastes managed in solid storage and drylot should also be included in the emissions from soils (see footnote "c" in Table 4-22 in the Reference Manual); however, this instruction appeared to be an error (and footnote "b" should have been listed next to "Solid storage and drylot" in Table 4-22). Therefore, N_2O emissions from livestock wastes managed in solid storage and drylot are reported under manure management, rather than here, under agricultural soil management. (See Annex H for a discussion of the activity data used to calculate emissions from the manure management source category.)

11 The activity data for livestock nitrogen excretion include nitrogen excreted by all livestock, so manure used as fertilizer is excluded to avoid double counting the nitrogen contained in manure used as commercial fertilizer.

plied, and 20 percent of the total livestock nitrogen excretion were volatilized to NH_3 and NO_x, and 1 percent of the total volatilized nitrogen returned to the soils and was emitted as N_2O (IPCC/UNEP/OECD/IEA 1997). These emission levels are presented in Table 5-22.

To estimate N_2O emissions from leaching and runoff, it was assumed that 30 percent of the non-volatilized nitrogen applied or excreted (i.e., 30 percent of the sum of 90 percent of synthetic fertilizer nitrogen plus 80 percent of non-manure organic fertilizer nitrogen plus 80 percent of total livestock nitrogen) was lost to leaching and surface runoff, and 2.5 percent of the lost nitrogen was emitted as N_2O (IPCC/UNEP/OECD/IEA 1997). These emission levels are also presented in Table 5-22.

Table 5-15: Commercial Fertilizer Consumption (Metric Tons of Nitrogen)

Fertilizer Type	1990	1991	1992	1993	1994	1995	1996
Synthetic	10,110,726	10,271,698	10,335,778	10,727,695	11,171,243	10,794,578	10,996,568
Manure	976	332	597	1,056	1,206	1,339	1,099
Other Organics	763	1,210	1,256	1,121	1,101	1,374	1,544

Table 5-16: Animal Excretion (Metric Tons of Nitrogen)

Activity	1990	1991	1992	1993	1994	1995	1996
Daily Spread	816,082	883,915	867,342	853,218	839,146	838,323	819,968
Pasture, Range, & Paddock	4,742,247	4,761,332	4,881,526	4,952,799	5,095,815	5,192,152	5,099,242
All Management Systems	7,931,542	8,177,248	8,283,417	8,379,216	8,581,138	8,645,896	8,518,518

Table 5-17: Bean, Pulse, and Alfalfa Production (Metric Tons of Product)

Product Type	1990	1991	1992	1993	1994	1995	1996
Soybeans	52,415,690	54,064,730	59,611,670	50,919,130	69,625,980	59,243,170	64,837,320
Peanuts	1,634,590	2,234,650	1,943,380	1,538,770	1,934,370	1,570,100	1,660,690
Dry Edible Beans	1,468,690	1,531,550	1,025,800	993,960	1,323,900	1,397,610	1,268,240
Dry Edible Peas	107,590	168,510	114,990	149,320	102,290	209,060	121,150
Austrian Winter Peas	5,760	6,300	4,490	7,030	2,310	5,400	4,670
Lentils	66,459	104,090	71,030	90,990	84,190	97,300	60,460
Wrinkled Seed Peas	41,820	41,960	24,360	38,510	34,200	47,540	24,860
Alfalfa	75,671,002	75,585,727	71,794,602	72,851,472	73,786,780	76,670,720	72,136,611

Table 5-18: Corn and Wheat Production (Metric Tons of Product)

Product Type	1990	1991	1992	1993	1994	1995	1996
Corn for Grain	201,533,597	189,867,775	240,719,220	160,953,750	256,621,290	187,305,080	236,064,120
Wheat	74,292,383	53,890,553	67,135,240	65,220,410	63,166,750	59,400,390	62,191,130

Table 5-19: Histosol Area Cultivated

Year	Hectares
1990	843,386
1991	843,386
1992	843,386
1993	843,386
1994	843,386
1995	843,386
1996	843,386

Table 5-20: Direct N_2O Emissions from Agricultural Cropping Practices (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996
Commercial Fertilizers	15.1	15.4	15.5	16.0	16.7	16.1	16.4
Manure Managed as Daily Spread	1.1	1.2	1.2	1.1	1.1	1.1	1.1
N Fixation	10.3	10.6	11.1	9.9	12.5	11.3	11.8
Crop Residue	6.4	6.3	7.1	6.0	8.0	6.8	7.5
Histosol Cultivation	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total	**33.5**	**34.0**	**35.4**	**33.6**	**39.0**	**35.9**	**37.4**

Table 5-21: Direct N_2O Emissions from Pasture, Range, and Paddock Animals (MMTCE)

Animal Type	1990	1991	1992	1993	1994	1995	1996
Beef Cattle	9.0	9.1	9.3	9.5	9.8	10.0	9.8
Horses	0.5	0.5	0.6	0.6	0.6	0.6	0.6
Swine	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Sheep	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Goats	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	+	+	+	+	+	+	+
Total	**10.1**	**10.1**	**10.4**	**10.5**	**10.8**	**11.0**	**10.8**

+ Does not exceed 0.05 MMTCE

Table 5-22: Indirect N_2O Emissions (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996
Volatilization & Atmospheric Deposition	**3.5**	**3.5**	**3.6**	**3.7**	**3.8**	**3.7**	**3.7**
Synthetic Fertilizer	1.3	1.4	1.4	1.4	1.5	1.4	1.5
Animal Waste	2.1	2.2	2.2	2.2	2.3	2.3	2.3
Surface Run-off & Leaching	**15.4**	**15.7**	**15.9**	**16.3**	**16.9**	**16.6**	**16.7**
Synthetic Fertilizer	9.1	9.2	9.3	9.6	10	9.7	9.9
Animal Waste	6.3	6.5	6.6	6.7	6.8	6.9	6.8
Total	**18.8**	**19.3**	**19.4**	**20**	**20.6**	**20.3**	**20.4**

Note: Totals may not sum do to independent rounding.

Uncertainty

A number of conditions can affect nitrification and denitrification rates in soils, including: water content, which regulates oxygen supply; temperature, which controls rates of microbial activity; nitrate or ammonium concentration, which regulate reaction rates; available organic carbon, which is required for microbial activity; and soil pH, which is a controller of both nitrification and denitrification rates and the ratio of N_2O/N_2 from denitrification. These conditions vary greatly by soil type, climate, cropping system, and soil management regime. Although numerous emissions measurement data have been collected under a wide variety of controlled conditions, the interaction of these conditions and their combined effect on the processes leading to N_2O emissions are not fully understood. Moreover, the amount of added nitrogen from each source (fertilizers, animal wastes, nitrogen fixation, crop residues, cultivation of histosols, atmospheric deposition, or leaching and runoff) that is not absorbed by crops or wild vegetation, but remains in the soil and is available for production of N_2O, is uncertain. Therefore, it is not yet possible to develop statistically valid estimates of emission factors for all possible combinations of soil, climate, and management conditions. The emission factors used were midpoint estimates based on measurements described in the scientific literature, and as such, are representative of current scientific understanding. Nevertheless, estimated ranges around each midpoint estimate are wide; most are an order of magnitude or larger (IPCC/UNEP/OECD/IEA 1997).

Uncertainties also exist in the activity data used to derive emission estimates. In particular, the fertilizer statistics include only those organic fertilizers that enter the commercial market, so any non-commercial fertilizer use (other than daily spread livestock waste and incorporation of crop residues) has not been captured. Also, the nitrogen content of organic fertilizers varies by type, as well as within individual types; however, average values were used to estimate total organic fertilizer nitrogen consumed. Conversion factors for the bean, pulse, and alfalfa production statistics were based on a limited number of studies, and may not be representative of all conditions in the United States. It was assumed that the entire crop residue for corn, wheat, beans, and pulses was returned to the soils, with the exception of the fraction burned. A portion of this residue may be disposed of through other practices, such as composting or landfilling; however, data on these practices are not available. Statistics on the histosol area cultivated annually were not available either; the point estimate reported should be considered highly uncertain. Lastly, the livestock excretion values, while based on detailed population and weight statistics, were derived using simplifying assumptions concerning the types of management systems employed.

Agricultural Residue Burning

Large quantities of agricultural crop residues are produced by farming activities. There are a variety of ways to dispose of these residues. For example, agricultural residues can be plowed back into the field, composted, landfilled, or burned in the field. Alternatively, they can be collected and used as a fuel or sold in supplemental feed markets. Field burning of crop residues is not considered a net source of carbon dioxide (CO_2) because the carbon released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), and nitrogen oxide (NO_x), which are released during combustion. In addition, field burning may result in enhanced emissions of N_2O and NO_x many days after burning (Anderson *et al.* 1988, Levine *et al.* 1988), although this process is highly uncertain and was not addressed.

Field burning is not a common method of agricultural residue disposal in the United States; therefore, emissions from this source are minor. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, peanut, soybeans, barley, and corn, and of these residues, generally less than 5 percent is burned each year.[12] Annual emissions from this source over the period 1990 through 1996 averaged approximately 0.21 MMTCE (36 Gg) of CH_4, 0.11 MMTCE (1 Gg) of N_2O, 783 Gg of CO, and 32 Gg of

[12] The fraction of rice straw burned each year is thought to be significantly higher (see "Data Sources" discussion below).

NO_x (see Table 5-23 and Table 5-24). These estimates are significantly higher than those in the previous U.S. inventories as a result of new research indicating that residues from a greater number of crop types are typically burned. The average annual emission estimates for field burning of crop residues from 1990 through 1996 represent 1 percent of total U.S. CO emissions.

Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). In order to estimate the amounts of carbon and nitrogen released during burning, the following equations were used:

Carbon Released = (Annual Crop Production) x (Residue/Crop Product Ratio) x (Fraction of Residues Burned *in situ*) x (Dry Matter content of the Residue) x (Burning Efficiency) x (Carbon Content of the Residue) x (Combustion Efficiency)[13]

Nitrogen Released = (Annual Crop Production) x (Residue/Crop Product Ratio) x (Fraction of Residues Burned *in situ*) x (Dry Matter Content of the Residue) ´ (Burning Efficiency) ´ (Nitrogen Content of the Residue) x (Combustion Efficiency)

Emissions of CH_4 and CO were calculated by multiplying the amount of carbon released by the appropriate emission ratio (i.e., CH_4/C or CO/C). Similarly, N_2O and NO_x emissions were calculated by multiplying the amount of nitrogen released by the appropriate emission ratio (i.e., N_2O/N or NO_x/N).

Data Sources

The crop residues burned in the United States were determined from various state level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992). Crop production data were taken from the

Table 5-23: Emissions from Agricultural Residue Burning (MMTCE)

Gas/Crop Type	1990	1991	1992	1993	1994	1995	1996
CH_4	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
N_2O	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Soybeans	0.1	0.1	0.1	+	0.1	0.1	0.1
Peanuts	+	+	+	+	+	+	+
Total	**0.3**	**0.3**	**0.3**	**0.3**	**0.4**	**0.3**	**0.3**

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

[13] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to CO_2. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" was added to the calculations.

Table 5-24: Emissions from Agricultural Residue Burning (Gg)

Gas/Crop Type	1990	1991	1992	1993	1994	1995	1996
CH_4	**37**	**34**	**40**	**32**	**41**	**34**	**37**
Wheat	7	5	6	6	6	5	5
Rice	4	4	5	4	4	3	3
Sugarcane	1	1	1	1	1	1	1
Corn	17	16	19	14	20	16	19
Barley	1	1	1	1	1	1	1
Soybeans	7	7	8	7	9	8	9
Peanuts	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**2**	**1**	**1**
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	1	+	1	+	1
Barley	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+
NO_x	**30**	**30**	**34**	**27**	**37**	**30**	**34**
Wheat	1	1	1	1	1	1	1
Rice	3	3	3	2	3	2	2
Sugarcane	+	+	+	+	+	+	+
Corn	11	11	13	9	14	10	13
Barley	+	+	+	+	+	+	+
Soybeans	14	14	16	14	18	16	17
Peanuts	+	+	+	+	+	+	+
CO	**768**	**718**	**833**	**674**	**858**	**704**	**783**
Wheat	137	99	124	120	116	109	114
Rice	93	94	98	77	87	67	57
Sugarcane	18	20	20	20	20	20	19
Corn	354	333	404	296	425	326	393
Barley	15	16	16	14	13	13	14
Soybeans	148	153	168	144	194	167	183
Peanuts	2	3	3	2	3	2	2

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

USDA's *Crop Production Summaries* (USDA 1993, 1994, 1995, 1996, 1997). The percentage of crop residue burned was assumed to be 3 percent for all crops, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). For rice, the only data that were available were for California (Jenkins 1997), which was responsible for about 21 percent of the annual U.S. rice production. Until 1991, 99 percent of California's rice area was burned each year after harvest. Since then, California has tightened restrictions on burning, such that today, only about half of its rice area is burned each year. Therefore, a weighted average fraction burned was calculated for rice for each year assuming that the fraction of rice residue burned in California declined linearly from 99 to 50 percent between 1991 and 1996, while the fraction burned in the rest of the country stayed constant at 3 percent.

Residue/crop product ratios, residue dry matter contents, residue carbon contents, and residue nitrogen contents for all crops except sugarcane, peanuts, and soybeans were taken from Strehler and Stützle (1987). These data for sugarcane were taken from University of California (1977) and Turn et al. (1997). Residue/crop product ratios and residue dry matter contents for peanuts and soybeans were taken from Strehler and Stützle (1987); residue carbon contents for these crops were set at 0.45 and residue nitrogen contents were taken from Barnard and Kristoferson (1985) (the value for peanuts

was set equal to the soybean value). The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent for all crop types (EPA 1994). Emission ratios for all gases were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Uncertainty

The largest source of uncertainty in the calculation of non-CO_2 emissions from field burning of agricultural residues is in the estimates of the fraction of residue of each crop type burned each year. Data on the fraction burned, or even the gross amount of residue burned each year, are not collected at either the national or state level. In addition, burning practices are highly variable among crops, as well as among states. The fractions of residue burned used in these calculations were based upon information collected by state agencies and in published literature. It is likely that these emission estimates will continue to change as more information becomes available.

Other sources of uncertainty include the residue/crop product ratios, residue dry matter contents, burning and combustion efficiencies, and emission ratios. A residue/crop product ratio for a specific crop can vary among cultivars, and for all crops except sugarcane, generic residue/crop product ratios, rather than ratios specific to the United States, have been used. Residue dry matter contents, burning and combustion efficiencies, and emission ratios, all can vary due to weather and other combustion conditions, such as fuel geometry. Values for these variables were taken from literature on agricultural biomass burning.

6. Land-Use Change and Forestry

This chapter provides an assessment of the net carbon dioxide (CO_2) flux caused by changes in forest carbon stocks (trees, understory, forest floor, forest soil, wood products, and landfilled wood), and a preliminary assessment of the net CO_2 flux caused by changes in non-forest soil carbon stocks (see Table 6-1 and 6-2). Unlike the assessments for other sectors, which are based on annual activity data, estimates for the Land-Use Change and Forestry sector are based on periodic activity data in the form of forest, wood product, and landfilled wood surveys. As a result, the CO_2 flux from forest carbon stocks was calculated on an average annual basis. This annual average value was then applied to the years between surveys. In addition, because the most recent national compilation of state forest surveys was completed for the year 1992, and the most recent wood product and landfilled wood surveys were completed for the year 1990, the estimates of the CO_2 flux from forest carbon stocks are based in part on modeled projections of stock estimates for the year 2000.

Carbon dioxide fluxes caused by changes in forest floor, forest soil, and non-forest soil carbon stocks were not assessed in previous U.S. greenhouse gas inventories due to insufficient data and lack of accepted guidelines. The assessment of CO_2 flux from forest floor and forest soil carbon stocks in this inventory was based on stock estimates developed by the U.S. Forest Service, and is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The assessment of CO_2 flux from non-forest soils was based on the *Revised 1996 IPCC Guidelines*, which includes methodologies for calculating non-forest soil carbon flux from three land-use practices: (1) cultivation of mineral soils, (2) cultivation of organic soils, and (3) liming of agricultural soils. However, due to insufficient data about these land-use activities in the United States, this chapter provides only a preliminary assessment of CO_2

Table 6-1: Net CO_2 Flux from Land-Use Change and Forestry (MMTCE)

Description	1990	1991	1992	1993	1994	1995	1996
Forests	**(274.2)**	**(274.2)**	**(274.2)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**
Trees	(95.6)	(95.6)	(95.6)	(74.0)	(74.0)	(74.0)	(74.0)
Understory	(2.4)	(2.4)	(2.4)	(1.3)	(1.3)	(1.3)	(1.3)
Forest Floor	(20.8)	(20.8)	(20.8)	(9.8)	(9.8)	(9.8)	(9.8)
Soil	(155.2)	(155.2)	(155.2)	(86.3)	(86.3)	(86.3)	(86.3)
Harvested Wood	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**
Wood Products	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)
Landfilled Wood	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)
Total Net Flux*	**(311.5)**	**(311.5)**	**(311.5)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**

Note: Parentheses indicate sequestration. Totals may not sum due to independent rounding. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
*The total net flux excludes preliminary flux estimates for non-forest soils due to the high level of uncertainty of these estimates.

Table 6-2: Net CO_2 Flux from Land-Use Change and Forestry (Tg CO_2)

Description	1990	1991	1992	1993	1994	1995	1996
Forests	**(1,005.4)**	**(1,005.4)**	**(1,005.4)**	**(627.9)**	**(627.9)**	**(627.9)**	**(627.9)**
Trees	(350.5)	(350.5)	(350.5)	(271.3)	(271.3)	(271.3)	(271.3)
Understory	(8.8)	(8.8)	(8.8)	(4.6)	(4.6)	(4.6)	(4.6)
Forest Floor	(76.3)	(76.3)	(76.3)	(35.8)	(35.8)	(35.8)	(35.8)
Soil	(569.1)	(569.1)	(569.1)	(316.3)	(316.3)	(316.3)	(316.3)
Harvested Wood	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**
Wood Products	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)
Landfilled Wood	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)
Total Net Flux*	**(1,142.2)**	**(1,142.2)**	**(1,142.2)**	**(764.7)**	**(764.7)**	**(764.7)**	**(764.7)**

Note: Parentheses indicate sequestration. Totals may not sum due to independent rounding. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
*The total net flux excludes preliminary flux estimates for non-forest soils due to the high level of uncertainty of these estimates.

fluxes from two of the three land-use practices: cultivation of organic soils and liming of agricultural soils. Because of the high level of uncertainty associated with these two flux estimates, and the lack of a flux estimate for the third activity, the non-forest soil flux estimates have not been incorporated into the total fluxes reported for the Land-Use Change and Forestry sector.

Changes in Forest Carbon Stocks

Globally, the most important human activity that affects forest carbon fluxes is deforestation, particularly the clearing of tropical forests for agricultural use. Tropical deforestation is estimated to have released nearly 6 billion metric tons of CO_2 per year during the 1980s, or about 23 percent of global CO_2 emissions from anthropogenic activities. Conversely, during this period about 7 percent of global CO_2 emissions were offset by CO_2 uptake due to forest regrowth in the Northern Hemisphere (Houghton et al. 1995).

In the United States, the amount of forest land has remained fairly constant during the last several decades. The United States covers roughly 2,263 million acres, of which 33 percent (737 million acres) is forest land (Powell et al. 1993). The amount of forest land declined by approximately 5.2 million acres between 1977 and 1987 (USFS 1990, Waddell et al. 1989), and increased by about 5.3 million acres between 1987 and 1992 (Powell et al. 1993). These changes represent average fluctuations of only about 0.1 percent per year. Other major land-use categories in the United States include range and pasture lands (29 percent), cropland (17 percent), urban areas (3 percent), and other lands (18 percent) (Daugherty 1995).

Given the low rate of change in U.S. forest land area, the major influences on the current net carbon flux from forest land are management activities and ongoing impacts of previous land-use changes. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems. For example, intensified management of forests can increase both the rate of growth and the eventual biomass density of the forest, thereby increasing the uptake of carbon. The reversion of cropland to forest land through natural regeneration also will, over decades, result in increased carbon storage in biomass and soils.

Forests are complex ecosystems with several interrelated components, each of which acts as a carbon storage pool, including:

- Trees (i.e., living trees, standing dead trees, roots, stems, branches, and foliage)
- Understory vegetation (i.e., shrubs and bushes)
- The forest floor (i.e., woody debris, tree litter, and humus)
- Soil

As a result of biological processes in forests (e.g., growth and mortality) and anthropogenic activities (e.g., harvesting, thinning, and replanting), carbon is continuously cycled through these ecosystem components, as well as between the forest ecosystem and the atmosphere. For example, the growth of trees results in the uptake of carbon from the atmosphere and storage of carbon in living biomass. As trees age, they continue to accumu-

late carbon until they reach maturity, at which point they are relatively constant carbon stores. As trees die and otherwise deposit litter and debris on the forest floor, decay processes release carbon to the atmosphere and also increase soil carbon. The net change in forest carbon is the sum of the net changes in the total amount of carbon stored in each of the forest carbon pools over time.

The net change in forest carbon, however, may not be equivalent to the net flux between forests and the atmosphere because timber harvests may not always result in an immediate flux of carbon to the atmosphere.[1] Harvesting in effect transfers carbon from one of the "forest pools" to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 if the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested for energy use, combustion results in an immediate release of carbon. Conversely, if timber is harvested and subsequently used as lumber in a house, it may be many decades or even centuries before the lumber is allowed to decay and carbon is released to the atmosphere. If wood products are disposed of in landfills, the carbon contained in the wood may be released years or decades later, or may even be stored permanently in the landfill.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in an annual net uptake (i.e., sequestration) of carbon. Also due to improvements in U.S. agricultural productivity, the rate of forest land clearing for crop cultivation and pasture slowed in the late 19th century, and by 1920 this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were brought out of crop production, primarily between 1920 and 1950, and were allowed to revert to forest land or were actively reforested. The impacts of these land-use changes are still affecting carbon fluxes from forests in the East. In addition to land-use changes in the early part of this century, in recent decades carbon fluxes from Eastern forests were affected by a trend toward managed growth on private land, resulting in a near doubling of the biomass density in eastern forests since the early 1950s. More recently, the 1970s and 1980s saw a resurgence of federally sponsored 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 activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net carbon fluxes. Because most of the timber that is harvested from U.S. forests is used in wood products and much of the discarded wood products are disposed of by landfilling—rather than incineration—significant quantities of this harvested carbon are transferred to long-term storage pools rather than being released to the atmosphere. The size of these long-term carbon storage pools has also increased steadily over the last century.

As shown in Table 6-3, U.S. forest components, wood product pools, and landfill wood were estimated to account for an average annual net sequestration of 311.5 MMTCE from 1990 through 1992, and 208.6 MMTCE from 1993 through 1996. The net carbon sequestration reported for 1996 represents an offset of about 14 percent of the 1996 CO_2 emissions from fossil fuel combustion. The average annual net carbon sequestration reported for 1993 through 1996 represents a 33 percent decrease relative to the average annual net carbon sequestration reported for 1990 through 1992. The overall decrease in annual net sequestration between 1990 and 1992 and between 1993 and 1996 is due to changes in the aggregate age structure of U.S. forests caused by the maturation of existing forests and the slowed expansion of Eastern forest cover. The abrupt shift in annual net sequestration from 1992 to 1993 is the result of calculating average annual fluxes using periodic activity data as well as models that project decadal rather than annual sequestration estimates.

The estimates of total net flux in Table 6-3 are significantly higher than those provided in previous inventories (EPA 1995, 1997). These earlier inventories in-

[1] For this reason, the term "apparent flux" is used in this chapter.

Table 6-3: Net CO_2 Flux from U.S. Forests (MMTCE)

Description	1990	1991	1992	1993	1994	1995	1996
Apparent Forest Flux	**(274.2)**	**(274.2)**	**(274.2)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**
Trees	(95.6)	(95.6)	(95.6)	(74.0)	(74.0)	(74.0)	(74.0)
Understory	(2.4)	(2.4)	(2.4)	(1.3)	(1.3)	(1.3)	(1.3)
Forest Floor	(20.8)	(20.8)	(20.8)	(9.8)	(9.8)	(9.8)	(9.8)
Forest Soils	(155.2)	(155.2)	(155.2)	(86.3)	(86.3)	(86.3)	(86.3)
Apparent Harvested Wood Flux	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**
Apparent Wood Product Flux	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)
Apparent Landfilled Wood Flux	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)
Total Net Flux	**(311.5)**	**(311.5)**	**(311.5)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**

Note: Parentheses indicate net carbon "sequestration" (i.e., sequestration or accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word "apparent" is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

cluded only tree and understory fluxes, whereas the estimates in this inventory account for changes in all four forest carbon storage components: (1) trees, (2) understory, (3) forest floor, and (4) soil. In addition, the earlier inventories accounted for wood products and landfilled wood associated with harvests from private timberland only, whereas the revised estimates presented here account for wood products and landfilled wood associated with harvests from both private and public timberland.

Methodology

The methodology for estimating annual forest carbon flux in the United States differs from the methodologies employed for other sources because the forest carbon flux estimates for the Land-Use Change and Forestry sector were derived from periodic surveys of forest carbon stocks rather than annual activity data. Three surveys of forest carbon stocks were used: (1) timber stocks, (2) wood products, and (3) landfilled wood. In addition, because national compilations of state forest surveys have not been completed for 1997, projections of forest carbon stocks, rather than complete historical data, were used to derive some of the annual flux estimates.

Timber stock data from forest surveys were used to derive estimates of carbon contained in the four forest ecosystem components (trees, understory, forest floor, and soil) for the survey years. The apparent annual forest carbon flux for a specific year was estimated as the average annual change in the total forest carbon stocks between the preceding and succeeding timber survey years. The most recent national compilations of state forest surveys were conducted for the years 1987 and 1992, and a projection has been prepared for the year 2000. Therefore, the apparent annual forest carbon flux estimate for the years 1990 through 1992 was calculated from forest carbon stocks reported for 1987 and 1992, and the apparent annual forest carbon flux estimate for the years 1993 through 1996 was calculated from forest carbon stocks for 1992 and projected forest carbon stocks for the year 2000.

Carbon stocks contained in the wood product and landfilled wood pools were estimated for 1990 using historical forest harvest data, and were estimated for 2000 using projections of forest harvest. Therefore, apparent annual wood product and landfilled wood fluxes for the years 1990 through 1996 were calculated from a 1990 historical estimate and a 2000 projection.

The total annual net carbon flux from forests was obtained by summing the apparent carbon fluxes associated with changes in forest stocks, wood product pools, and landfilled wood pools.

The inventory methodology described above is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The IPCC identifies two approaches to developing an emissions inventory for the Land-Use Change and Forestry sector: (1) using average annual statistics on land-use change and forest management activities, and applying carbon density and flux rate data to these activity estimates to derive total flux

values; or (2) using carbon stock estimates derived from periodic inventories of forest stocks, and measuring net changes in carbon stocks over time. The latter approach was employed because the United States conducts periodic surveys of national forest stocks. In addition, the IPCC identifies two approaches to accounting for carbon emissions from harvested wood: (1) assuming that all of the harvested wood replaces wood products that decay in the inventory year so that the amount of carbon in annual harvests equals annual emissions from harvests; or (2) accounting for the variable rate of decay of harvested wood according to its disposition (e.g., product pool, landfill, combustion). The latter approach was applied for this inventory using estimates of carbon stored in wood products and landfilled wood.[2] Although there are large uncertainties associated with the data used to develop the flux estimates presented here, the use of direct measurements from forest surveys and associated estimates of product and landfilled wood pools is likely to result in more accurate flux estimates than the alternative IPCC methodology.

Data Sources

The estimates of forest, product, and landfill carbon stocks used in this inventory to derive carbon fluxes were obtained from Birdsey and Heath (1995), Heath et al. (1996), and Heath (1997). The amount of carbon in trees, understory vegetation, the forest floor, and forest soil in 1987 and 1992 was estimated using timber volume data collected by the U.S. Forest Service (USFS) for those years (Waddell et al. 1989, Powell et al. 1993). The timber volume data include timber stocks on forest land classified as timberland, reserved forest land, or other forest land[3] in the contiguous United States, but do not include stocks on forest land in Alaska or Hawaii or trees on non-forest land (e.g., urban trees).[4] The timber volume data include estimates by tree species, size class, and other categories.

The amount of carbon in trees, understory vegetation, the forest floor, and forest soil in 2000 was estimated by Birdsey and Heath (1995) using the FORCARB forest carbon model (Plantinga and Birdsey 1993) linked to the TAMM/ATLAS forest sector model (Adams and Haynes 1980, Alig 1985, Haynes and Adams 1985, Mills and Kincaid 1992). The forest stock projections for 2000, therefore, are based on multiple variables, including projections of prices, consumption, and production of timber and wood products; and projections of forest area, forest inventory volume, growth, and removals.

The amount of carbon in aboveground and belowground tree biomass in forests was calculated by multiplying timber volume by conversion factors derived from studies in the United States (Cost et al. 1990, Koch 1989). Carbon stocks in the forest floor and understory vegetation were estimated based on simple models (Vogt et al. 1986) and review of numerous intensive ecosystem studies (Birdsey 1992). Soil carbon stocks were calculated using a model similar to Burke et al. (1989) based on data from Post et al. (1982).

Carbon stocks in wood products in use and in wood stored in landfills were estimated by applying the HARVCARB model (Row and Phelps 1991) to historical harvest data from the USFS (Powell et al. 1993) and harvest projections for 2000 (Adams and Haynes 1980, Mills and Kincaid 1992). The HARVCARB model allocates harvested carbon to disposition categories (products, landfills, energy use, and emissions), and tracks the accumulation of carbon in different disposition categories over time.

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2 This calculation does not account for carbon stored in imported wood products. It does include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

3 Forest land in the U.S. includes all land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, growing at a rate of 20 cubic feet per acre per year or more. In 1992, there were about 490 million acres of Timberlands, which represented 66 percent of all forest lands (Powell et al. 1993). Forest land classified as Timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 34 percent of forest land is classified as Productive Reserved Forest Land, which is withdrawn from timber use by statute or regulation, or Other Forest Land, which includes unreserved and reserved unproductive forest land.

4 Although forest carbon stocks in Alaska and Hawaii are large compared to the U.S. total, net carbon fluxes from forest stocks in Alaska and Hawaii are believed to be minor. Net carbon fluxes from urban tree growth are also believed to be minor.

Table 6-4: U.S. Forest Carbon Stock Estimates[5] (Tg of Carbon)

Description	1987	1990	1992	2000
Forests	36,353	NA	37,724	39,094
Trees	13,009	NA	13,487	14,079
Understory	558	NA	570	580
Forest Floor	2,778	NA	2,882	2,960
Forest Soil	20,009	NA	20,785	21,475
Harvested Wood	NA	3,739	NA	4,112
Wood Products	NA	2,061	NA	2,240
Landfilled Wood	NA	1,678	NA	1,872

NA (Not Available)
Note: Forest carbon stocks do not include forest stocks in Alaska or Hawaii, or trees on non-forest land (e.g., urban trees); wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 6-4 presents the carbon stock estimates for forests (including trees, understory, forest floor, and forest soil), wood products, and landfilled wood used in this inventory. The increase in all of these stocks over time indicates that, during the examined periods, forests, forest product pools, and landfilled wood all accumulated carbon (i.e., carbon sequestration by forests was greater than carbon removed in wood harvests and released through decay; and carbon accumulation in product pools and landfills was greater than carbon emissions from these pools by decay and burning).

Uncertainty

There are considerable uncertainties associated with the estimates of the net carbon flux from U.S. forests. The first source of uncertainty stems from the underlying forest survey data. These surveys are based on a statistical sample designed to represent a wide variety of growth conditions present over large territories. Therefore, the actual timber volumes contained in forests are represented by average values that are subject to sampling and estimation errors. In addition, the forest survey data that are currently available exclude timber stocks on forest land in Alaska or Hawaii, and trees on non-forest land (e.g., urban trees); however, net carbon fluxes from these stocks are believed to be minor.

The second source of uncertainty results from deriving carbon storage estimates for the forest floor, understory vegetation, and soil from models that are based on data from forest ecosystem studies. In order to extrapolate results of these studies to all forest lands, it was assumed that they adequately describe regional or national averages. This assumption can potentially introduce the following errors: (1) bias from applying data from studies that inadequately represent average forest conditions, (2) modeling errors (erroneous assumptions), and (3) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). In particular, the impacts of forest management activities, including harvest, on soil carbon are not well understood. Moore et al. (1981) found that harvest may lead to a 20 percent loss of soil carbon, while little or no net change in soil carbon following harvest was reported in another study (Johnson 1992). Since forest soils contain over 50 percent of the total stored forest carbon in the United States, this difference can have a large impact on flux estimates.

The third source of uncertainty results from the use of projections of forest carbon stocks for the year 2000 (Birdsey and Heath 1995) to estimate annual net carbon sequestration from 1993 to 1996. These projections are the product of two linked models (FORCARB and TAMM/ATLAS) that integrate multiple uncertain variables related to future forest growth and economic forecasts. Because these models project decadal rather than annual carbon fluxes, estimates of annual net carbon sequestration from 1993 to 1996 are calculated as *average* annual estimates based on projected long-term changes in U.S. forest stocks.

[5] Sources: Heath (1997), Heath et al. (1996), and Birdsey and Heath (1995).

The fourth source of uncertainty results from incomplete accounting of wood products. Because the wood product stocks were estimated using U.S. harvest statistics, these stocks include exports, even if the logs were processed in other countries, and exclude imports. Haynes (1990) estimates that imported timber accounts for about 12 percent of the timber consumed in the United States, and that exports of roundwood and primary products account for about 5 percent of harvested timber.

Changes in Non-Forest Soil Carbon Stocks

The amount of organic carbon contained in soils depends on the balance between inputs of photosynthetically fixed carbon (i.e., organic matter such as decayed detritus and roots) and loss of carbon through decomposition. The quantity and quality of organic matter inputs, and the rate of decomposition, are determined by the combined interaction of climate, soil properties, and land-use. Agricultural practices and other land-use activities, such as clearing, drainage, tillage, planting, crop residue management, fertilization, and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net flux of carbon dioxide (CO_2) to or from soils. The addition of carbonate minerals to soils through liming operations also results in net emissions of CO_2. Changes in non-forest soil carbon stocks include net fluxes of CO_2 from three categories of land-use/land-management activities: (1) activities on organic soils, especially cultivation and conversion to pasture and forest; (2) activities on mineral soils, especially land-use change activities; and (3) liming of soils.[6] Organic soils and mineral soils are treated separately because each responds differently to land-use practices.

Organic soils contain extremely deep and rich layers of organic matter. When these soils are cultivated, tilling or mixing of the soil brings buried organic matter to the soil surface, thereby accelerating the rate of decomposition and CO_2 generation. Because of the depth and richness of the organic layer, carbon loss from cultivated organic soils can be sustained over long periods of time (IPCC/UNEP/OECD/IEA 1997). Conversion of organic soils to agricultural uses typically involves drainage as well, which also exacerbates soil carbon oxidation. When organic soils are disturbed, through cultivation and/or drainage, the rate at which organic matter decomposes, and therefore the rate at which CO_2 emissions are generated, is determined primarily by climate, the composition (decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for upland crops results in greater carbon loss than conversion to pasture or forests, due to deeper drainage and/or more intensive management practices (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997).

Mineral soils generally have fairly shallow organic layers and therefore have low organic carbon contents relative to organic soils. Consequently, it is possible to entirely deplete the carbon stock of a mineral soil within the first 10 to 20 years of disturbance, depending on the type of disturbance, climate, and soil type. Once the majority of the native carbon stock has been depleted, an equilibrium is reached that reflects a balance between accumulation from plant residues and loss of carbon through decomposition. Various land-use practices, such as incorporation of crop residues and cultivation of certain crops, can result in a net accumulation of carbon stocks in mineral soils.

Lime in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) is commonly added to agricultural soils to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating CO_2. The rate of degradation is determined by soil conditions and the type of mineral applied; it can take several years for agriculturally-applied lime to degrade completely.

[6] Fluxes of CO_2 from forest soils are excluded from this section because they are included in the previous section (Changes in Forest Carbon Stocks).

Table 6-5: CO_2 Flux From Non-Forest Soils (MMTCE)

Year	Mineral Soils	Organic Soils	Liming of Soils
1990	NA	5.9	2.3
1991	NA	5.9	2.8
1992	NA	5.9	2.2
1993	NA	5.9	2.1
1994	NA	5.9	2.3
1995	NA	5.9	2.2
1996	NA	5.9	2.8

NA (Not Available)
Note: The CO_2 flux from non-forest soils has been excluded from the total flux reported for the land-use change and forestry sector due to the high level of uncertainty associated with these estimates.

Table 6-6: CO_2 Flux From Non-Forest Soils (Tg CO_2)

Year	Nuberak Soils	Organic Soils	Liming of Soils
1990	NA	21.8	8.4
1991	NA	21.8	10.2
1992	NA	21.8	8.0
1993	NA	21.8	7.7
1994	NA	21.8	8.5
1995	NA	21.8	7.9
1996	NA	21.8	10.1

NA (Not Available)
Note: The CO_2 flux from non-forest soils has been excluded from the total flux reported for the land-use change and forestry sector due to the high level of uncertainty associated with these estimates.

Only two categories of land-use/land-management activities—agricultural use of organic soils and liming—are included in the estimates of CO_2 emissions presented here, because insufficient activity data are available to estimate fluxes from mineral soils. Net annual emissions of CO_2 from organic soils and liming of soils in the United States over the period 1990 through 1996 totaled approximately 8 to 9 MMTCE (30 to 32 Tg) (see Table 6-5 and Table 6-6).

Annual CO_2 emissions from agricultural use of organic soils were estimated to be 5.9 MMTCE (21.8 Tg) over the 1990 through 1996 period. Organic soil data were available for only 1982; therefore, emissions from organic soils were assumed to stay constant at the 1982 level for the years 1990 to 1996. Liming accounted for net annual CO_2 emissions of approximately 2.1 to 2.8 MMTCE (8 to 10 Tg). There was no apparent trend over the seven year period.

The emission estimates and analysis in this section are restricted to CO_2 fluxes associated with the management of non-forest organic soils and liming of soils. However, it is important to note that land-use and land-use change activities may also result in fluxes of non-CO_2 greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO), to and from soils. For example, when lands are flooded with freshwater, such as during hydroelectric dam construction, CH_4 is produced and emitted to the atmosphere due to anaerobic decomposition of organic material in the soil and water column. Conversely, when flooded lands, such as lakes and wetlands, are drained, anaerobic decomposition and associated CH_4 emissions will be reduced. Dry soils are a sink of CH_4, so eventually, drainage may result in soils that were once a source of CH_4 becoming a sink of CH_4. However, once the soils become aerobic, oxidation of soil carbon and other organic material will result in elevated emissions of CO_2. Moreover, flooding and drainage may also affect net soil fluxes of N_2O and CO, although these fluxes are highly uncertain. The fluxes of CH_4, and other gases, due to flooding and drainage are not assessed in this inventory due to a lack of activity data on the extent of these practices in the United States as well as scientific uncertainties about the variables that control fluxes.[7]

Methodology and Data Sources

The methodologies used to calculate CO_2 emissions from cultivation of organic soils and liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

To estimate annual CO_2 emissions from organic soils, the area under agricultural usage was divided into broad climatic regions, and the area in each climatic region was multiplied by an emission factor. (All areas were cropped rather than utilized for pasture or forestry,

[7] However, methane emissions due to flooding of rice fields are included. These are addressed under Rice Cultivation in the Agriculture sector.

so there was no need to further divide areas into general land-use types). Annual statistics on the area of organic soils under agricultural usage were not available for the years 1990 through 1996; therefore, an estimate for the area cultivated in 1982 (Mausbach and Spivey 1993) was used for all years in the 1990 to 1996 series. The area estimate was derived from USDA land-use statistics. Of the 850,000 hectares of organic soils under cultivation in 1982, Mausbach and Spivey (1993) estimated that two-thirds were located in warm, temperate regions and one-third was located in cool, temperate regions (Table 6-7). The IPCC default emission factors (10 metric tons C/ hectare/year for warm, temperate regions, 1.0 metric tons C/hectare/year for cool, temperate regions) were applied to these areas to estimate annual CO_2 emissions resulting from cultivation of organic soils.

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were calculated by multiplying the annual amounts of limestone and dolomite applied, by CO_2 emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite).[8] These emission factors are based on the assumption that all of the carbon in these materials evolves as CO_2. The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the U.S. Geological Survey's Mineral Resources Program crushed stone reports (USGS 1997a, 1997b, 1996, 1995, 1993). To develop these data, the Mineral Resources Program obtained production and use information by surveying crushed stone manufacturers. Because some manufacturers were reluctant to provide information, the estimates of total crushed limestone and dolomite production and use are divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production). To estimate the total amounts of crushed limestone and dolomite applied to agricultural soils, it was assumed that the fractions of "unspecified" and "estimated" production that were applied to agricultural soils were equal to the fraction of "specified" production that was applied to agricultural soils. In addition, the total crushed limestone and dolomite production figures for 1991, 1993, and 1994 were revised by the Mineral Resources Program in later reports, but end uses were not specified. To estimate the amounts applied to agricultural soils, it was assumed that the fractions estimated using the previously published data did not change.

Uncertainty

Uncertainties in the emission estimates presented result primarily from the underlying activity data used in the calculations. In particular, statistics on the areas of organic soil cultivated or managed as pasture or forest were not available, and the point estimate of total organic soil cultivated is highly uncertain. In addition, the breakdown of the cultivated organic soil area by climate region was based upon a qualitative assessment of the location of cultivated organic soils. Furthermore, there

Table 6-7: Areas of Cultivated Organic Soils and Quantities of Applied Minerals

Description	1990	1991	1992	1993	1994	1995	1996
Organic Soils Area Cultivated (hectares)							
Warm Temperate Regions	566,000	566,000	566,000	566,000	566,000	566,000	566,000
Cool Temperate Regions	284,000	284,000	284,000	284,000	284,000	284,000	284,000
Applied Minerals (Gg)							
Limestone	16,385	19,820	15,574	15,340	16,730	15,050	19,657
Dolomite	2,543	3,154	2,417	2,040	2,294	2,770	3,051

[8] Note: the default emission factor for dolomite provided in the Workbook volume of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/ OECD/IEA 1997) is incorrect. The value provided is 0.122 metric ton carbon/ metric ton of dolomite; the correct value is 0.130 metric ton carbon/ metric ton of dolomite.

are uncertainties in the estimates of total limestone and dolomite applied to agricultural soils, which are based on estimates as well as reported quantities.

The emission factors used in the calculations are an additional source of uncertainty. As discussed above, CO_2 emissions from cultivation of organic soils are controlled by climate, the composition of the soil organic matter, and cultivation practices. Only the first variable is taken into account, and only in a general way, in deriving the emission factors. Moreover, measured carbon loss rates from cultivated organic soils vary by as much as an order of magnitude.

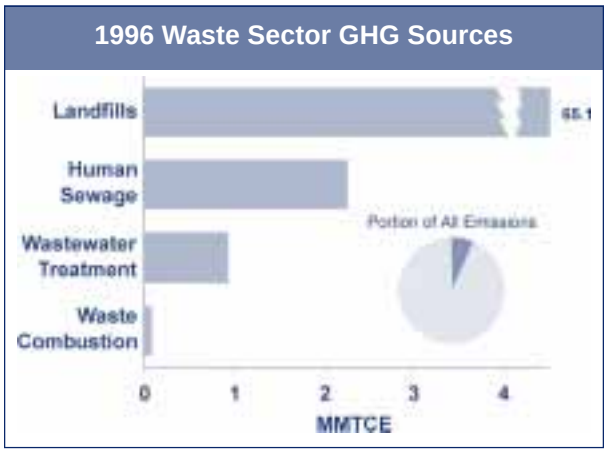
The rate of degradation of applied limestone and dolomite is determined by soil conditions and the type of mineral applied. It can take several years for agriculturally-applied lime to degrade completely. The approach used to estimate CO_2 emissions from liming assumed that the amount of mineral applied in any year was equal to the amount that degrades in that year, so annual application rates could be used to derive annual emissions.; however, this assumption may be incorrect. Moreover, soil conditions were not taken into account in the calculations.

Because the estimates of CO_2 fluxes from non-forest soils are based on limited and highly uncertain activity data and cover only a subset of the CO_2 fluxes associated with this source, the estimate of CO_2 flux from non-forest soils has been excluded from the total flux reported for the Land-Use Change and Forestry sector.

7. Waste

Certain waste management and treatment activities are sources of greenhouse gas emissions. Particularly the anaerobic decomposition of organic wastes by bacteria can result in the generation of methane (C. Currently, anaerobic decomposition processes in landfills are estimated to be the largest anthropogenic source of methane emissions in the United States, accounting for just over 36 percent of the total (see Figure 7-1). Smaller amounts of methane are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of nitrous oxide (N_2O) emissions; however, methodologies are not currently available to develop a complete estimate. Emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Waste combustion, both in incinerators and through open burning, is a small source of N_2O. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by each of these sources, but are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste sector is presented in Table 7-1 and Table 7-2.

Figure 7-1



Landfills

Landfills are the largest anthropogenic source of methane (CH_4) emissions in the United States. In 1996, emissions were approximately 65.1 MMTCE (11.4 Tg), or just over 36 percent of U.S. methane emissions (see Table 7-3 and Table 7-4). Emissions from municipal solid waste (MSW) landfills, which received about 62 percent of the total solid waste generated in the United States, accounted for about 93 percent of total landfill emissions, while industrial landfills accounted for the remaining. There are over 6,000 landfills in the United States, with 1,300 of the largest landfills receiving almost all the waste and generating the vast majority of the emissions.

Methane emissions result from the decomposition of organic landfill materials such as yard waste, household garbage, food waste, and paper. This decomposition process is a natural mechanism through which microorganisms derive energy. After being placed in a landfill, organic waste first decomposes aerobically (in the presence of oxygen) and is then attacked by anaerobic bacteria, which convert organic matter to substances such as cellulose, amino acids, and sugars. These simple substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Methane producing anaerobic

Table 7-1: Emissions from the Waste Sector (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CH_4	**57.1**	**58.4**	**58.7**	**60.6**	**62.5**	**64.5**	**66.0**
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	**1.4**	**1.4**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
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	**59.3**	**60.6**	**61.0**	**62.8**	**64.8**	**66.9**	**68.4**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from the Waste Sector (Tg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CH_4	**10.0**	**10.2**	**10.3**	**10.6**	**10.9**	**11.3**	**11.5**
Landfills	9.8	10.0	10.1	10.4	10.8	11.1	11.4
Wastewater Treatment	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Human Sewage	+	+	+	+	+	+	+
Waste Combustion	+	+	+	+	+	+	+

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

bacteria then convert these fermentation products into stabilized organic materials and a biogas consisting of approximately 50 percent carbon dioxide and 50 percent methane by volume. In general, the CO_2 emitted is of biogenic origin and primarily results from the decomposition—either aerobic or anaerobic—of organic matter such as food or yard wastes.[1] The percentage of carbon dioxide in the biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Methane production typically begins one or two years after waste placement in a landfill and may last from 10 to 60 years.

Between 1990 and 1996, estimates of methane emissions from landfills have increased slightly. The relatively constant emissions estimates are a result of two counter-acting factors: (1) the amount of MSW in landfills contributing to methane emissions has increased (thereby increasing the potential for emissions), and (2) the amount of landfill gas collected and combusted by landfill operators has also increased (thereby reducing emissions).

Methane emissions from landfills are a function of several factors, including: the total amount of MSW landfilled over the last 30 years, which is related to total MSW landfilled per year; composition of the waste in place; the amount of methane that is recovered and either flared or used for energy purposes; and the amount of methane oxidized in landfills before being released into the atmosphere. The estimated total quantity of waste in place contributing to emissions increased from about 4,926 teragrams in 1990 to 5,676 teragrams in 1996, an increase of 15 percent (see Annex I). During this same period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 1.5 teragrams (Tg) of methane were recovered and combusted (i.e., used for energy or flared) from landfills. In 1992, the estimated quantity of methane recovered and combusted increased to 1.8 Tg.[2]

Over the next several years, the total amount of MSW generated is expected to continue increasing. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In ad-

1 Emissions and sinks of biogenic carbon are accounted for under the Land-Use Change and Forestry sector.

2 EPA is presently reviewing new data on landfill gas recovery and flaring. It is anticipated that the national total for methane recovery and flaring will be significantly larger based on this new information.

Table 7-3: CH_4 Emissions from Landfills (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996
MSW Landfills	60.6	61.9	63.8	65.5	67.3	69.2	70.6
Industrial Landfills	4.2	4.3	4.4	4.5	4.6	4.8	4.9
Recovered	(8.6)	(8.6)	(10.3)	(10.3)	(10.3)	(10.3)	(10.3)
Net Emissions	**56.2**	**57.6**	**57.8**	**59.7**	**61.6**	**63.6**	**65.1**

Note: Totals may not sum due to independent rounding.

Table 7-4: CH_4 Emissions from Landfills (Tg)

Activity	1990	1991	1992	1993	1994	1995	1996
MSW Landfills	10.6	10.8	11.1	11.4	11.7	12.1	12.3
Industrial Landfills	0.7	0.7	0.8	0.8	0.8	0.8	0.8
Recovered	(1.5)	(1.5)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)
Net Emissions	**9.8**	**10.0**	**10.1**	**10.4**	**10.8**	**11.1**	**11.4**

Note: Totals may not sum due to independent rounding.

dition, the quantity of methane that is recovered and either flared or used for energy purposes is expected to increase, partially as a result of a new regulation that will require large landfills to collect and combust landfill gas. The impact of such shifts in activity on emissions cannot be fully assessed at this time.

Methodology

Based on the available information, methane emissions from landfills were estimated to equal methane production from municipal landfills, plus methane produced by industrial landfills, minus methane recovered and combusted, and minus the methane oxidized before being released into the atmosphere.

The methodology for estimating CH_4 emissions from municipal landfills is based on an updated model that tracks changes in the population of landfills in the United States over time. This model is based on the pattern of actual waste disposal by each individual landfill surveyed by the EPA's Office of Solid Waste in 1987. A second model was employed to estimate emissions from the landfill population data (EPA 1993). For each landfill in the data set, the amount of waste in place contributing to methane generation was estimated using its year of opening, its waste acceptance rate, and total waste disposed in landfills. Data on national waste disposed in landfills each year was apportioned by landfill. Emissions from municipal landfills were then estimated by multiplying the quantity of waste contributing to emissions by emission factors (EPA 1993). For further information see Annex I.

To estimate landfill gas recovered per year, data on current and planned landfill gas recovery projects in the United States were obtained from Governmental Advisory Associates (GAA 1994). The GAA report, considered to be the most comprehensive source of information on gas recovery in the United States, has estimates for gas recovery in 1990 and 1992. In addition, a number of landfills were believed to recover and flare methane without energy recovery and were not included in the GAA database. To account for the amount of methane flared without energy recovery, the estimate of gas recovered was increased by 25 percent (EPA 1993).

The amount of methane oxidized was assumed to be 10 percent of the methane generated. Methane recovered and oxidized was subtracted from the methane generated from municipal and industrial landfills to arrive at net methane emissions. Emissions from industrial sites were assumed to be a fixed percentage of total emissions from municipal landfills.

Data Sources

The model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA Office of Solid Waste (EPA 1988). National landfill waste disposal data for 1988 through 1996 were obtained from *Biocycle* (1997). Documentation on the landfill methane emissions methodology em-

ployed is available in EPA's "Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress" (EPA 1993). Emission factors were taken from Bingemer and Crutzen (1987) and the Governmental Advisory Associates (GAA 1994).

Uncertainty

There are several uncertainties associated with the estimates of methane emissions from landfills. The primary one concerns the characterization of landfills. There is a lack of information on the area landfilled and total waste in place (the fundamental factors that affect methane production). In addition, little information is available on the quantity of methane flared at non-energy related projects and the number of landfill closures. Finally, the statistical model used to estimate emissions is based upon methane generation at landfills that currently have developed energy recovery projects, and may not precisely capture the relationship between emissions and various physical characteristics of individual landfills. Overall, uncertainty is estimated to be roughly ±30 percent.

Wastewater Treatment

The breakdown of organic material in wastewater treatment systems produces methane when it occurs under anaerobic conditions. During collection and treatment, wastewater may be incidentally as well as deliberately maintained under anaerobic conditions. The methane produced during deliberate anaerobic treatment is typically collected and flared or combusted for energy. However, whenever anaerobic conditions develop, some of the methane generated is incidentally released to the atmosphere. Untreated wastewater may also produce methane if held under anaerobic conditions.

Organic content, expressed in terms of biochemical oxygen demand (BOD), determines the methane producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. Under anaerobic conditions, however, wastewater with higher BOD concentrations will produce more methane than wastewater with lower BOD. The amount of methane produced is driven by the extent to which the organic material is broken down under anaerobic versus aerobic conditions.

Table 7-5: CH_4 Emissions from Domestic Wastewater Treatment

Year	MMTCE	Tg
1990	0.9	0.2
1991	0.9	0.2
1992	0.9	0.2
1993	0.9	0.2
1994	0.9	0.2
1995	0.9	0.2
1996	0.9	0.2

In 1996, methane emissions from municipal wastewater were 0.9 MMTCE (0.2 Tg), or less than one percent of total U.S. methane emissions. Emissions have increased slightly since 1990 reflecting the increase in the U.S. human population. No estimates have been developed to indicate any changes in the manner in which wastewater is managed in the United States during this period. Table 7-5 provides emission estimates from domestic wastewater treatment.

At this time, data are not sufficient to estimate methane emissions from industrial wastewater sources. Further research is ongoing at the EPA to better quantify emissions from this source.

Methodology

Wastewater methane emissions are estimated using the default IPCC methodology (IPCC/UNEP/OECD/IEA 1997). The total population for each year was multiplied by a wastewater BOD production rate to determine total wastewater BOD produced. It was assumed that, per capita, 0.05 kilograms of wastewater BOD5[3] is produced per day and that 15 percent of wastewater BOD5 is anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.22 Gg of CH_4 per Gg of BOD5.

[3] The 5 day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972).

Table 7-6: U.S. Population (millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD5*
1990	250.7	4,578
1991	253.6	4,631
1992	256.5	4,685
1993	259.2	4,733
1994	261.7	4,779
1995	264.2	4,824
1996	266.5	4,867

* The 5 day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972)

Data Sources

Human population data for 1990 to 1996 were supplied by the U.S. Census Bureau (1997). The emission factor employed was taken from Metcalf & Eddy (1972). Table 7-6 provides U.S. population and wastewater BOD data.

Uncertainty

Domestic wastewater emissions estimates are highly uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, especially incidental occurrences. It is also believed that industrial wastewater is responsible for significantly more methane emissions than domestic wastewater treatment.

Human Sewage

Human sewage is transported for treatment in the form of domestic wastewater. Nitrous oxide (N_2O) is emitted from both domestic and industrial wastewater containing nitrogen-based organic matter and is produced through natural processes known as nitrification and denitrification. Nitrification occurs aerobically and converts ammonia into nitrate, while denitrification occurs anaerobically, and converts nitrate to N_2O. It is estimated that the amount of N_2O emitted from wastewater treatment plants accounts for approximately 5 to 10 percent of annual global discharge (Spector 1997, McElroy et al. 1978). Human sewage is believed to constitute a significant portion of the material responsible for N_2O emissions from wastewater (Spector 1997). There is insufficient information available at this time to estimate emissions from industrial wastewater and the other components of domestic wastewater. In general, N_2O generation in wastewater systems is affected by temperature, pH, biochemical oxygen demand (BOD), and nitrogen concentration. BOD is the amount of dissolved oxygen used by aerobic microorganisms to completely consume the available organic matter (Metcalf and Eddy 1972).

Emissions of N_2O from human sewage treated in wastewater systems was estimated to be 2.3 MMTCE (27 Gg) in 1996. An increase in the U.S. population and the per capita protein intake resulted in an overall increase of 8 percent in N_2O emissions from human sewage between 1990 and 1996 (see Table 7-7).

Table 7-7: N_2O Emissions from Human Sewage

Year	MMTCE	Gg
1990	2.1	25
1991	2.1	25
1992	2.2	26
1993	2.2	26
1994	2.3	27
1995	2.2	26
1996	2.3	27

Methodology

Nitrous oxide emissions from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). The equation in IPCC was modified slightly to convert N_2O-N to N_2O by using a conversion factor of the atomic weight of N_2O to that of N_2 (44/28). This is illustrated below:

$$N_20(s)=(\text{Protein})x(\text{Frac}_{NPR})x(\text{NR People})x(EF)x(44/28)$$

where,

$N_2O(s)$ = N_2O emissions from human sewage

Protein = Annual, per capita protein consumption

Frac_{NPR} = fraction of nitrogen in protein

NR People = U.S. population

EF = Emission factor

(44/28) = The atomic weight ratio of N_2O to N_2

Data Sources

U.S. population data were taken from the U.S. Census Bureau (1997). Data on the annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 1997). Because data on protein intake were unavailable for 1996, the average value of per capita protein consumption over the years 1990 through 1995 was used (see Table 7-8). An emission factor has not been specifically estimated for the United States. As a result, the default IPCC value (0.01 kg N_2O-N/kg sewage-N produced) was applied. Similarly, the fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 7-8: U.S. Population (millions) and Average Protein Intake (kg/person/year)

Year	Population	Protein
1990	250.7	39.06
1991	253.6	39.42
1992	256.5	39.79
1993	259.2	40.15
1994	261.7	40.88
1995	264.2	39.79
1996	266.5	39.79

Uncertainty

The U.S. population (NR people) and per capita protein intake data (Protein) are believed to be highly certain. There is significant uncertainty, however, in the emission factor (EF) due to regional differences that would likely affect N_2O emissions but are not accounted for in the default IPCC factor. In contrast, the fraction of nitrogen in protein ($Frac_{NPR}$) is believed to be quite accurate. Despite the increase in N_2O emissions from 1990 through 1996, these estimates from human sewage are significantly lower than other more recent estimates (Spector 1997) of total N_2O emissions from both domestic and industrial wastewater treatment. EPA is currently supporting further research to develop a comprehensive estimate of emissions from this source.

Waste Combustion

Waste combustion involves the burning of garbage and non-hazardous solids, called municipal solid waste (MSW), and has been identified as a source of nitrous oxide (N_2O) emissions.[4] In 1992, there were over 160 municipal waste combustion plants in the United States (EPA 1997b). Emissions from this source are dependent on the types of waste burned and combustion temperatures (De Soete 1993). Nitrous oxide emissions from MSW combustion were estimated to be 0.1 MMTCE (1 Gg) in 1996, and have fluctuated only slightly since 1990 (see Table 7-9).

Table 7-9: N_2O Emissions from Waste Combustion

Year	MMTCE	Gg
1990	0.1	1
1991	0.1	1
1992	0.1	1
1993	0.1	1
1994	0.1	1
1995	0.1	1
1996	0.1	1

Methodology

Estimates of nitrous oxide emissions from MSW combustion in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1997a). It is based upon the quantity of MSW combusted at waste combustion facilities and an emission factor of N_2O emission per unit mass of waste combusted (30 g N_2O/metric ton MSW).

Data Sources

Data on the quantity of MSW generated and combusted was taken from the April 1997 issue of *BioCycle* (Goldstein 1997). Table 7-10 provides MSW generation and percentage combustion data. The emission factor of N_2O emissions per quantity of MSW combusted was taken from De Soete (1993).

[4] Emissions of carbon dioxide from the combustion of petroleum-based plastics are accounted for under CO_2 from fossil fuel combustion as a non-fuel use of petroleum.

Table 7-10: Municipal Solid Waste Generation (Metric Tons) and Percent Incinerated

Year	Waste Generation	Combusted (%)
1990	266,541,881	11.5
1991	254,796,765	10.0
1992	264,843,388	11.0
1993	278,572,955	10.0
1994	293,109,556	10.0
1995	296,586,430	10.0
1996	297,268,188	10.0

Table 7-11: U.S. Municipal Solid Waste Combusted by Data Source (Metric Tons)

Year	BioCycle	EPA
1990	30,652,316	28,958,820
1991	25,479,677	30,256,974
1992	29,132,773	29,675,982
1993	27,857,295	29,884,776
1994	29,310,956	29,494,422
1995	29,658,643	30,384,066
1996	29,726,819	NA

NA (Not Available)

Uncertainty

As with other combustion related sources of nitrous oxide, emissions are affected by combustion conditions. In part, because insufficient data exists to provide detailed estimates of N_2O emissions for individual combustion facilities, the estimates presented are highly uncertain. MSW combustion data published in *BioCycle* were compared with data published by the EPA's Office of Solid Waste (EPA 1997b) and were found to be relatively consistent (see Table 7-11). The emission factor for N_2O from MSW combustion facilities has also been found to vary by an order of magnitude (between 25 and 293 g N_2O/metric ton MSW combusted) (Watanabe, et al. 1992).

Waste Sources of Criteria Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are sources of criteria air pollutant emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from the Waste sector for the years 1990 through 1996 are provided in Table 7-12.

Table 7-12: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
NO_x	**83**	**86**	**87**	**112**	**103**	**89**	**91**
Landfills	+	+	+	1	1	1	1
Wastewater Treatment	+	+	+	+	+	+	+
Waste Combustion[a]	82	85	86	107	99	88	89
Miscellaneous[b]	+	1	1	4	3	1	1
CO	**979**	**1,012**	**1,032**	**1,133**	**1,111**	**1,075**	**1,091**
Landfills	1	1	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+
Waste Combustion[a]	978	1,011	1,030	1,130	1,108	1,073	1,089
Miscellaneous[b]	+	+	+	1	1	1	1
NMVOCs	**895**	**907**	**916**	**949**	**949**	**968**	**393**
Landfills	58	60	63	67	73	68	20
Wastewater Treatment	57	58	61	63	64	61	58
Waste Combustion[a]	222	227	230	256	248	237	240
Miscellaneous[b]	558	562	563	563	564	602	75

[a] Includes waste incineration and open burning (EPA 1997)
[b] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 Gg

Methodology and Data Sources

These emission estimates were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1996* (EPA 1997b). This EPA report provides emission estimates of these gases by sector, using a "top down" estimating procedure¾emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997a). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA data bases.

Uncertainty

Uncertainties in these estimates are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

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Annexes

The following seventeen annexes provide additional information to the material presented in the main body of this report. Annexes A through I discuss methodologies for individual source categories in greater detail than was presented in the main body of the report and include explicit activity data and emission factor tables. Annex J lists the Global Warming Potential (GWP) values used in this report as provided in IPCC (1996). Annexes K and J summarize U.S. emissions of ozone depleting substances (e.g., CFCs and HCFCs) and sulfur dioxide (SO_2), respectively. Annex M provides a complete list of emission sources assessed in this report. Annexes N and O present U.S. greenhouse gas emission estimates in the reporting format recommended in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the IPCC reference approach for estimating CO_2 emissions from fossil fuel combustion, respectively.

Preliminary greenhouse gas emission estimates for 1997 are provided in Annex P, which will be revised in future reports. Finally, Annex Q addresses the criteria for the inclusion of an emission source category and some of the sources which meet the criteria but are nonetheless excluded from U.S. estimates.

List of Annexes

- Annex A Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
- Annex B Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Stationary Combustion
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- Annex D Methodology for Estimating Methane Emissions from Coal Production
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- Annex G Methodology for Estimating Methane Emissions from Enteric Fermentation
- Annex H Methodology for Estimating Methane Emissions from Manure Management
- Annex I Methodology for Estimating Methane Emissions from Landfills
- Annex J Global Warming Potentials
- Annex K Ozone Depleting Substance Emissions
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- Annex M Complete List of Sources
- Annex N IPCC Reporting Tables
- Annex O IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion
- Annex P Preliminary 1997 Estimates of U.S. Greenhouse Gas Emissions and Sinks
- Annex Q Sources of Greenhouse Gas Emissions Excluded

Annex A

Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion

Carbon dioxide (CO_2) emissions from fossil fuel combustion were estimated using a "bottom-up" methodology characterized by six steps. These steps are described below. Methodological and data changes from previous inventories are outlined at the end of this discussion.

Step 1: Determine Energy Consumption by Fuel Type and End-Use Sector

The bottom-up methodology used by the United States for estimating CO_2 emissions from fossil fuel combustion is conceptually similar to the approach recommended by the Intergovernmental Panel on Climate Change (IPCC) for countries that intend to develop detailed, sectoral-based emission estimates (IPCC/UNEP/OECD/IEA 1997). Basic consumption data are presented in Columns 2-8 of Table A-1 through Table A-7, with totals by fuel type in Column 8 and totals by end-use sector in the last rows. Fuel consumption data for the bottom-up approach were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy. The EIA data were collected through surveys at the point of delivery or use; therefore, they reflect the reported consumption of fuel by end-use sector and fuel type. Individual data elements were supplied by a variety of sources within EIA. Most information was taken from published reports, although some data were drawn from unpublished energy studies and databases maintained by EIA.

Energy consumption data were aggregated by end-use sector (i.e., residential, commercial, industrial, transportation, electric utilities, and U.S. territories), primary fuel type (e.g., coal, natural gas, and petroleum), and secondary fuel type (e.g., motor gasoline, distillate fuel, etc.). The 1996 total energy consumption across all sectors, including territories, and energy types was 79,419 trillion Btu, as indicated in the last entry of Column 8 in Table A-1. This total includes fuel used for non-fuel purposes and fuel consumed as international bunkers, both of which are deducted in later steps.

There are two modifications made in this report that may cause consumption information herein to differ from figures given in the cited literature. These are the consideration of synthetic natural gas production and ethanol added to motor gasoline.

First, a portion of industrial coal accounted for in EIA combustion figures is actually used to make "synthetic natural gas" via coal gasification. The energy in this gas enters the natural gas stream, and is accounted for in natural gas consumption statistics. Because this energy is already accounted for as natural gas, it is deducted from industrial coal consumption to avoid double counting. This makes the figure for other industrial coal consumption in this report slightly lower than most EIA sources.

Second, ethanol has been added to the motor gasoline stream for several years, but prior to 1993 this addition was not captured in EIA motor gasoline statistics. Starting in 1993, ethanol was included in gasoline statistics. However, because ethanol is a biofuel, which is assumed to result in no net CO_2 emissions, the amount of ethanol added is subtracted from total gasoline consumption. Thus, motor gasoline consumption statistics given in this report may be slightly lower than in EIA sources.

There are also three basic differences between the consumption figures presented in Table A-1 and those recommended in the IPCC emission inventory methodology.

First, consumption data in the U.S. inventory are presented using higher heating values (HHV)[1] rather than the lower heating values (LHV)[2] reflected in the IPCC emission inventory methodology. This convention is followed because data obtained from EIA are based on HHV.

[1] Also referred to as Gross Calorific Values (GCV).
[2] Also referred to as Net Calorific Values (NCV).

Second, while EIA's energy use data for the United States includes only the 50 U.S. states and the District of Columbia, the data reported to the Framework Convention on Climate Change are to include energy consumption within territories. Therefore, consumption estimates for U.S. territories were added to domestic consumption of fossil fuels. Energy consumption data from U.S. territories are presented in Column 7 of Table A-1. It is reported separately from domestic sectoral consumption, because it is collected separately by EIA with no sectoral disaggregation.

Third, the domestic sectoral consumption figures in Table A-1 include bunker fuels and non-fuel uses of energy. The IPCC recommends that countries estimate emissions from bunker fuels separately and exclude these emissions from national totals, so bunker fuel emissions have been estimated in Table A-8 and deducted from national estimates (see Step 4). Similarly, fossil fuels used to produce non-energy products that store carbon rather than release it to the atmosphere are provided in Table A-9 and deducted from national emission estimates (see Step 3).

Step 2: Determine the Carbon Content of All Fuels

The carbon content of combusted fossil fuels was estimated by multiplying energy consumption (Columns 2 through 8 of Table A-1) by fuel specific carbon content coefficients (Table A-10 and Table A-11) that reflected the amount of carbon per unit of energy inherent in each fuel. The resulting carbon contents are sometimes referred to as potential emissions, or the maximum amount of carbon that could potentially be released to the atmosphere if all carbon in the fuels were converted to CO_2. The carbon content coefficients used in the U.S. inventory were derived by EIA from detailed fuel information and are similar to the carbon content coefficients contained in the IPCC's default methodology (IPCC/UNEP/OECD/IEA 1997), with modifications reflecting fuel qualities specific to the United States.

Step 3: Adjust for the amount of Carbon Stored in Products

Depending on the end-use, non-fuel uses of fossil fuels can result in long term storage of some or all of the carbon contained in the fuel. For example, asphalt made from petroleum can sequester up to 100 percent of the carbon contained in the petroleum feedstock for extended periods of time. Other non-fuel products, such as lubricants or plastics also store carbon, but can lose or emit some of this carbon when they are used and/or burned as waste.

The amount of carbon sequestered or stored by non-fuel uses of fossil fuel products was based upon data that addressed the ultimate fate of various energy products, with all non-fuel use attributed to the industrial, transportation, and territories end-use sectors. This non-fuel consumption is presented in Table A-9. Non-fuel consumption was then multiplied by fuel specific carbon content coefficients (Table A-10 and Table A-11) to obtain the carbon content of the fuel, or the maximum amount of carbon that could be sequestered if all the carbon in the fuel were stored in non-fuel products (Columns 5 and 6 of Table A-9). This carbon content was then multiplied by the fraction of carbon assumed to actually have been sequestered in products (Column 7 of Table A-9), resulting in the final estimates of carbon stored by sector and fuel type, which are presented in Columns 8 through 10 of Table A-3. The portions of carbon sequestered were based on EIA data.

Step 4: Subtract Carbon from Bunker Fuels.

Emissions from international transport activities, or bunker fuel consumption, were not included in national totals. There is currently disagreement internationally as to which countries are responsible for these emissions, and until this issue is resolved, countries are asked to report these emissions separately. However, EIA data includes bunker fuels—primarily residual oil—as part of fuel consumption by the transportation end-use sector. To compensate for this inclusion, bunker fuel emissions were calculated separately (Table A-8) and the carbon content of these fuels was subtracted from the transportation end-use sector. The calculations of bunker fuel emissions followed the same procedures used for other fuel emissions (i.e., estimation of consumption, determination of carbon content, and adjustment for the fraction of carbon not oxidized).

Step 5: Account for Carbon that Does Not Oxidize During Combustion

Because combustion processes are not 100 percent efficient, some of the carbon contained in fuels is not emitted to the atmosphere. Rather, it remains behind as soot, particulate matter, or other by-products of inefficient

combustion. The estimated fraction of carbon not oxidized in U.S. energy conversion processes due to inefficiencies during combustion ranges from 0.5 percent for natural gas to 1 percent for petroleum and coal. Except for coal these assumptions are consistent with the default values recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997). In the U.S. unoxidized carbon from coal combustion was estimated to be no more than one percent (Bechtel 1993). Table A-10 presents fractions oxidized by fuel type, which are multiplied by the net carbon content of the combusted energy to give final emissions estimates.

Step 6: Summarize Emission Estimates

Actual CO_2 emissions in the United States were summarized by major fuel (i.e., coal, petroleum, natural gas, geothermal) and consuming sector (i.e., residential, commercial, industrial, transportation, electric utilities, and territories). Adjustments for bunker fuels and carbon sequestered in products were made. Emission estimates are expressed in terms of million metric tons of carbon equivalents (MMTCE).

To determine total emissions by final end-use sector, emissions from electric utilities were distributed over the five end-use sectors according to their share of electricity consumed (see Table A-12).

Differences with Previous Years' Inventories

Two minor changes were made to the estimates of CO_2 emissions from energy consumption in this year's report. The first change concerns how emissions from unmetered natural gas consumption were handled. The second change pertains to accounting for non-fuel uses of fossil fuels in U.S. territories.

Previous inventories included calculations of emissions from unmetered natural gas consumption. Previously, the EIA provided this consumption data, which was calculated as the difference between reported gas production and reported consumption. For many years, the reported amount of gas produced was greater than the amount of gas consumed. EIA assumed that this difference was due to leakage and measurement errors and unmetered consumption. However, during the past two years, the reported amount of gas consumed was higher than the quantity of gas reported to have been produced. This occurrence casts doubt on what composes this difference. Therefore, this year calculations of emissions from unmetered natural gas consumption were not included in the emission estimates.

This year's estimates account for the non-fuel use in U.S. territories. Previous inventories overlooked this small source (0.17 MMTCE in 1996) of carbon sequestration.

Table A-1: 1996 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
	Consumption (TBtu)							Emissions (MMTCE) including Adjustments* and Fraction Oxidized						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Utility**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Utility**	**Terr.**	**Total**
Residential Coal	53.7						53.7	1.4						1.4
Commercial Coal		81.0					81.0		2.1					2.1
Industrial Coking Coal			849.7				849.7			20.9				20.9
Industrial Other Coal			1,489.3				1,489.3			38.5				38.5
Coke Imports			(0.3)				(0.3)			(0.0)				(0.0)
Transportation Coal				0.0			0.0				0.0			0.0
Utility Coal					18,086.4		18,086.4					460.9		460.9
US Territory Coal (bit)						10.3	10.3						0.255	0.3
Total Coal	53.7	81.0	2,338.7	0.0	18,086.4	10.3	20,570.0	1.4	2.1	59.4	0.0	460.9	0.3	524.0
Natural Gas	5,375.8	3,289.9	10,311.3	730.6	2,800.8	NA	22,508.4	77.4	47.4	143.0	10.5	40.3	NA	318.6
Asphalt & Road Oil	0.0	0.0	1,175.9	0.0	0.0		1,175.9	0.0	0.0	(0.0)	0.0	0.0	0.000	(0.0)
Aviation Gasoline	0.0	0.0	0.0	37.4	0.0		37.4	0.0	0.0	0.0	0.7	0.0	0.000	0.7
Distillate Fuel Oil	937.5	493.7	1,166.3	4,468.0	109.0	130.7	7,305.2	18.5	9.8	23.0	86.1	2.2	2.581	142.1
Jet Fuel	0.0	0.0	0.0	3,274.2	0.0	79.1	3,353.4	0.0	0.0	0.0	56.7	0.0	1.514	58.2
Kerosene	82.1	24.6	21.4	0.0	0.0		128.1	1.6	0.5	0.4	0.0	0.0	0.000	2.5
LPG	422.0	74.5	2,130.4	34.3	0.0	5.6	2,666.7	7.1	1.3	13.0	0.6	0.0	0.094	22.0
Lubricants	0.0	0.0	172.5	163.0	0.0	1.3	336.8	0.0	0.0	1.7	1.6	0.0	0.013	3.4
Motor Gasoline	0.0	26.2	199.8	14,879.2	0.0	93.7	15,198.9	0.0	0.5	3.8	285.5	0.0	1.783	291.6
Residual Fuel	0.0	156.8	376.0	813.0	605.9	151.7	2,103.4	0.0	3.3	8.0	3.1	12.9	3.227	30.6
Other Petroleum						76.7	76.7						1.367	1.4
AvGas Blend Components			7.0				7.0			0.1				0.1
Crude Oil			13.7				13.7			0.3				0.3
MoGas Blend Components			0.0				0.0			0.0				0.0
Misc. Products			89.0				89.0			1.8				1.8
Naphtha (<401 deg. F)			479.3				479.3			8.6				8.6
Other Oil (>401 deg. F)			729.6				729.6			14.4				14.4
Pentanes Plus			355.0				355.0			1.8				1.8
Petrochemical Feedstocks			0.0				0.0			(13.7)				(13.7)
Petroleum Coke			816.0		20.5		836.5			19.6		0.6		20.2
Still Gas			1,437.1				1,437.1			24.9				24.9
Special Naphtha			74.5				74.5			1.5				1.5
Unfinished Oils			(112.8)				(112.8)			(2.3)				(2.3)
Waxes			48.7				48.7			1.0				1.0
Other Wax & Misc.			0.0				0.0			(3.4)				(3.4)
Total Petroleum	1,441.6	775.8	9,179.5	23,669.1	735.5	538.8	36,340.2	27.2	15.3	104.6	434.3	15.6	10.580	607.7
Geothermal					0.018		0.018					0.0369		0.0369
TOTAL (All Fuels)	6,871.0	4,146.7	21,829.5	24,399.7	21,622.7	549.1	79,418.7	106.0	64.8	307.0	444.8	516.9	10.835	1,450.3

*Adjustments include: international bunker fuel consumption (see Table A-8) and carbon stored in products (see Table A-9)
NA (Not Available)

Table A-2: 1995 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
	Consumption (TBtu)							Emissions (MMTCE) including Adjustments* and Fraction Oxidized						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Utility**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Utility**	**Terr.**	**Total**
Residential Coal	53.7						53.7	1.4						1.4
Commercial Coal		81.0					81.0		2.1					2.1
Industrial Coking Coal			884.7				884.7			21.8				21.8
Industrial Other Coal			1,530.7				1,530.7			39.6				39.6
Coke Imports			26.4				26.4			0.7				0.7
Transportation Coal				0.0			0.0				0.0			0.0
Utility Coal					16,978.9		16,978.9					432.7		432.7
US Territory Coal (bit)						10.2	10.2						0.255	0.3
Total Coal	53.7	81.0	2,441.9	0.0	16,978.9	10.2	19,565.7	1.4	2.1	62.1	0.0	432.7	0.3	498.5
Natural Gas	4,981.3	3,185.2	10,064.3	722.0	3,276.4	NA	22,229.3	71.7	45.9	139.7	10.4	47.2	NA	314.8
Asphalt & Road Oil	0.0	0.0	1,178.2	0.0	0.0		1,178.2	0.0	0.0	0.0	0.0	0.0	0.000	0.0
Aviation Gasoline	0.0	0.0	0.0	39.6	0.0		39.6	0.0	0.0	0.0	0.7	0.0	0.000	0.7
Distillate Fuel Oil	893.1	470.3	1,118.7	4,244.4	90.7	135.5	6,952.5	17.6	9.3	22.1	81.8	1.8	2.675	135.3
Jet Fuel	0.0	0.0	0.0	3,132.2	0.0	81.6	3,213.8	0.0	0.0	0.0	54.2	0.0	1.562	55.8
Kerosene	71.7	21.5	18.7	0.0	0.0		111.8	1.4	0.4	0.4	0.0	0.0	0.000	2.2
LPG	398.3	70.3	2,010.8	32.4	0.0	5.6	2,517.3	6.7	1.2	12.5	0.5	0.0	0.095	21.0
Lubricants	0.0	0.0	177.8	167.9	0.0	1.4	347.1	0.0	0.0	1.8	1.7	0.0	0.014	3.5
Motor Gasoline	0.0	25.8	196.7	14,586.4	0.0	97.9	14,906.8	0.0	0.5	3.8	279.9	0.0	1.863	286.0
Residual Fuel	0.0	168.9	371.5	870.0	544.4	156.2	2,110.9	0.0	3.6	7.9	2.9	11.6	3.323	29.3
Other Petroleum						79.3	79.3						1.414	1.4
AvGas Blend Components			5.3				5.3			0.1				0.1
Crude Oil			14.5				14.5			0.3				0.3
MoGas Blend Components			0.0				0.0			0.0				0.0
Misc. Products			97.1				97.1			1.9				1.9
Naphtha (<401 deg. F)			373.0				373.0			6.7				6.7
Other Oil (>401 deg. F)			801.0				801.0			15.8				15.8
Pentanes Plus			337.9				337.9			1.7				1.7
Petrochemical Feedstocks			0.0				0.0			(12.9)				(12.9)
Petroleum Coke			779.0		22.9		802.0			18.9		0.6		19.5
Still Gas			1,417.5				1,417.5			24.6				24.6
Special Naphtha			70.8				70.8			1.4				1.4
Unfinished Oils			(320.9)				(320.9)			(6.4)				(6.4)
Waxes			40.6				40.6			0.8				0.8
Other Wax & Misc.			0.0				0.0			(3.3)				(3.3)
Total Petroleum	1,363.0	756.8	8,688.1	23,072.9	658.0	557.5	35,096.2	25.7	15.0	97.9	421.7	14.0	10.946	585.3
Geothermal					0.016		0.016					0.0328		0.0328
TOTAL (All Fuels)	6,398.0	4,023.0	21,194.3	23,794.8	20,913.3	567.7	76,891.1	98.8	62.9	299.7	432.1	493.9	11.201	1,398.7

*Adjustments include: international bunker fuel consumption (see Table A-8) and carbon stored in products (see Table A-9)
NA (Not Available)

Table A-3: 1994 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
	Consumption (TBtu)							Emissions (MMTCE) including Adjustments* and Fraction Oxidized						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Utility**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Utility**	**Terr.**	**Total**
Residential Coal	55.5						55.5	1.4						1.4
Commercial Coal		83.5					83.5		2.1					2.1
Industrial Coking Coal			850.6				850.6			21.0				21.0
Industrial Other Coal			1,589.4				1,589.4			41.1				41.1
Coke Imports			23.6				23.6			0.7				0.7
Transportation Coal				0.0			0.0				0.0			0.0
Utility Coal					16,895.2		16,895.2					430.2		430.2
US Territory Coal (bit)						10.2	10.2						0.255	0.3
Total Coal	55.5	83.5	2,463.7	0.0	16,895.2	10.2	19,508.1	1.4	2.1	62.7	0.0	430.2	0.3	496.7
Natural Gas	4,988.3	2,980.8	9,609.3	705.2	3,052.9	NA	21,336.5	71.8	42.9	133.3	10.2	44.0	NA	302.1
Asphalt & Road Oil	0.0	0.0	1,172.9	0.0	0.0		1,172.9	0.0	0.0	(0.0)	0.0	0.0	0.000	(0.0)
Aviation Gasoline	0.0	0.0	0.0	38.1	0.0		38.1	0.0	0.0	0.0	0.7	0.0	0.000	0.7
Distillate Fuel Oil	880.0	464.3	1,108.8	4,175.0	95.2	101.3	6,824.6	17.4	9.2	21.9	80.4	1.9	2.001	132.7
Jet Fuel	0.0	0.0	0.0	3,154.5	0.0	80.7	3,235.2	0.0	0.0	0.0	54.9	0.0	1.546	56.4
Kerosene	64.9	19.5	16.9	0.0	0.0		101.3	1.3	0.4	0.3	0.0	0.0	0.000	2.0
LPG	395.5	69.8	1,996.5	32.2	0.0	9.2	2,503.1	6.7	1.2	12.8	0.5	0.0	0.156	21.3
Lubricants	0.0	0.0	180.9	170.8	0.0	2.1	353.8	0.0	0.0	1.8	1.7	0.0	0.021	3.5
Motor Gasoline	0.0	25.2	191.9	14,214.1	0.0	131.4	14,562.7	0.0	0.5	3.7	273.7	0.0	2.500	280.4
Residual Fuel	0.0	174.6	417.6	896.0	846.6	171.1	2,505.9	0.0	3.7	8.9	4.6	18.0	3.641	38.8
Other Petroleum						72.6	72.6						1.294	1.3
AvGas Blend Components			6.1				6.1			0.1				0.1
Crude Oil			18.7				18.7			0.4				0.4
MoGas Blend Components			0.0				0.0			0.0				0.0
Misc. Products			105.9				105.9			2.1				2.1
Naphtha (<401 deg. F)			398.3				398.3			7.2				7.2
Other Oil (>401 deg. F)			838.6				838.6			16.6				16.6
Pentanes Plus			338.7				338.7			2.4				2.4
Petrochemical Feedstocks			0.0				0.0			(13.6)				(13.6)
Petroleum Coke			793.0		26.3		819.4			19.4		0.7		20.1
Still Gas			1,439.4				1,439.4			25.0				25.0
Special Naphtha			81.1				81.1			1.6				1.6
Unfinished Oils			(279.2)				(279.2)			(5.6)				(5.6)
Waxes			40.6				40.6			0.8				0.8
Other Wax & Misc.			0.0				0.0			(3.5)				(3.5)
Total Petroleum	1,340.4	753.3	8,866.8	22,680.7	968.2	568.5	35,177.9	25.3	14.9	102.2	416.6	20.6	11.159	590.7
Geothermal					0.024		0.024					0.0492		0.0492
TOTAL (All Fuels)	6,384.2	3,817.6	20,939.8	23,385.9	20,916.2	578.7	76,022.4	98.6	60.0	298.1	426.7	494.8	11.414	1,389.6

*Adjustments include: international bunker fuel consumption (see Table A-8) and carbon stored in products (see Table A-9)
NA (Not Available)

Table A-4: 1993 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
	Consumption (TBtu)							Emissions (MMTCE) including Adjustments* and Fraction Oxidized						
Fuel Type	Res.	Comm.	Ind.	Trans.	Utility	Terr.	Total	Res.	Comm.	Ind.	Trans.	Utility	Terr.	Total
Residential Coal	56.6						56.6	1.5						1.5
Commercial Coal		85.5					85.5		2.2					2.2
Industrial Coking Coal			839.5				839.5			20.7				20.7
Industrial Other Coal			1,588.0				1,588.0			41.1				41.1
Coke Imports			17.3				17.3			0.5				0.5
Transportation Coal				0.0			0.0				0.0			0.0
Utility Coal					16,841.1		16,841.1					428.7		428.7
US Territory Coal (bit)						8.1	8.1						0.201	0.2
Total Coal	56.6	85.5	2,444.8	0.0	16,841.1	8.1	19,436.1	1.5	2.2	62.2	0.0	428.7	0.2	494.7
Natural Gas	5,097.5	2,995.8	9,387.4	643.1	2,744.1	NA	20,867.9	73.4	43.1	131.0	9.3	39.5	NA	296.3
Asphalt & Road Oil	0.0	0.0	1,149.0	0.0	0.0		1,149.0	0.0	0.0	0.0	0.0	0.0	0.000	0.0
Aviation Gasoline	0.0	0.0	0.0	38.4	0.0		38.4	0.0	0.0	0.0	0.7	0.0	0.000	0.7
Distillate Fuel Oil	912.9	463.9	1,099.7	3,912.9	76.7	92.3	6,558.3	18.0	9.2	21.7	75.2	1.5	1.823	127.5
Jet Fuel	0.0	0.0	0.0	3,028.0	0.0	71.4	3,099.4	0.0	0.0	0.0	52.7	0.0	1.369	54.1
Kerosene	75.6	14.0	13.1	0.0	0.0		102.7	1.5	0.3	0.3	0.0	0.0	0.000	2.0
LPG	398.6	70.3	1,794.4	18.9	0.0	12.8	2,295.1	6.7	1.2	12.0	0.3	0.0	0.217	20.4
Lubricants	0.0	0.0	173.1	163.5	0.0	0.2	336.7	0.0	0.0	1.7	1.6	0.0	0.002	3.4
Motor Gasoline	0.0	29.6	179.4	14,000.5	0.0	115.9	14,325.5	0.0	0.6	3.5	269.3	0.0	2.206	275.5
Residual Fuel	0.0	175.0	451.8	913.4	938.6	153.6	2,632.4	0.0	3.7	9.6	4.2	20.0	3.269	40.7
Other Petroleum						83.2	83.2						1.482	1.5
AvGas Blend Components			0.1				0.1			0.0				0.0
Crude Oil			21.2				21.2			0.4				0.4
MoGas Blend Components			0.0				0.0			0.0				0.0
Misc. Products			94.7				94.7			1.9				1.9
Naphtha (<401 deg. F)			350.6				350.6			6.3				6.3
Other Oil (>401 deg. F)			844.1				844.1			16.7				16.7
Pentanes Plus			332.3				332.3			2.0				2.0
Petrochemical Feedstocks			0.0				0.0			(13.1)				(13.1)
Petroleum Coke			767.3		36.8		804.1			18.9		1.0		19.9
Still Gas			1,430.2				1,430.2			24.8				24.8
Special Naphtha			104.6				104.6			2.1				2.1
Unfinished Oils			(396.0)				(396.0)			(7.9)				(7.9)
Waxes			40.0				40.0			0.8				0.8
Other Wax & Misc.			0.0				0.0			(3.3)				(3.3)
Total Petroleum	1,387.0	752.8	8,449.6	22,075.5	1,052.0	529.5	34,246.5	26.2	14.9	98.3	404.1	22.5	10.368	576.4
Geothermal					0.026		0.026					0.0533		0.0533
TOTAL (All Fuels)	6,541.1	3,834.2	20,281.8	22,718.6	20,637.3	537.5	74,550.5	101.0	60.2	291.5	413.4	490.7	10.569	1,367.5

*Adjustments include: international bunker fuel consumption (see Table A-8) and carbon stored in products (see Table A-9)
NA (Not Available)

Table A-5: 1992 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
	Consumption (TBtu)							Emissions (MMTCE) including Adjustments* and Fraction Oxidized						
Fuel Type	Res.	Comm.	Ind.	Trans.	Utility	Terr.	Total	Res.	Comm.	Ind.	Trans.	Utility	Terr.	Total
Residential Coal	56.7						56.7	1.5						1.5
Commercial Coal		85.7					85.7		2.2					2.2
Industrial Coking Coal			867.4				867.4			21.2				21.2
Industrial Other Coal			1,573.1				1,573.1			40.7				40.7
Coke Imports			27.2				27.2			0.7				0.7
Transportation Coal				0.0			0.0				0.0			0.0
Utility Coal					16,192.0		16,192.0					411.8		411.8
US Territory Coal (bit)						8.8	8.8						0.220	0.2
Total Coal	56.7	85.7	2,467.7	0.0	16,192.0	8.8	18,810.9	1.5	2.2	62.6	0.0	411.8	0.2	478.3
Natural Gas	4,821.1	2,884.2	8,996.4	608.4	2,828.5	NA	20,138.6	69.4	41.5	125.8	8.8	40.7	NA	286.2
Asphalt & Road Oil	0.0	0.0	1,102.2	0.0	0.0		1,102.2	0.0	0.0	(0.0)	0.0	0.0	0.000	(0.0)
Aviation Gasoline	0.0	0.0	0.0	41.1	0.0		41.1	0.0	0.0	0.0	0.8	0.0	0.000	0.8
Distillate Fuel Oil	864.9	464.0	1,144.5	3,810.2	67.3	78.7	6,429.6	17.1	9.2	22.6	73.4	1.3	1.554	125.2
Jet Fuel	0.0	0.0	0.0	3,001.3	0.0	65.8	3,067.1	0.0	0.0	0.0	52.3	0.0	1.264	53.5
Kerosene	65.0	11.1	9.8	0.0	0.0		85.9	1.3	0.2	0.2	0.0	0.0	0.000	1.7
LPG	382.5	67.5	1,859.8	18.4	0.0	11.8	2,340.0	6.4	1.1	12.6	0.3	0.0	0.199	20.6
Lubricants	0.0	0.0	170.0	160.5	0.0	0.0	330.5	0.0	0.0	1.7	1.6	0.0	0.000	3.3
Motor Gasoline	0.0	79.5	194.3	13,698.8	0.0	114.4	14,087.0	0.0	1.5	3.7	263.4	0.0	2.176	270.8
Residual Fuel	0.0	191.2	391.3	1,082.0	835.6	154.5	2,654.6	0.0	4.1	8.3	5.5	17.8	3.288	39.0
Other Petroleum						61.4	61.4						1.095	1.1
AvGas Blend Components			0.2				0.2			0.0				0.0
Crude Oil			27.4				27.4			0.5				0.5
MoGas Blend Components			75.7				75.7			1.5				1.5
Misc. Products			100.1				100.1			2.0				2.0
Naphtha (<401 deg. F)			377.3				377.3			6.8				6.8
Other Oil (>401 deg. F)			814.9				814.9			16.1				16.1
Pentanes Plus			322.7				322.7			4.9				4.9
Petrochemical Feedstocks			0.0				0.0			(13.1)				(13.1)
Petroleum Coke			813.1		30.1		843.2			19.0		0.8		19.9
Still Gas			1,447.6				1,447.6			25.1				25.1
Special Naphtha			104.6				104.6			2.1				2.1
Unfinished Oils			(355.0)				(355.0)			(7.1)				(7.1)
Waxes			37.3				37.3			0.7				0.7
Other Wax & Misc.			0.0				0.0			(3.3)				(3.3)
Total Petroleum	1,312.4	813.3	8,637.7	21,812.3	933.0	486.6	33,995.3	24.8	16.1	104.3	397.3	19.9	9.575	572.0
Geothermal					0.028		0.028					0.0574		0.0574
TOTAL (All Fuels)	6,190.2	3,783.2	20,101.8	22,420.7	19,953.5	495.5	72,944.8	95.7	59.9	292.6	406.1	472.5	9.795	1,336.6

*Adjustments include: international bunker fuel consumption (see Table A-8) and carbon stored in products (see Table A-9)
NA (Not Available)

Table A-6: 1991 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
	Consumption (TBtu)							Emissions (MMTCE) including Adjustments* and Fraction Oxidized						
Fuel Type	Res.	Comm.	Ind.	Trans.	Utility	Terr.	Total	Res.	Comm.	Ind.	Trans.	Utility	Terr.	Total
Residential Coal	56.3						56.3	1.4						1.4
Commercial Coal		84.5					84.5		2.2					2.2
Industrial Coking Coal			907.3				907.3			22.6				22.6
Industrial Other Coal			1,629.2				1,629.2			42.0				42.0
Coke Imports			8.9				8.9			0.2				0.2
Transportation Coal				0.0			0.0				0.0			0.0
Utility Coal					16,012.4		16,012.4					407.2		407.2
US Territory Coal (bit)						7.0	7.0						0.175	0.2
Total Coal	56.3	84.5	2,545.4	0.0	16,012.4	7.0	18,705.6	1.4	2.2	64.8	0.0	407.2	0.2	475.8
Natural Gas	4,685.0	2,807.7	8,637.2	621.5	2,853.6	NA	19,605.0	67.5	40.4	120.0	8.9	41.1	NA	277.9
Asphalt & Road Oil	0.0	0.0	1,076.5	0.0	0.0		1,076.5	0.0	0.0	(0.0)	0.0	0.0	0.000	(0.0)
Aviation Gasoline	0.0	0.0	0.0	41.7	0.0		41.7	0.0	0.0	0.0	0.8	0.0	0.000	0.8
Distillate Fuel Oil	831.5	481.6	1,139.2	3,677.6	80.0	72.2	6,282.1	16.4	9.5	22.5	70.5	1.6	1.426	121.9
Jet Fuel	0.0	0.0	0.0	3,025.0	0.0	80.8	3,105.8	0.0	0.0	0.0	53.0	0.0	1.551	54.6
Kerosene	72.3	12.1	11.4	0.0	0.0		95.8	1.4	0.2	0.2	0.0	0.0	0.000	1.9
LPG	389.5	68.7	1,749.3	19.9	0.0	13.7	2,241.1	6.5	1.2	10.9	0.3	0.0	0.233	19.1
Lubricants	0.0	0.0	166.7	157.5	0.0	0.0	324.2	0.0	0.0	1.7	1.6	0.0	0.000	3.2
Motor Gasoline	0.0	85.0	193.3	13,502.6	0.0	117.3	13,898.2	0.0	1.6	3.7	259.5	0.0	2.232	267.0
Residual Fuel	0.0	213.2	335.9	1,031.9	1,076.1	135.0	2,792.1	0.0	4.5	7.1	5.5	22.9	2.872	42.9
Other Petroleum						122.7	122.7						2.186	2.2
AvGas Blend Components			(0.1)				(0.1)			(0.0)				(0.0)
Crude Oil			38.9				38.9			0.8				0.8
MoGas Blend Components			(25.9)				(25.9)			(0.5)				(0.5)
Misc. Products			152.6				152.6			3.1				3.1
Naphtha (<401 deg. F)			298.9				298.9			5.4				5.4
Other Oil (>401 deg. F)			827.3				827.3			16.3				16.3
Pentanes Plus			294.0				294.0			4.7				4.7
Petrochemical Feedstocks			0.0				0.0			(12.2)				(12.2)
Petroleum Coke			700.2		21.7		722.0			17.1		0.6		17.7
Still Gas			1,426.6				1,426.6			24.7				24.7
Special Naphtha			88.0				88.0			1.7				1.7
Unfinished Oils			(450.2)				(450.2)			(9.0)				(9.0)
Waxes			35.1				35.1			0.7				0.7
Other Wax & Misc.			0.0				0.0			(4.4)				(4.4)
Total Petroleum	1,293.3	860.6	8,057.8	21,456.2	1,177.8	541.7	33,387.5	24.4	17.1	94.5	391.1	25.1	10.500	562.6
Geothermal					0.028		0.028					0.0574		0.0574
TOTAL (All Fuels)	6,034.6	3,752.8	19,240.4	22,077.7	20,043.8	548.7	71,698.1	93.3	59.7	279.3	400.1	473.5	10.675	1,316.4

*Adjustments include: international bunker fuel consumption (see Table A-8) and carbon stored in products (see Table A-9)
NA (Not Available)

Table A-7: 1990 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
	Consumption (TBtu)							Emissions (MMTCE) including Adjustments* and Fraction Oxidized						
Fuel Type	Res.	Comm.	Ind.	Trans.	Utility	Terr.	Total	Res.	Comm.	Ind.	Trans.	Utility	Terr.	Total
Residential Coal	61.9						61.9	1.6						1.6
Commercial Coal		92.9					92.9		2.4					2.4
Industrial Coking Coal			1,041.8				1,041.8			25.9				25.9
Industrial Other Coal			1,646.1				1,646.1			42.4				42.4
Coke Imports			4.8				4.8			0.1				0.1
Transportation Coal				0.0			0.0				0.0			0.0
Utility Coal					16,087.8		16,087.8					409.0		409.0
US Territory Coal (bit)						4.9	4.9						0.122	0.1
Total Coal	61.9	92.9	2,692.7	0.0	16,087.8	4.9	18,940.2	1.6	2.4	68.5	0.0	409.0	0.1	481.6
Natural Gas	4,518.7	2,698.1	8,519.7	682.4	2,861.4	NA	19,280.3	65.1	38.8	118.2	9.8	41.2	NA	273.1
Asphalt & Road Oil	0.0	0.0	1,170.2	0.0	0.0		1,170.2	0.0	0.0	0.0	0.0	0.0	0.000	0.0
Aviation Gasoline	0.0	0.0	0.0	45.0	0.0		45.0	0.0	0.0	0.0	0.8	0.0	0.000	0.8
Distillate Fuel Oil	837.4	487.0	1,180.9	3,830.5	86.3	73.9	6,496.0	16.5	9.6	23.3	73.4	1.7	1.459	126.1
Jet Fuel	0.0	0.0	0.0	3,129.5	0.0	63.5	3,193.0	0.0	0.0	0.0	55.0	0.0	1.220	56.3
Kerosene	63.9	11.8	12.3	0.0	0.0		88.0	1.2	0.2	0.2	0.0	0.0	0.000	1.7
LPG	365.0	64.4	1,607.7	21.8	0.0	14.4	2,073.3	6.1	1.1	10.9	0.4	0.0	0.244	18.7
Lubricants	0.0	0.0	186.3	176.0	0.0	0.8	363.1	0.0	0.0	1.9	1.8	0.0	0.008	3.6
Motor Gasoline	0.0	110.6	184.1	13,577.1	0.0	100.8	13,972.6	0.0	2.1	3.5	260.9	0.0	1.918	268.5
Residual Fuel	0.0	233.1	417.2	1,030.2	1,139.4	121.8	2,941.7	0.0	5.0	8.9	6.7	24.2	2.590	47.4
Other Petroleum						85.2	85.2						1.518	1.5
AvGas Blend Components			0.2				0.2			0.0				0.0
Crude Oil			50.9				50.9			1.0				1.0
MoGas Blend Components			53.7				53.7			1.0				1.0
Misc. Products			137.8				137.8			2.8				2.8
Naphtha (<401 deg. F)			347.8				347.8			6.2				6.2
Other Oil (>401 deg. F)			753.9				753.9			14.9				14.9
Pentanes Plus			250.3				250.3			3.3				3.3
Petrochemical Feedstocks			0.0				0.0			(12.1)				(12.1)
Petroleum Coke			719.9		24.7		744.6			17.3		0.7		18.0
Still Gas			1,473.2				1,473.2			25.5				25.5
Special Naphtha			107.1				107.1			2.1				2.1
Unfinished Oils			(369.0)				(369.0)			(7.4)				(7.4)
Waxes			33.3				33.3			0.7				0.7
Other Wax & Misc.			0.0				0.0			(3.9)				(3.9)
Total Petroleum	1,266.3	906.9	8,317.9	21,810.1	1,250.4	460.3	34,011.9	23.9	18.0	100.2	399.0	26.6	8.957	576.7
Geothermal					0.029		0.029					0.0595		0.0595
TOTAL (All Fuels)	5,846.9	3,697.9	19,530.3	22,492.5	20,199.6	465.2	72,232.4	90.6	59.2	286.8	408.9	476.9	9.079	1,331.4

*Adjustments include: international bunker fuel consumption (see Table A-8) and carbon stored in products (see Table A-9)
NA (Not Available)

Table A-8: 1996 Emissions From International Bunker Fuel Consumption

1	2	3	4	5	6
Fuel Type	Bunker Fuel Consumption (TBtu)	Carbon Content Coefficient (MMTCE/QBtu)[3]	Carbon Content (MMTCE)	Fraction Oxidized	Emissions (MMTCE)
Distillate Fuel	109	19.95	2	0.99	2
Jet Fuel	312	19.33	6	0.99	6
Residual Fuel	665	21.49	14	0.99	14
Total	1,085		22.5		22.3

Table A-9: 1996 Carbon Stored In Products

1	2	3	4	5	6	7	8	9	10
	Non-Fuel Use (TBtu)		Carbon Content Coefficient	Carbon Content (MMTCE)		Fraction Sequestered	Carbon Stored (MMTCE)		
Fuel Type	Ind.	Trans.	(MMTCE/QBtu)	Ind.	Trans.		Ind.	Trans.	Total
Industrial Coking Coal	28		25.53	0.7		0.75	0.532		0.532
Natural Gas	381		14.47	6		1.00	5.520		5.520
Asphalt & Road Oil	1,176		20.62	24		1.00	24.248		24.248
Distillate Fuel Oil	[a]		19.95	0		[a]	[a]		[a]
LPG	1,699		16.99	29		0.80	23.088		23.088
Lubricants	173	163	20.24	3	3	0.50	1.746	1.649	3.395
Residual Fuel	[a]		21.49	0		[a]	[a]		[a]
Naphtha (<401 deg. F)	[b]		18.14	0		[b]	[b]		[b]
Other Oil (>401 deg. F)	[b]		19.95	0		[b]	[b]		[b]
Pentanes Plus	319		18.24	6		0.80	4.651		4.651
Petrochemical Feedstocks	1,204		19.37	21		0.75	13.812		13.812
Petroleum Coke	208		27.85	6		0.50	2.897		2.897
Special Naphtha	75		19.86	1		0.00	0.000		0.000
Other Wax & Misc.	192		19.81	4		1.00	3.417		3.417
Total	5,453	163		101	3		79.9	1.6	81.6

[a] Non-fuel use values of distillate fuel and residual fuel were relatively small and included in the "Other Waxes and Misc." category.
[b] Non-fuel use values of Naphtha (<401 deg. F) and Other Oil (>401 deg. F) are reported in the "Petrochemical Feedstocks" category.

[3] One QBtu is one quadrillion Btu, or 10^{15} Btu. This unit is commonly referred to as a "Quad."

Table A-10: Key Assumptions for Estimating Carbon Dioxide Emissions

Fuel Type	Carbon Content Coefficient (MMTCE/QBtu)	Fraction Oxidized
Coal		
Residential Coal	[a]	0.99
Commercial Coal	[a]	0.99
Industrial Coking Coal	[a]	0.99
Industrial Other Coal	[a]	0.99
Coke Imports	27.85	0.99
Transportation Coal	NC	0.99
Utility Coal	[a]	0.99
U.S. Territory Coal (bit)	25.14	0.99
Natural Gas	14.47	0.995
Petroleum		
Asphalt & Road Oil	20.62	0.99
Aviation Gasoline	18.87	0.99
Distillate Fuel Oil	19.95	0.99
Jet Fuel	[a]	0.99
Kerosene	19.72	0.99
LPG	[a]	0.99
Lubricants	20.24	0.99
Motor Gasoline	[a]	0.99
Residual Fuel	21.49	0.99
Other Petroleum		
AvGas Blend Components	18.87	0.99
Crude Oil	[a]	0.99
MoGas Blend Components	19.39	0.99
Misc. Products	20.23	0.99
Naphtha (<401 deg. F)	18.14	0.99
Other Oil (>401 deg. F)	19.95	0.99
Pentanes Plus	18.24	0.99
Petrochemical Feedstocks	19.37	0.99
Petroleum Coke	27.85	0.99
Still Gas	17.51	0.99
Special Naphtha	19.86	0.99
Unfinished Oils	20.23	0.99
Waxes	19.81	0.99
Other Wax & Misc.	19.81	0.99
Geothermal	2.05	NA

Sources: Carbon Coefficients and stored carbon from EIA. Combustion efficiency for coal from Bechtel (1993) and for petroleum and natural gas from IPCC (IPCC/UNEP/OECD/IEA 1997, vol. 2).

NA (Not Applicable)

NC (Not Calculated)

[a] These coefficients vary annually due to fluctuations in fuel quality (see Table A-11).

Table A-11: Annually Variable Carbon Content Coefficients by Year (MMTCE/QBtu)

Fuel Type	1990	1991	1992	1993	1994	1995	1996
Residential Coal	25.92	26.00	26.13	25.97	25.95	26.00	26.00
Commercial Coal	25.92	26.00	26.13	25.97	25.95	26.00	26.00
Industrial Coking Coal	25.51	25.51	25.51	25.51	25.52	25.53	25.53
Industrial Other Coal	25.58	25.59	25.62	25.61	25.63	25.63	25.63
Utility Coal	25.68	25.69	25.69	25.71	25.72	25.74	25.74
LPG	16.99	16.98	16.99	16.97	17.01	17.00	16.99
Motor Gasoline	19.41	19.41	19.42	19.43	19.45	19.38	19.38
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33
Crude Oil	20.14	20.16	20.20	20.20	20.19	20.21	20.23

Source: EIA

Table A-12: Electricity Consumption by End-Use Sector (Billion Kilowatt-hours)

End-Use Sector	1990	1991	1992	1993	1994	1995	1996
Residential	924	955	936	995	1,008	1,043	1,078
Commercial	839	856	851	886	914	954	985
Industrial	946	947	973	977	1,008	1,013	1,017
Transportation	4	4	4	4	4	4	4
U.S. Territories*	-	-	-	-	-	-	-
Total	2,713	2,762	2,764	2,862	2,934	3,014	3,084

*EIA electric utility fuel consumption data does not include the U.S. territories.
- Not applicable
Source: EIA

Annex B

Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Stationary Sources

Estimates of CH_4 and N_2O Emissions from Stationary Combustion

Methane (CH_4) and nitrous oxide (N_2O) emissions from stationary source fossil fuel combustion were estimated using IPCC emission factors and methods. Estimates were obtained by multiplying emission factors (by sector and fuel type) by fossil fuel and wood consumption data. This "top-down" methodology is characterized by two basic steps, described below. Data are presented in Table B-1 through Table B-9. Changes in the methodology for this source are outlined at the end of this discussion.

Step 1: Determine Energy Consumption by Sector and Fuel Type

Greenhouse gas emissions from stationary combustion activities were grouped into four sectors: industrial, commercial/institutional, residential, and electric utilities. For CH_4 and N_2O, estimates were based upon consumption of coal, gas, oil, and wood. Energy consumption data were obtained from EIA's Monthly Energy Review (1997), and adjusted to lower heating values assuming a 10 percent reduction for natural gas and a 5 percent reduction for coal and petroleum fuels. Table B-1 provides annual energy consumption data for the years 1990 through 1996.

Step 2: Determine the Amount of CH_4 and N O Emitted

Activity data for each sector and fuel type were multiplied by emission factors to obtain emissions estimates. Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Table B-2 provides emission factors used for each sector and fuel type.

Estimates of NO , CO, and NMVOC Emissions from Stationary Combustion

For criteria pollutants, the major source categories included were those identified in EPA (1997): coal, fuel oil, natural gas, wood, other fuels (including bagasse, liquefied petroleum gases, coke, coke oven gas, and others), and stationary internal combustion (which includes emissions from internal combustion engines not used in transportation). EPA (1997) periodically estimates emissions of NO_x, CO, and NMVOCs by sector and fuel type using a "bottom-up" estimating procedure. In other words, the emissions were calculated either for individual sources (e.g., industrial boilers) or for many sources combined, using basic activity data (e.g., fuel consumption or deliveries, etc.) as indicators of emissions. EPA (1997) projected emissions for years subsequent to their bottom-up estimates. The national activity data used to calculate the individual categories were obtained from various sources. Depending upon the category, these activity data may include fuel consumption or deliveries of fuel, tons of refuse burned, raw material processed, etc. Activity data were used in conjunction with emission factors that relate the quantity of emissions to the activity. Table B-3 through Table B-9 present criteria pollutant emission estimates for 1990 through 1996.

The basic calculation procedure for most source categories presented in EPA (1997) is represented by the following equation:

$$E_{p,s} = A_s \times Ef_{p,s} \times (1 - C_{p,s}/100)$$

where,

E = emissions

p = pollutant

s = source category

A = activity level

EF = emission factor

C = percent control efficiency

The EPA currently derives the overall emission control efficiency of a category from a variety of sources, including published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of NO_x, CO, and NMVOCs from stationary combustion as described above is similar to the methodology recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

Differences with Previous Years' Inventories

In previous editions of the Inventory, methane emissions from stationary sources were calculated using a different methodology. Rather than using activity data and emission factors, CH_4 emissions were calculated as a ratio of NMVOC emissions. The accuracy of stationary source methane emissions have been improved in this year's inventory with the use of fuel type and end-use specific emission factors in place of the previous NMVOC ratio.

Table B-1: Fuel Consumption by Stationary Sources for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1991	1992	1993	1994	1995	1996
Coal	18,935.3	18,698.6	18,802.1	19,428.0	19,497.8	19,555.4	20,559.8
Residential	61.9	56.3	56.7	56.6	55.5	53.7	53.7
Commercial/Institutional	92.9	84.5	85.7	85.5	83.5	81.0	81.0
Industry	2,692.7	2,545.4	2,467.7	2,444.8	2,463.7	2,441.9	2,338.7
Utilities	16,087.8	16,012.4	16,192.0	16,841.1	16,895.2	16,978.9	18,086.4
Petroleum	11,741.5	11,389.6	11,696.4	11,641.5	11,928.7	11,465.9	12,132.3
Residential	1,266.3	1,293.3	1,312.4	1,387.0	1,340.4	1,363.0	1,441.6
Commercial/Institutional	906.9	860.6	813.3	752.8	753.3	756.8	775.8
Industry	8,317.9	8,057.8	8,637.7	8,449.6	8,866.8	8,688.1	9,179.5
Utilities	1,250.4	1,177.8	933.0	1,052.0	968.2	658.0	735.5
Natural Gas	18,597.9	18,983.5	19,530.2	20,224.9	20,631.3	21,507.3	21,777.8
Residential	4,518.7	4,685.0	4,821.1	5,097.5	4,988.3	4,981.3	5,375.8
Commercial/Institutional	2,698.1	2,807.7	2,884.2	2,995.8	2,980.8	3,185.2	3,289.9
Industry	8,519.7	8,637.2	8,996.4	9,387.4	9,609.3	10,064.3	10,311.3
Utilities	2,861.4	2,853.6	2,828.5	2,744.1	3,052.9	3,276.4	2,800.8
Wood	2,185.0	2,181.0	2,279.0	2,228.0	2,266.0	2,350.0	2,440
Residential	581.0	613.0	645.0	548.0	537.0	596.0	595.0
Commercial/Institutional	30.0	30.0	30.0	44.0	45.0	45.0	49.0
Industrial	1,562.0	1,528.0	1,593.0	1,625.0	1,673.0	1,698.0	1,784.0
Utilities	12.0	10.0	11.0	11.0	11.0	11.0	12.0

Table B-2: CH_4 and N_2O Emission Factors by Fuel Type and Sector (g/GJ)[4]

Fuel/End-Use Sector	CH_4	N_2O
Coal		
Residential	300	1.4
Commercial/Institutional	10	1.4
Industry	10	1.4
Utilities	1	1.4
Petroleum		
Residential	10	0.6
Commercial/Institutional	10	0.6
Industry	2	0.6
Utilities	3	0.6
Natural Gas		
Residential	5	0.1
Commercial/Institutional	5	0.1
Industry	5	0.1
Utilities	1	0.1
Wood		
Residential	300	4.0
Commercial/Institutional	300	4.0
Industrial	30	4.0
Utilities	30	4.0

[4] GJ (Gigajoule) = 10^9 joules. One joule = 9.486×10^{-4} Btu

Table B-3: 1996 NO_x, NMVOC, and CO Emissions from Stationary Sources (Gg)

Sector/Fuel Type	NO_x	NMVOC	CO
Electric Utilities	5,473	341	41
Coal	5,004	238	28
Fuel Oil	87	10	3
Natural gas	244	40	2
Wood	NA	NA	NA
Internal Combustion	137	53	9
Industrial	2,875	972	188
Coal	543	90	5
Fuel Oil	223	65	11
Natural gas	1,212	316	66
Wood	NA	NA	NA
Other Fuels[a]	113	277	46
Internal Combustion	784	224	60
Commercial/Institutional	366	227	21
Coal	35	14	1
Fuel Oil	93	17	3
Natural gas	212	49	10
Wood	NA	NA	NA
Other Fuels[a]	26	148	8
Residential	804	3,866	724
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	44	3,621	687
Other Fuels[a]	760	244	37
Total	9,518	5,407	975

NA (Not Available)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1997).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1997).
Note: Totals may not sum due to independent rounding.

Table B-4: 1995 NO_x, NMVOC, and CO Emissions from Stationary Sources (Gg)

Sector/Fuel Type	NO_x	NMVOC	CO
Electric Utilities	5,791	40	338
Coal	5,060	26	227
Fuel Oil	87	2	9
Natural gas	510	2	49
Wood	NA	NA	NA
Internal Combustion	134	9	52
Industrial	2,852	187	958
Coal	541	5	88
Fuel Oil	224	11	64
Natural gas	1,201	66	313
Wood	NA	NA	NA
Other Fuels[a]	111	45	270
Internal Combustion	774	59	222
Commercial/Institutional	365	21	211
Coal	35	1	14
Fuel Oil	94	3	17
Natural gas	210	10	49
Wood	NA	NA	NA
Other Fuels[a]	27	8	132
Residential	812	725	3,876
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	44	688	3,628
Other Fuels[a]	768	37	248
Total	9,820	973	5,382

NA (Not Available)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1997).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1997).
Note: Totals may not sum due to independent rounding.

Table B-5: 1994 NO_x, NMVOC, and CO Emissions from Stationary Sources (Gg)

Sector/Fuel Type	NO_x	NMVOC	CO
Electric Utilities	5,955	41	335
Coal	5,112	26	224
Fuel Oil	148	4	13
Natural gas	536	2	48
Wood	NA	NA	NA
Internal Combustion	159	9	50
Industrial	2,854	178	944
Coal	546	7	91
Fuel Oil	219	11	60
Natural gas	1,209	57	306
Wood	NA	NA	NA
Other Fuels[a]	113	45	260
Internal Combustion	767	58	228
Commercial/Institutional	365	21	212
Coal	36	1	13
Fuel Oil	86	3	16
Natural gas	215	10	49
Wood	NA	NA	NA
Other Fuels[a]	28	8	134
Residential	817	657	3,514
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	40	621	3,271
Other Fuels[a]	777	36	243
Total	9,990	897	5,006

NA (Not Available)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1997).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1997).
Note: Totals may not sum due to independent rounding.

Table B-6: 1993 NO_x, NMVOC, and CO Emissions from Stationary Sources (Gg)

Sector/Fuel Type	NO_x	NMVOC	CO
Electric Utilities	6,033	41	329
Coal	5,210	26	223
Fuel Oil	163	4	15
Natural gas	500	2	45
Wood	NA	NA	NA
Internal Combustion	160	9	46
Industrial	2,858	169	946
Coal	534	5	92
Fuel Oil	222	11	60
Natural gas	1,206	46	292
Wood	NA	NA	NA
Other Fuels[a]	113	46	259
Internal Combustion	782	60	243
Commercial/Institutional	360	22	207
Coal	37	1	14
Fuel Oil	84	3	16
Natural gas	211	10	48
Wood	NA	NA	NA
Other Fuels[a]	28	8	129
Residential	827	670	3,585
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	40	633	3,337
Other Fuels[a]	786	36	248
Total	10,077	901	5,067

NA (Not Available)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1997).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1997).
Note: Totals may not sum due to independent rounding.

Table B-7: 1992 NO_x, NMVOC, and CO Emissions from Stationary Sources (Gg)

Sector/Fuel Type	NO_x	NMVOC	CO
Electric Utilities	**5,899**	**40**	**318**
Coal	5,060	25	214
Fuel Oil	154	4	14
Natural gas	526	2	47
Wood	NA	NA	NA
Internal Combustion	159	9	43
Industrial	**2,785**	**169**	**866**
Coal	521	7	92
Fuel Oil	222	11	58
Natural gas	1,180	47	272
Wood	NA	NA	NA
Other Fuels[a]	115	45	239
Internal Combustion	748	60	205
Commercial/Institutional	**348**	**20**	**204**
Coal	35	1	13
Fuel Oil	84	3	16
Natural gas	204	9	46
Wood	NA	NA	NA
Other Fuels[a]	25	7	128
Residential	**879**	**782**	**4,194**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	48	746	3,929
Other Fuels[a]	831	36	265
Total	**9,912**	**1,010**	**5,582**

NA (Not Available)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1997).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1997).
Note: Totals may not sum due to independent rounding.

Table B-8: 1991 NO_x, NMVOC, and CO Emissions from Stationary Sources (Gg)

Sector/Fuel Type	NO_x	NMVOC	CO
Electric Utilities	**5,913**	**40**	**317**
Coal	5,042	25	212
Fuel Oil	192	5	17
Natural gas	526	2	46
Wood	NA	NA	NA
Internal Combustion	152	9	41
Industrial	**2,702**	**177**	**834**
Coal	517	5	92
Fuel Oil	215	10	54
Natural gas	1,134	54	257
Wood	NA	NA	NA
Other Fuels[a]	117	47	242
Internal Combustion	720	61	189
Commercial/Institutional	**333**	**18**	**196**
Coal	33	1	13
Fuel Oil	80	2	16
Natural gas	191	8	40
Wood	NA	NA	NA
Other Fuels[a]	29	7	128
Residential	**829**	**739**	**3,964**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	45	704	3,710
Other Fuels[a]	784	35	254
Total	**9,777**	**975**	**5,312**

NA (Not Available)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1997).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1997).
Note: Totals may not sum due to independent rounding.

Table B-9: 1990 NO_x, NMVOC, and CO Emissions from Stationary Sources (Gg)

Sector/Fuel Type	NO_x	NMVOC	CO
Electric Utilities	**6,043**	**43**	**329**
Coal	5,117	25	213
Fuel Oil	200	5	18
Natural gas	513	2	46
Wood	NA	NA	NA
Internal Combustion	213	11	52
Industrial	**2,753**	**165**	**797**
Coal	530	7	95
Fuel Oil	240	11	67
Natural gas	1,072	52	205
Wood	NA	NA	NA
Other Fuels[a]	119	46	253
Internal Combustion	792	49	177
Commercial/Institutional	**336**	**18**	**205**
Coal	36	1	13
Fuel Oil	88	3	16
Natural gas	181	7	40
Wood	NA	NA	NA
Other Fuels[a]	31	8	136
Residential	**749**	**686**	**3,667**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	42	651	3,429
Other Fuels[a]	707	35	238
Total	**9,881**	**912**	**4,998**

NA (Not Available)

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 1997).

[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 1997).

Note: Totals may not sum due to independent rounding.

Annex C

Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Mobile Sources

Estimates of CH_4 and N_2O Emissions from Mobile Combustion

Greenhouse gas emissions from mobile sources are reported by transport mode (e.g., road, rail, air, and water), vehicle type, and fuel. EPA does not systematically track emissions of CH_4 and N_2O; therefore, estimates of these gases were developed using a methodology similar to that outlined in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Step 1: Determine Vehicle Miles Traveled or Fuel Consumption by Vehicle Type, Fuel Type, and Model Year

Activity data were obtained from a number of U.S. government agency publications. Depending on the category, these basic activity data included such information as fuel consumption, fuel deliveries, and vehicle miles traveled (VMT). The activity data for highway vehicles included estimates of VMT by vehicle type and model year from EPA (1997a) and the MOBILE5a emissions model (EPA 1997b).

National VMT data for gasoline and diesel highway vehicles are presented in Table C-1 and Table C-2, respectively. Total VMT for each highway category (i.e., gasoline passenger cars, light-duty gasoline trucks, heavy-duty gasoline vehicles, diesel passenger cars, light-duty diesel trucks, heavy-duty diesel vehicles, and motorcycles) were distributed across 25 model years based on the temporally fixed age distribution of VMT by the U.S. vehicle fleet in 1990 (see Table C-3) as specified in MOBILE5a. Activity data for gasoline passenger cars and light-duty trucks in California were developed separately due to the different emission control technologies deployed in that state relative to the rest of the country. Unlike the rest of the United States, beginning in model year 1994, a fraction of the California VMT for gasoline passenger cars and light-duty trucks was attributed to for low emission vehicles (LEVs). LEVs have not yet been widely deployed in other states. Based upon U.S. Department of Transportation statistics for 1994, it was assumed that 8.7 percent of national VMT occurred in California.

Activity data for non-highway vehicles were based on annual fuel consumption statistics by transportation mode and fuel type. Consumption data for distillate and residual fuel oil by ocean-going ships (i.e., marine bunkers), boats, construction equipment, farm equipment, and locomotives were obtained from EIA (1997). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from FAA (1997). Consumption of motor gasoline by boats, construction equipment, farm equipment, and locomotives data were drawn from FHWA (1997). The activity data used for non-highway vehicles are included in Table C-4.

Step 2: Allocate VMT Data to Control Technology Type for Highway Vehicles

For highway sources, VMT by vehicle type for each model year were distributed across various control technologies as shown in Table C-5, Table C-6, Table C-7, Table C-8, and Table C-9. Again, California gasoline-fueled passenger cars and light-duty trucks were treated separately due to that state's distinct mobile source emission standards—including the introduction of LEVs in 1994—compared with the rest of the United States. The categories "Tier 0" and "Tier 1" have been substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. Tier 0, Tier 1, and LEV are actually U.S. emission regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. Tier 1 and its predecessor Tier 0 both apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and "advance three-way catalysts" as described in the *Revised 1996 IPCC Guidelines*, roughly correspond to the introduction of Tier 0 and Tier 1 regulations (EPA 1998).

Step 3: Determine the Amount of CH_4 and N_2O Emitted by Vehicle, Fuel, and Control Technology Type

Emissions of CH_4 from mobile source combustion were calculated by multiplying emission factors in IPCC/UNEP/OECD/IEA (1997) by activity data for each vehicle type as described in Step 1 (see Table C-10 and Table C-11). The CH_4 emission factors for highway sources were derived from EPA's MOBILE5a mobile source emissions model (EPA 1997b). The MOBILE5a model uses information on ambient temperature, diurnal temperature range, altitude, vehicle speeds, national vehicle registration distributions, gasoline volatility, emission control technologies, fuel composition, and the presence or absence of vehicle inspection/maintenance programs in order to produce these factors.

Emissions of N_2O—in contrast to CH_4, CO, NO_x, and NMVOCs—have not been extensively studied and are currently not well characterized. The limited number of studies that have been done on highway vehicle emissions of N_2O have shown that emissions are generally greater from vehicles with catalytic converter systems than those without such controls, and greater from aged than from new catalysts. These systems control tailpipe emissions of NO_x (i.e., NO and NO_2) by catalytically reducing NO_x to N_2. Suboptimal catalyst performance, caused by as yet poorly understood factors, results in incomplete reduction and the conversion of some NO_x to N_2O rather than to N_2. Fortunately, newer vehicles with catalyst and engine designs meeting the more recent Tier 1 and LEV standards have shown reduced emission rates of both NO_x and N_2O.

In order to better characterize the process by which N_2O is formed by catalytic controls and to develop a more accurate national emission estimate, the EPA's Office of Mobile Sources—at its National Vehicle and Fuel Emissions Laboratory (NVFEL)—recently conducted a series of tests in order to measure emission rates of N_2O from used Tier 1 and LEV gasoline-fueled passenger cars and light-duty trucks equipped with catalytic converters. These tests and a review of the literature were used to develop the emission factors for nitrous oxide used in this inventory (EPA 1998). The following references were used in developing the N_2O emission factors for gasoline-fueled highway passenger cars presented in Table C-10:

- *LEVs*. Tests performed at NVFEL (EPA 1998)[5]
- *Tier 1*. Tests performed at NVFEL (EPA 1988)
- *Tier 0*. Smith and Carey (1982), Barton and Simpson (1994), and one car tested at NVFEL (EPA 1998)
- *Oxidation Catalyst*. Smith and Carey (1982), Urban and Garbe (1979)
- *Non-Catalyst*. Prigent and de Soete (1989), Dasch (1992), and Urban and Garbe (1979)

Nitrous oxide emission factors for other types of gasoline-fueled vehicles—light-duty trucks, heavy-duty vehicles, and motorcycles—were estimated by adjusting the factors for gasoline passenger cars, as described above, by their relative fuel economies. This adjustment was performed using the carbon dioxide emission rates in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) as a proxy for fuel economy (see Table C-10). Data from the literature and tests performed at NVFEL support the conclusion that light-duty trucks have higher emission rates than passenger cars. However, the use of fuel-consumption ratios to determine emission factors is considered a temporary measure only, to be replaced as soon as real data are available.

The resulting N_2O emission factors employed for gasoline highway vehicles are lower than the U.S. default values presented in the *Revised 1996 IPCC Guidelines*, but are higher than the European default values, both of which were published before the more recent tests and literature review conducted by the NVFEL. The U.S. defaults in the *Guidelines* were based on three studies that tested a total of five cars using European rather than U.S. test procedures. Nitrous oxide emission factors for diesel highway vehicles were taken from the European default values found in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). There is little data addressing N_2O emissions from U.S. diesel-fueled vehicles, and in general, European countries have had more experience with diesel-fueled vehicles. U.S. default values in the *Revised 1996 IPCC Guidelines* were used for non-highway vehicles.

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5 It was assumed that LEVs would be operated using low-sulfur fuel (i.e., Indolene at 24 ppm sulfur). All other NVFEL tests were performed using a standard commercial fuel (CAAB at 285 ppm sulfur). Emission tests by NVFEL have consistently exhibited higher N_2O emission rates from higher sulfur fuels on Tier 1 and LEV vehicles.

Compared to regulated tailpipe emissions, there is relatively little data available to estimate emission factors for nitrous oxide. Nitrous oxide is not a criteria pollutant, and measurements of it in automobile exhaust have not been routinely collected. Further testing is needed to reduce the uncertainty in nitrous oxide emission factors for all classes of vehicles, using realistic driving regimes, environmental conditions, and fuels.

Estimates of NO_x, CO, and NMVOC Emissions From Mobile Combustion

The emission estimates of NO_x, CO, and NMVOCs for mobile sources were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900 - 1996* (EPA 1997a). This EPA report provides emission estimates for these gases by sector and fuel type using a "top down" estimating procedure whereby emissions were calculated using basic activity data, such as amount of fuel delivered or miles traveled, as indicators of emissions. Table C-12 through Table C-18 provide complete emissions estimates for 1990 through 1996.

Table C-1: Vehicle Miles Traveled for Gasoline Highway Vehicles (10^9 Miles)

Year	Passenger Cars[a]	Light-Duty Trucks[a]	Heavy-Duty Vehicles	Motorcycles	Passenger Cars (CA)[b]	Light-Duty Trucks (CA)[b]
1990	1362.75	422.09	43.32	9.57	129.86	40.22
1991	1381.11	428.12	43.60	9.20	131.61	40.80
1992	1437.57	431.76	43.39	9.55	136.99	41.14
1993	1462.88	450.30	45.96	9.89	139.40	42.91
1994	1426.55	531.21	49.67	10.25	135.94	50.62
1995	1466.04	545.90	51.04	10.52	139.70	52.02
1996	1492.35	555.84	52.00	10.73	142.21	52.97

[a] Excludes California
[b] California VMT for passenger cars and light-duty trucks was treated separately and estimated as 8.7 percent of national total.
Source: VMT data are the same as those used in EPA (1997a).

Table C-2: Vehicle Miles Traveled for Diesel Highway Vehicles (10^9 Miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles
1990	20.59	3.77	112.20
1991	20.87	3.84	112.91
1992	21.72	3.92	114.95
1993	22.09	4.08	119.61
1994	21.55	4.82	126.99
1995	22.14	4.95	130.50
1996	22.55	5.05	132.95

Source: VMT data are the same as those used in EPA (1997a).

Table C-3: VMT Profile by Vehicle Age (years) and Vehicle/Fuel Type for Highway Vehicles (percent of VMT)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
1	4.9%	6.3%	2.3%	4.9%	6.3%	3.4%	14.4%
2	7.9%	8.4%	4.7%	7.9%	8.4%	6.7%	16.8%
3	8.3%	8.4%	4.7%	8.3%	8.4%	6.7%	13.5%
4	8.2%	8.4%	4.7%	8.2%	8.4%	6.7%	10.9%
5	8.4%	8.4%	4.7%	8.4%	8.4%	6.7%	8.8%
6	8.1%	6.9%	3.8%	8.1%	6.9%	7.3%	7.0%
7	7.7%	5.9%	3.3%	7.7%	5.9%	6.1%	5.6%
8	5.6%	4.4%	2.1%	5.6%	4.4%	4.0%	4.5%
9	5.0%	3.6%	2.6%	5.0%	3.6%	4.1%	3.6%
10	5.1%	3.1%	2.9%	5.1%	3.1%	5.1%	2.9%
11	5.0%	3.0%	3.4%	5.0%	3.0%	5.3%	2.3%
12	5.4%	5.3%	6.4%	5.4%	5.3%	6.6%	9.7%
13	4.7%	4.7%	5.4%	4.7%	4.7%	5.5%	0%
14	3.7%	4.6%	5.8%	3.7%	4.6%	5.7%	0%
15	2.4%	3.6%	5.1%	2.4%	3.6%	4.5%	0%
16	1.9%	2.8%	3.8%	1.9%	2.8%	1.9%	0%
17	1.4%	1.7%	4.3%	1.4%	1.7%	2.3%	0%
18	1.5%	2.2%	4.1%	1.5%	2.2%	2.8%	0%
19	1.1%	1.7%	3.5%	1.1%	1.7%	2.4%	0%
20	0.8%	1.4%	2.9%	0.8%	1.4%	1.6%	0%
21	0.6%	0.9%	2.1%	0.6%	0.9%	1.1%	0%
22	0.5%	0.8%	2.2%	0.5%	0.8%	0.9%	0%
23	0.4%	0.8%	2.2%	0.4%	0.8%	0.7%	0%
24	0.3%	0.5%	1.4%	0.3%	0.5%	0.5%	0%
25	1.0%	2.5%	11.7%	1.0%	2.5%	1.6%	0%

LDGV (gasoline passenger cars, also referred to as light-duty gas vehicles)
LDGT (light-duty gas trucks)
HDGV (heavy-duty gas vehicles)
LDDV (diesel passenger cars, also referred to as light-duty diesel vehicles)
LDDT (light-duty diesel trucks)
HDDV (heavy-duty diesel vehicles)
MC (motorcycles)

Table C-4: Fuel Consumption for Non-Highway Vehicles by Fuel Type (U.S. Gallons)

Vehicle Type/Year	Residual	Diesel	Jet Fuel	Other
Aircraft[a]				
1990	-	-	12,986,111,661	353,100,000
1991	-	-	11,995,880,426	353,600,000
1992	-	-	12,279,912,686	314,000,000
1993	-	-	12,326,549,428	268,400,000
1994	-	-	12,855,125,825	264,100,000
1995	-	-	13,140,841,990	258,100,000
1996	-	-	13,677,564,463	275,800,000
Marine Bunkers				
1990	4,686,071,250	549,251,000	-	-
1991	5,089,541,250	541,910,000	-	-
1992	5,399,308,500	560,042,500	-	-
1993	4,702,411,500	510,936,250	-	-
1994	4,458,628,500	506,724,750	-	-
1995	4,823,428,500	494,526,250	-	-
1996	4,353,732,750	544,402,000	-	-
Boats[b]				
1990	1,562,023,750	1,647,753,000	-	1,300,400,000
1991	1,696,513,750	1,625,730,000	-	1,709,700,000
1992	1,799,769,500	1,680,127,500	-	1,316,170,000
1993	1,567,470,500	1,532,808,750	-	873,687,000
1994	1,486,209,500	1,520,174,250	-	896,700,000
1995	1,607,809,500	1,483,578,750	-	1,060,394,000
1996	1,451,244,250	1,633,206,000	-	1,060,394,000
Construction Equipment[c]				
1990	-	2,508,300,000	-	1,523,600,000
1991	-	2,447,400,000	-	1,384,900,000
1992	-	2,287,642,000	-	1,492,200,000
1993	-	2,323,183,000	-	1,464,599,000
1994	-	2,437,142,000	-	1,492,152,000
1995	-	2,273,162,000	-	1,499,346,000
1996	-	2,386,973,000	-	1,499,346,000
Farm Equipment				
1990	-	3,164,200,000	-	812,800,000
1991	-	3,144,200,000	-	776,200,000
1992	-	3,274,811,000	-	805,500,000
1993	-	3,077,122,000	-	845,320,000
1994	-	3,062,436,000	-	911,996,000
1995	-	3,093,224,000	-	926,732,000
1996	-	3,225,029,000	-	926,732,000
Locomotives				
1990	25,422	3,210,111,000	-	-
1991	6,845	3,026,292,000	-	-
1992	8,343	3,217,231,000	-	-
1993	4,065	2,906,998,000	-	-
1994	5,956	3,063,441,000	-	-
1995	6,498	3,191,023,000	-	-
1996	6,498	3,266,861,000	-	-

- Not applicable

Sources: FWHA 1997, EIA 1997, and FAA 1997.

[a] Other Fuel = Aviation Gasoline.

[b] Other Fuel = Motor Gasoline

[c] Construction Equipment includes snowmobiles. Other Fuel = Motor Gasoline

Table C-5: Control Technology Assignments for Gasoline Passenger Cars (percentage of VMT)*

Model Years	Uncontrolled	Non-catalyst	Oxidation	Tier 0	Tier 1
≤1972	100%				
1973-1974		100%			
1975		20%	80%		
1976-1977		15%	85%		
1978-1979		10%	90%		
1980		5%	88%	7%	
1981			15%	85%	
1982			14%	86%	
1983			12%	88%	
1984-1993				100%	
1994				60%	40%
1995				20%	80%
1996					100%

* Excluding California VMT

Table C-6: Control Technology Assignments for Gasoline Light-Duty Trucks (percentage of VMT)*

Model Years	Uncontrolled	Non-catalyst	Oxidation	Tier 0	Tier 1
≤1972	100%				
1973-1974		100%			
1975		30%	70%		
1976		20%	80%		
1977-1978		25%	75%		
1979-1980		20%	80%		
1981			95%	5%	
1982			90%	10%	
1983			80%	20%	
1984			70%	30%	
1985			60%	40%	
1986			50%	50%	
1987-1993			5%	95%	
1994				60%	40%
1995				20%	80%
1996					100%

* Excluding California VMT

Table C-7: Control Technology Assignments for California Gasoline Passenger Cars and Light-Duty Trucks (percentage of VMT)

Model Years	Uncontrolled	Non-catalyst	Oxidation	Tier 0	Tier 1	LEV
≤1972	100%					
1973-1974		100%				
1975-1979			100%			
1980-1981			15%	85%		
1982			14%	86%		
1983			12%	88%		
1984-1991				100%		
1992				60%	40%	
1993				20%	80%	
1994					90%	10%
1995					85%	15%
1996					80%	20%

Table C-8: Control Technology Assignments for Gasoline Heavy-Duty Vehicles (percentage of VMT)

Model Years	Uncontrolled	Non-catalyst	Oxidation	Tier 0
≤1981	100%			
1982-1984	95%		5%	
1985-1986		95%	5%	
1987		70%	15%	15%
1988-1989		60%	25%	15%
1990-2003		45%	30%	25%
2004				100%

Table C-9: Control Technology Assignments for Diesel Highway VMT

Vehicle Type/Control Technology	Model Years
Diesel Passenger Cars and Light-Duty Trucks	
Uncontrolled	1966-1982
Moderate control	1983-1995
Advanced control	1996
Heavy-Duty Diesel Vehicles	
Uncontrolled	1966-1972
Moderate control	1983-1995
Advanced control	1996
Motorcycles	
Uncontrolled	1966-1995
Non-catalyst controls	1996

* California VMT only

Table C-10: Emission Factors (g/km) for CH_4 and N_2O and "Fuel Economy" (g CO_2/km)[c] for Highway Mobile Sources

Vehicle Type/Control Technology	N_2O	CH_4	g CO_2/km
Gasoline Passenger Cars			
Low Emission Vehicles[a]	0.0176	0.025	280
Tier 1	0.0288	0.030	285
Tier 0	0.0507	0.040	298
Oxidation Catalyst	0.0322	0.070	383
Non-Catalyst	0.0103	0.120	531
Uncontrolled	0.0103	0.135	506
Gasoline Light-Duty Trucks			
Low Emission Vehicles[a]	0.0249	0.030	396
Tier 1	0.0400	0.035	396
Tier 0	0.0846	0.070	498
Oxidation Catalyst	0.0418	0.090	498
Non-Catalyst	0.0117	0.140	601
Uncontrolled	0.0118	0.135	579
Gasoline Heavy-Duty Vehicles			
Tier 0	0.1729	0.075	1,017
Oxidation Catalyst[b]	0.0870	0.090	1,036
Non-Catalyst Control	0.0256	0.125	1,320
Uncontrolled	0.0269	0.270	1,320
Diesel Passenger Cars			
Advanced	0.0100	0.01	237
Moderate	0.0100	0.01	248
Uncontrolled	0.0100	0.01	319
Diesel Light Trucks			
Advanced	0.0200	0.01	330
Moderate	0.0200	0.01	331
Uncontrolled	0.0200	0.01	415
Diesel Heavy-Duty Vehicles			
Advanced	0.0300	0.04	987
Moderate	0.0300	0.05	1,011
Uncontrolled	0.0300	0.06	1,097
Motorcycles			
Non-Catalyst Control	0.0042	0.26	219
Uncontrolled	0.0054	0.13	266

[a] Applied to California VMT only

[b] Methane emission factor assumed based on light-duty trucks oxidation catalyst value

[c] The carbon emission factor (g CO_2/km) was used as a proxy for fuel economy because of the greater number of significant figures compared to the km/L values presented in (IPCC/UNEP/OECD/IEA 1997).

NA (Not Available)

Table C-11: Emission Factors for CH_4 and N_2O Emissions from Non-Highway Mobile Sources (g/kg fuel)

Vehicle Type/Fuel Type	N_2O	CH_4
Marine Bunkers (Ocean-Going Ships)		
Residual*	0.08	0.3
Distillate*	0.08	0.3
Boats		
Residual	0.08	0.23
Distillate	0.08	0.23
Gasoline	0.08	0.23
Locomotives		
Residual	0.08	0.25
Diesel	0.08	0.25
Coal	0.08	0.25
Farm Equipment		
Gas/Tractor	0.08	0.45
Other Gas	0.08	0.45
Diesel/Tractor	0.08	0.45
Other Diesel	0.08	0.45
Construction		
Gas Construction	0.08	0.18
Diesel Construction	0.08	0.18
Other Non-Highway		
Gas Snowmobile	0.08	0.18
Gas Small Utility	0.08	0.18
Gas HD Utility	0.08	0.18
Diesel HD Utility	0.08	0.18
Aircraft		
Jet Fuel	NA	0.087
Av. Gas	0.04	2.64

* Methane emission factor value assumed based on value of diesel heavy oil in (IPCC/UNEP/OECD/IEA 1997)
NA (Not Available)

Table C-12: 1996 Emissions of NO_x, CO, and NMVOC from Mobile Sources (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,752**	**46,712**	**4,709**
Passenger Cars	3,075	29,883	2,979
Light-Duty Trucks	1,370	13,377	1,435
Heavy-Duty Vehicles	295	3,267	259
Motorcycles	12	185	35
Diesel Highway	**1,753**	**1,318**	**283**
Passenger Cars	35	30	12
Light-Duty Trucks	9	7	4
Heavy-Duty Vehicles	1,709	1,280	267
Non-Highway	**4,183**	**15,424**	**2,201**
Boats and Vessels	244	1,684	460
Locomotives	836	102	44
Farm Equipment	1,012	901	207
Construction Equipment	1,262	1,066	184
Aircraft	151	861	161
Other*	678	10,810	1,144
Total	**10,688**	**63,455**	**7,192**

* "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.

Note: Totals may not sum due to independent rounding.

Table C-13: 1995 Emissions of NO_x, CO, and NMVOC from Mobile Sources (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,804**	**47,767**	**4,883**
Passenger Cars	3,112	30,391	3,071
Light-Duty Trucks	1,378	13,453	1,478
Heavy-Duty Vehicles	301	3,741	297
Motorcycles	12	182	37
Diesel Highway	**1,839**	**1,318**	**290**
Passenger Cars	35	30	12
Light-Duty Trucks	9	7	4
Heavy-Duty Vehicles	1,795	1,281	274
Non-Highway	**4,241**	**15,278**	**2,207**
Boats and Vessels	244	1,674	436
Locomotives	898	103	45
Farm Equipment	1,007	885	207
Construction Equipment	1,265	1,053	184
Aircraft	150	855	161
Other*	678	10,709	1,175
Total	**10,884**	**64,363**	**7,380**

* "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.

Note: Totals may not sum due to independent rounding.

Table C-14: 1994 Emissions of NO_x, CO, and NMVOC from Mobile Sources (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**5,063**	**54,778**	**5,507**
Passenger Cars	3,230	33,850	3,367
Light-Duty Trucks	1,503	15,739	1,731
Heavy-Duty Vehicles	318	5,013	375
Motorcycles	11	177	33
Diesel Highway	**1,897**	**1,316**	**300**
Passenger Cars	35	29	12
Light-Duty Trucks	9	7	4
Heavy-Duty Vehicles	1,854	1,280	284
Non-Highway	**4,485**	**15,308**	**2,376**
Boats and Vessels	233	1,663	575
Locomotives	859	104	45
Farm Equipment	1,113	998	229
Construction Equipment	1,443	1,146	204
Aircraft	146	830	159
Other*	692	10,566	1,164
Total	**11,445**	**71,402**	**8,184**

* "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.

Note: Totals may not sum due to independent rounding.

Table C-15: 1993 Emissions of NO_x, CO, and NMVOC from Mobile Sources (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,913**	**53,375**	**5,248**
Passenger Cars	3,327	35,357	3,427
Light-Duty Trucks	1,289	13,786	1,494
Heavy-Duty Vehicles	286	4,061	296
Motorcycles	11	172	31
Diesel Highway	**1,900**	**1,240**	**288**
Passenger Cars	36	30	12
Light-Duty Trucks	7	6	3
Heavy-Duty Vehicles	1,857	1,205	273
Non-Highway	**4,332**	**15,053**	**2,341**
Boats and Vessels	230	1,651	571
Locomotives	857	108	47
Farm Equipment	1,090	1,011	226
Construction Equipment	1,344	1,061	190
Aircraft	142	821	160
Other*	669	10,400	1,148
Total	**11,145**	**69,668**	**7,878**

* "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.

Note: Totals may not sum due to independent rounding.

Table C-16: 1992 Emissions of NO_x, CO, and NMVOC from Mobile Sources (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,788**	**53,077**	**5,220**
Passenger Cars	3,268	35,554	3,447
Light-Duty Trucks	1,230	13,215	1,440
Heavy-Duty Vehicles	280	4,145	303
Motorcycles	11	163	30
Diesel Highway	**1,962**	**1,227**	**288**
Passenger Cars	35	28	12
Light-Duty Trucks	7	6	3
Heavy-Duty Vehicles	1,920	1,193	274
Non-Highway	**4,226**	**14,855**	**2,314**
Boats and Vessels	239	1,639	568
Locomotives	858	113	49
Farm Equipment	1,078	993	223
Construction Equipment	1,256	999	178
Aircraft	142	818	162
Other*	653	10,293	1,134
Total	**10,975**	**69,158**	**7,822**

* "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.
Note: Totals may not sum due to independent rounding.

Table C-17: 1991 Emissions of NO_x, CO, and NMVOC from Mobile Sources (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,654**	**55,104**	**5,607**
Passenger Cars	3,133	36,369	3,658
Light-Duty Trucks	1,215	13,621	1,531
Heavy-Duty Vehicles	296	4,953	384
Motorcycles	10	161	33
Diesel Highway	**2,035**	**1,210**	**290**
Passenger Cars	34	27	11
Light-Duty Trucks	7	5	3
Heavy-Duty Vehicles	1,995	1,177	276
Non-Highway	**4,099**	**14,551**	**2,271**
Boats and Vessels	246	1,624	563
Locomotives	842	109	47
Farm Equipment	1,035	935	213
Construction Equipment	1,197	961	171
Aircraft	141	806	161
Other*	638	10,116	1,116
Total	**10,788**	**70,865**	**8,167**

* "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.
Note: Totals may not sum due to independent rounding.

Table C-18: 1990 Emissions of NO_x, CO, and NMVOC from Mobile Sources (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,356**	**51,332**	**5,444**
Passenger Cars	2,910	33,746	3,524
Light-Duty Trucks	1,140	12,534	1,471
Heavy-Duty Vehicles	296	4,863	392
Motorcycles	11	190	56
Diesel Highway	**2,031**	**1,147**	**283**
Passenger Cars	35	28	11
Light-Duty Trucks	6	5	2
Heavy-Duty Vehicles	1,989	1,115	269
Non-Highway	**4,167**	**14,622**	**2,270**
Boats and Vessels	235	1,600	555
Locomotives	843	110	48
Farm Equipment	1,028	969	214
Construction Equipment	1,268	1,023	181
Aircraft	143	820	163
Other*	650	10,099	1,109
Total	**10,554**	**67,101**	**7,997**

* "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.

Note: Totals may not sum due to independent rounding.

Annex D

Methodology for Estimating Methane Emissions from Coal Mining

The methodology for estimating methane emissions from coal mining consists of two distinct steps. The first step addresses emissions from underground mines. For these mines, emissions were estimated on a mine-by-mine basis and then are summed to determine total emissions. The second step of the analysis involved estimating methane emissions for surface mines and post-mining activities. In contrast to the methodology for underground mines, which used mine-specific data, the methodology for estimating emissions from surface mines and post-mining activities consists of multiplying basin-specific coal production by basin specific emissions factors.

Step 1: Estimate Methane Liberated and Methane Emitted from Underground Mines

Underground mines liberate methane from ventilation systems and from degasification systems. Some mines recover and use methane liberated from degasification systems, thereby reducing methane emissions to the atmosphere. Total methane emitted from underground mines equals methane liberated from ventilation systems, plus methane liberated from degasification systems, minus methane recovered and used.

Step 1.1 Estimate Methane Liberated from Ventilation Systems

All coal mines use ventilation systems for several air quality purposes and to ensure that methane levels remain within safe concentrations. Many coal mines do not have detectable methane emissions, while others emit several million cubic feet per day (MMCFD) from their ventilation systems. On a quarterly basis, the U.S. Mine Safety and Health Administration (MSHA) measures methane emissions levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of methane in their ventilation air.[6] Based on the four quarterly measurements, MSHA estimates average daily methane liberated at each of the underground mines with detectable emissions.

For the years 1990 through 1996, EPA obtained MSHA emissions data for a large but incomplete subset all mines with detectable emissions. This subset includes mines emitting at least 0.1 MMCFD for some years and at least 0.5 MMCFD for other years, as shown in Table D-1. Well over 90 percent of all ventilation emissions are concentrated in these subsets. For 1997, EPA obtained the complete MSHA database for all 586 mines with detectable methane emissions. These mines were assumed to account for 100 percent of methane liberated from underground mines.

Using this complete 1997 database, the portion of total emissions accounted for by mines emitting more and less than 0.1 MMCFD or 0.5 MMCFD was estimated. (see Table D-1). These proportions were then applied to the years 1990 through 1996 to account for the less than 10 percent of mines without MSHA data.

Average daily methane emissions were multiplied by 365 days per year to determine annual emissions for each mine. Total ventilation emissions for these mines were estimated by summing emissions from individual mines.

[6] MSHA records coal mine methane readings with concentrations of greater than 50 ppm (parts per million) methane. Readings below this threshold are considered non-detectable.

Table D-1: Mine-Specific Data Used to Estimate Ventilation Emissions

Year	Individual Mine Data Used
1990	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
1991	1990 Emissions Factors Used Instead of Mine Specific Data
1992	1990 Emissions Factors Used Instead of Mine Specific Data
1993	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
1994	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
1995	All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)*
1996	All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)*
1997	All Mines with Detectable Emissions (Assumed to Account for 100% of Total)

*Assumption based on complete set of individual mine data collected for 1997.

Step 1.2 Estimate Methane Liberated from Degasification Systems

Over 20 U.S. coal mines use degasification systems in addition to their ventilation systems for methane control. Coal mines use several different types of degasification systems to remove methane, including vertical wells and horizontal boreholes recover methane prior to mining of the coal seam. Gob wells and cross-measure boreholes recover methane from the overburden (i.e., GOB area) after mining of the seam (primarily in longwall mines).

MSHA collects information about the presence and type of degasification systems in some mines, but does not collect quantitative data on the amount of methane liberated. Thus, the methodology estimated degasification emissions on a mine-by-mine basis based on other sources of available data. Many of the coal mines employing degasification systems have provided EPA with information regarding methane liberated from their degasification systems. For these mines, this reported information was used as the estimate. In other cases in which mines sell methane recovered from degasification systems to a pipeline, gas sales were used to estimate methane liberated from degasification systems (see Step 1.3). Finally, for those mines that do not sell methane to a pipeline and have not provided information to EPA, methane liberated from degasification systems was estimated based on the type of system employed. For example, for coal mines employing gob wells and horizontal boreholes, the methodology assumes that degasification emissions account for 40 percent of total methane liberated from the mine.

Step 1.3: Estimate Methane Recovered from Degasification Systems and Used (Emissions Avoided)

In 1996, all 12 active U.S. coal mines that had developed methane recovery and use projects sold the recovered methane to a pipeline. One coal mine also used some recovered methane in a thermal dryer in addition to selling gas to a pipeline. Where available, state agency gas sales data were used to estimate emissions avoided for these projects. Emissions avoided were attributed to the year in which the coal seam was mined. For example, if a coal mine recovered and sold methane using a vertical well drilled five years in advance of mining, the emissions avoided associated with those gas sales were attributed to the year during which the well was mined-through (five years after the gas was sold). In order to estimate emissions avoided for those coal mines using degasification methods that recover methane in advance of mining, information was needed regarding the amount of gas recovered and the number of years in advance of mining that wells were drilled. In most cases, coal mine operators provided EPA with this information, which was then used to estimate emissions avoided for a particular year. Additionally, several state agencies made production data available for individual wells. For some mines, this individual well data were used to assign gas sales from individual wells to the appropriate emissions avoided year.

Step 2: Estimate Methane Emitted from Surface Mines and Post-Mining Activities

Mine-specific data was not available for estimating methane emissions from surface coal mines or for post-mining activities. For surface mines and post-mining activities, basin-specific coal production was multiplied by a basin-specific emission factors to determine methane emissions.

Step 2.1: Define the Geographic Resolution of the Analysis and Collect Coal Production Data

The first step in estimating methane emissions from surface mining and post-mining activities was to define the geographic resolution of the analysis and to collect coal production data at that level of resolution. The U.S. analysis was conducted by coal basin as defined in Table D-2.

The Energy Information Agency (EIA) Coal Industry Annual reports state- and county-specific underground and surface coal production by year. To calculate production by basin, the state level data were grouped into coal basins using the basin definitions listed in Table D-2. For two states—West Virginia and Kentucky—county-level production data was used for the basin assignments because coal production occurred from geologically distinct coal basins within these states. Table D-2 presents coal basin definitions by basin and by state. Table D-3 presents the coal production data aggregated by basin.

Step 2.2: Estimate Emissions Factors for Each Emissions Type

Emission factors for surface mined coal were developed from the *in situ* methane content of the surface coal in each basin. Based on an analysis presented in EPA (1993), the surface mining emission factors used were from 1 to 3 times the average *in situ* content in the basin. Furthermore, the post-mining emission factors used were assumed to be 25 to 40 percent of the average *in situ* content in the basin. Table D-4 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

Step 2.3: Estimate Methane Emitted

The total amount of methane emitted was calculated by multiplying the coal production in each basin by the appropriate emission factors.

Total annual methane emissions is equal to the sum of underground mine emissions plus surface mine emissions plus post-mining emissions. Table D-5 and Table D-6 present estimates of methane liberated, methane used, and methane emissions for 1990 through 1997 (1997 is a preliminary estimate).

Table D-2: Coal Basin Definitions by Basin and by State

Basin	States
Northern Appalachian Basin	Maryland, Ohio, Pennsylvania, West VA North
Central Appalachian Basin	Kentucky East, Tennessee, Virginia, West VA South
Warrior Basin	Alabama
Illinois Basin	Illinois, Indiana, Kentucky West
South West and Rockies Basin	Arizona, California, Colorado, New Mexico, Utah
North Great Plains Basin	Montana, North Dakota, Wyoming
West Interior Basin	Arkansas, Iowa, Kansas, Louisiana, Missouri, Oklahoma, Texas
Northwest Basin	Alaska, Washington
State	**Basin**
Alabama	Warrior Basin
Alaska	Northwest Basin
Arizona	South West And Rockies Basin
Arkansas	West Interior Basin
California	South West And Rockies Basin
Colorado	South West And Rockies Basin
Illinois	Illinois Basin
Indiana	Illinois Basin
Iowa	West Interior Basin
Kansas	West Interior Basin
Kentucky East	Central Appalachian Basin
Kentucky West	Illinois Basin
Louisiana	West Interior Basin
Maryland	Northern Appalachian Basin
Missouri	West Interior Basin
Montana	North Great Plains Basin
New Mexico	South West And Rockies Basin
North Dakota	North Great Plains Basin
Ohio	Northern Appalachian Basin
Oklahoma	West Interior Basin
Pennsylvania.	Northern Appalachian Basin
Tennessee	Central Appalachian Basin
Texas	West Interior Basin
Utah	South West And Rockies Basin
Virginia	Central Appalachian Basin
Washington	Northwest Basin
West Virginia South	Central Appalachian Basin
West Virginia North	Northern Appalachian Basin
Wyoming	North Great Plains Basin

Table D-3: Annual Underground Coal Production (thousand short tons)

Underground Coal Production

Basin	1990	1991	1992	1993	1994	1995	1996
Northern Appalachia	103,865	103,450	105,220	77,032	100,122	98,103	106,729
Central Appalachia	198,412	181,873	177,777	164,845	170,893	166,495	171,845
Warrior	17,531	17,062	15,944	15,557	14,471	17,605	18,217
Illinois	69,167	69,947	73,154	55,967	69,050	69,009	67,046
S. West/Rockies	32,754	31,568	31,670	35,409	41,681	42,994	43,088
N. Great Plains	1,722	2,418	2,511	2,146	2,738	2,018	2,788
West Interior	105	26	59	100	147	25	137
Northwest	0	0	0	0	0	0	0
Total	**423,556**	**406,344**	**406,335**	**351,056**	**399,102**	**396,249**	**409,850**

Surface Coal Production

Basin	1990	1991	1992	1993	1994	1995	1996
Northern Appalachia	60,761	51,124	50,512	48,641	44,960	39,372	39,788
Central Appalachia	94,343	91,785	95,163	94,433	106,129	106,250	108,869
Warrior	11,413	10,104	9,775	9,211	8,795	7,036	6,420
Illinois	72,000	63,483	58,814	50,535	51,868	40,376	44,754
S. West/Rockies	43,863	42,985	46,052	48,765	49,119	46,643	43,814
N. Great Plains	249,356	259,194	258,281	275,873	308,279	331,367	343,404
West Interior	64,310	61,889	63,562	60,574	58,791	59,116	60,912
Northwest	6,707	6,579	6,785	6,340	6,460	6,566	6,046
Total	**602,753**	**587,143**	**588,944**	**594,372**	**634,401**	**636,726**	**654,007**

Total Coal Production

Basin	1990	1991	1992	1993	1994	1995	1996
Northern Appalachia	164,626	154,574	155,732	125,673	145,082	137,475	146,517
Central Appalachia	292,755	273,658	272,940	259,278	277,022	272,745	280,714
Warrior	28,944	27,166	25,719	24,768	23,266	24,641	24,637
Illinois	141,167	133,430	131,968	106,502	120,918	109,385	111,800
S. West/Rockies	76,617	74,553	77,722	84,174	90,800	89,637	86,902
N. Great Plains	251,078	261,612	260,792	278,019	311,017	333,385	346,192
West Interior	64,415	61,915	63,621	60,674	58,938	59,141	61,049
Northwest	6,707	6,579	6,785	6,340	6,460	6,566	6,046
Total	**1,026,309**	**993,487**	**995,279**	**945,428**	**1,033,503**	**1,032,975**	**1,063,857**

Source: EIA (1990-96), Coal Industry Annual. U.S. Department of Energy, Washington, D.C., Table 3.
Note: Totals may not sum due to independent rounding.

Table D-4: Surface and Post-Mining Coal Emission Factors (ft^3 per short ton)

	Surface Average *in situ*	Underground Average *in situ*	Surface Mine Factors			Post-Mining Surface Factors			Post Mining Underground		
Basin	Content	Content	Low	Mid	High	Low	Mid	High	Low	Mid	High
Northern Appalachia	49.3	49.3	49.3	98.6	147.9	12.3	16.0	19.7	12.3	16.0	19.7
Central Appalachia	49.3	49.3	49.3	98.6	147.9	12.3	16.0	19.7	12.3	16.0	19.7
Warrior	49.3	49.3	49.3	98.6	147.9	12.3	16.0	19.7	12.3	16.0	19.7
Illinois	39.0	39.0	39.0	78.0	117.0	9.8	12.7	15.6	9.8	12.7	15.6
S. West/Rockies	15.3	15.3	15.3	30.6	45.9	3.8	5.0	6.1	3.8	5.0	6.1
N. Great Plains	3.2	3.2	3.2	6.4	9.6	0.8	1.0	1.3	0.8	1.0	1.3
West Interior	3.2	3.2	3.2	6.4	9.6	0.8	1.0	1.3	0.8	1.0	1.3
Northwest	3.2	3.2	3.2	6.4	9.6	0.8	1.0	1.3	0.8	1.0	1.3

Source: EPA (1993), Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress, U.S. Environmental Protection Agency, Air and Radiation, April.

Table D-5: Underground Coal Mining Methane Emissions (billion cubic feet)

Activity	1990	1991	1992	1993	1994	1995	1996	1997[b]
Ventilation Output	112	NA	NA	95	96	102	90	96
Adjustment Factor for Mine Data[a]	97.8%	NA	NA	97.8%	97.8%	91.4%	91.4%	100.0%
Ventilation Liberated	114	NA	NA	97	98	111	99	96
Degasification System Liberated	57	NA	NA	49	50	50	51	57
Total Underground Liberated	171	164	162	146	149	161	150	153
Recovered & Used	(15)	(15)	(19)	(24)	(29)	(31)	(35)	(42)
Total	**156**	**149**	**142**	**121**	**119**	**130**	**115**	**112**

[a] Refer to Table D-1

[b] Preliminary estimate.

Note: Totals may not sum due to independent rounding.

Table D-6: Total Coal Mining Methane Emissions (billion cubic feet)

Activity	1990	1991	1992	1993	1994	1995	1996	1997*
Underground Mining	156	149	142	121	119	130	115	112
Surface Mining	25	23	23	23	24	22	23	24
Post-Mining (Underground)	33	31	30	27	30	30	31	30
Post-Mining (Surface)	4	4	4	4	4	4	4	4
Total	**218**	**207**	**200**	**175**	**177**	**185**	**172**	**170**

* Preliminary estimate

Note: Totals may not sum due to independent rounding.

Annex E

Methodology for Estimating Methane Emissions from Natural Gas Systems

Step 1: Calculate Emission Estimates for Base Year 1992 Using GRI/EPA Study

The first step in estimating methane emissions from natural gas systems was to develop a detailed base year estimate of emissions. The study by GRI/EPA (1995) divides the industry into four stages to construct a detailed emissions inventory for the year 1992. These stages include: field production, processing, transmission and storage (both underground and liquefied gas storage), and distribution. This study produced emission factors and activity data for over 100 different emission sources within the natural gas system. Emissions for 1992 were estimated by multiplying activity levels by emission factors for each system component and then summing by stage. Since publication, EPA has updated activity data for some of the components in the system. Table E-1 displays the 1992 GRI/EPA activity levels and emission factors for venting and flaring from the field production stage, and the current EPA activity levels and emission factors. The data in Table E-1 is a representative sample of data used to calculate emission from all stages.

Step 2: Collect Aggregate Statistics on Main Driver Variables

As detailed data on each of the over 100 sources were not available for the period 1990 through 1996, activity levels were estimated using aggregate statistics on key drivers, including: number of producing wells (IPAA 1997), number of gas plants (AGA 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997), miles of transmission pipeline (AGA, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997), miles of distribution pipeline (AGA 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997), miles of distribution services (AGA 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997), and energy consumption (EIA 1996a). Data on the distribution of gas mains by material type was not available for certain years from AGA. For those years, the average distribution by type was held constant. Table E-2 provides the activity levels of some of the key drivers in the natural gas analysis.

Step 3: Estimate Emission Factor Changes Over Time

For the period 1990 through 1995, the emission factors were held constant, based on 1992 values. An assumed improvement in technology and practices was estimated to reduce emission factors by 5 percent by the year 2020. This assumption, annualized, amounts to a 0.2 percent decline in the 1996 emission factors.

Step 4: Estimate Emissions for Each Source

Emissions were estimated by multiplying the activity levels by emission factors. Table E-3 provides emission estimates for venting and flaring emissions from the field production stage.

Table E-1: 1992 Data and Emissions (Mg) for Venting and Flaring from Natural Gas Field Production Stage

Activity	*GRI/EPA Values* Activity Data	Emission Factor	Emissions	*EPA Adjusted Values* Activity Data	Emission Factor	Emissions
Drilling and Well Completion						
Completion Flaring	844 compl/yr	733 scf/comp	11.9	400 compl/yr	733 scf/comp	5.63
Normal Operations						
Pneumatic Device Vents	249,111 controllers	345 scfd/device	602,291	249,111 controllers	345 scfd/device	602,291
Chemical Injection Pumps	16,971 active pumps	248 scfd/pump	29,501	16,971 active pumps	248 scfd/pump	29,502
Kimray Pumps	11,050,000 MMscf/yr	368 scf/MMscf	78,024	7,380,194 MMscf/yr	992 scf/MMscf	140,566
Dehydrator Vents	12,400,000 MMscf/yr	276 scf/MMscf	65,608	8,200,215 MMscf/yr	276 scf/MMscf	43,387
Compressor Exhaust Vented						
Gas Engines	27,460 MMHPhr	0.24 scf/HPhr	126,536	27,460 MMHPhr	0.24 scf/HPhr	126,535
Routine Maintenance						
Well Workovers						
Gas Wells	9,392 w.o./yr	2,454 scfy/w.o.	443	9,392 w.o./yr	2,454 scfy/w.o.	443
Well Clean Ups (LP Gas Wells)	114,139 LP gas wells	49,570 scfy/LP well	108,631	114,139 LP gas wells	49,570 scfy/LP well	108,631
Blowdowns						
Vessel BD	255,996 vessels	78 scfy/vessel	383	242,306 vessels	78 scfy/vessel	363
Pipeline BD	340,000 miles (gath)	309 scfy/mile	2,017	340,200 miles (gath)	309 scfy/mile	2,018
Compressor BD	17,112 compressors	3,774 scfy/comp	1,240	17,112 compressors	3,774 scfy/comp	1,240
Compressor Starts	17,112 compressors	8,443 scfy/comp	2,774	17,112 compressors	8,443 scfy/comp	2,774
Upsets						
Pressure Relief Valves	529,440 PRV	34.0 scfy/PRV	346	529,440 PRV	34.0 scfy/PRV	346
ESD	1,115 platforms	256,888 scfy/plat	5,499	1,372 platforms	256,888 scfy/plat	6,767
Mishaps	340,000 miles	669 scfy/mile	4,367	340,200 miles	669 scfy/mile	4,370

Table E-2: Activity Factors for Key Drivers

Variable	Unit	1990	1991	1992	1993	1994	1995	1996
Transmission Pipelines Length	miles	280,100	281,600	284,500	269,600	268,300	264,900	257,000
Wells								
GSAM Appalachia Wells [a]	# wells	120,162	121,586	123,685	124,708	122,021	123,092	122,700
GSAM N Central Associated Wells [a]	# wells	3,862	3,890	3,852	3,771	3,708	3,694	3,459
GSAM N Central Non-Associated Wells [a]	# wells	3,105	3,684	4,317	4,885	5,813	6,323	7,073
GSAM Rest of US Wells [a]	# wells	145,100	147,271	152,897	156,568	160,011	164,750	173,928
GSAM Rest of US Associated Wells [a]	# wells	256,918	262,441	253,587	249,265	248,582	245,338	246,598
Appalch. + N. Central Non-Assoc. + Rest of US	# wells	268,367	272,541	280,899	286,161	287,845	294,165	303,701
Platforms								
Gulf of Mexico Off-shore Platforms	# platforms	3,798	3,834	3,800	3,731	3,806	3,868	3,846
Rest of U.S. (offshore platforms)	# platforms	24	24	24	24	23	23	24
N. Central Non-Assoc. + Rest of US Wells	# platforms	148,205	150,955	157,214	161,453	165,824	171,073	181,001
Gas Plants								
Number of Gas Plants	# gas plants	761	734	732	726	725	675	623
Distribution Services								
Steel - Unprotected	# of services	5,500,993	5,473,625	5,446,393	5,419,161	5,392,065	5,365,105	5,388,279
Steel - Protected	# of services	19,916,202	20,352,983	20,352,983	20,512,366	20,968,447	21,106,562	21,302,429
Plastic	# of services	16,269,414	17,654,006	17,681,238	18,231,903	19,772,041	20,270,203	20,970,924
Copper	# of services	228,240	233,246	233,246	235,073	240,299	241,882	244,127
Total	# of services	41,914,849	43,713,860	43,713,860	44,398,503	46,372,852	46,983,752	47,905,759
Distribution Mains								
Steel - Unprotected	miles	491,120	492,887	496,839	501,480	497,051	499,488	468,833
Steel - Protected	miles	91,267	90,813	90,361	89,909	89,460	89,012	88,567
Cast Iron	miles	52,644	52,100	51,800	50,086	48,542	48,100	47,100
Plastic	miles	202,269	221,600	244,300	266,826	284,247	294,400	329,700
Total	miles	837,300	857,400	883,300	908,300	919,300	931,000	934,200

[a] GSAM is the Gas Systems Analysis Model (GSAM 1997) of the Federal Energy Technology Center of the U.S. Department of Energy. It is a supply, demand and transportation model.

Table E-3: Emission Estimates for Venting and Flaring from the Field Production Stage (Mg)

Activity	1990	1991	1992	1993	1994	1995	1996
Drilling and Well Completion							
Completion Flaring	5.4	5.5	5.6	5.7	5.8	5.9	6.1
Normal Operations							
Pneumatic Device Vents	567,778	578,313	602,291	618,531	635,276	655,386	691,999
Chemical Injection Pumps	36,449	37,323	39,053	40,277	41,668	43,111	45,664
Kimray Pumps	134,247	136,380	140,566	143,211	144,040	147,191	151,565
Dehydrator Vents	41,436	42,095	43,387	44,203	44,459	45,432	46,782
Compressor Exhaust Vented							
Gas Engines	119,284	121,498	126,535	129,947	133,465	137,690	145,382
Routine Maintenance							
Well Workovers							
Gas Wells	531	540	556	567	570	582	600
Well Clean Ups (LP Gas Wells)	101,118	102,725	105,878	107,870	108,494	110,868	114,162
Blowdowns							
Vessel BD	256	261	271	278	284	292	306
Pipeline BD	1,710	1,729	1,772	1,772	1,818	1,852	1,908
Compressor BD	1,548	1,573	1,627	1,662	1,687	1,730	1,802
Compressor Starts	3,462	3,518	3,640	3,718	3,773	3,871	4,031
Upsets							
Pressure Relief Valves	326	332	346	355	365	376	397
ESD	6,764	6,827	6,767	6,646	6,773	6,882	6,834
Mishaps	925	936	959	974	984	1,003	1,033

Annex F

Methodology for Estimating Methane Emissions from Petroleum Systems

The methodology for estimating methane emissions from petroleum systems is being updated. EPA anticipates that current methodology understates emissions, and that the new methodology will be incorporated into future inventories.

Step 1: Production Field Operations

The American Petroleum Institute (API) publishes active oil well data in reports such as the *API Basic Petroleum Data Book*. To estimate activity data, the percentage of oil wells that were not associated with natural gas production, averaging approximately 56.4 percent over the period 1990 through 1996, was multiplied by the total number of wells in the United States. This number was then multiplied by per well emission factors for fugitive emissions and routine maintenance from Tilkicioglu & Winters (1989). Table F-1 displays the activity data, emission factors, and emissions estimates used.

Step 2: Crude Oil Storage

Methane emissions from storage were calculated as a function of annual U.S. crude stocks less strategic petroleum stocks for each year, obtained from annual editions of the *Petroleum Supply Annual* (EIA 1991, 1992, 1993, 1994, 1995, 1996, 1997). These stocks were multiplied by emission factors from Tilkicioglu & Winters (1989) to estimate emissions. Table F-2 displays the activity data, emission factors, and emissions estimates used.

Step 3: Refining

Methane emissions from refinery operations were based on U.S. refinery working storage capacity, found in annual editions of the *Petroleum Supply Annual* (EIA 1991, 1992, 1993, 1994, 1995, 1996, 1997). This capacity was multiplied by an emission factor from Tilkicioglu & Winters (1989) to estimate emissions. Table F-3 provides the activity data, emission factors, and emissions estimates used.

Step 4: Tanker Operations

Methane emissions from the transportation of petroleum on marine vessels were estimated using activity data on crude oil imports, U.S. crude oil production, Alaskan crude oil production, and Alaskan refinery crude oil capacity. All activity data were taken from annual editions of the *Petroleum Supply Annual* (EIA 1991, 1992, 1993, 1994, 1995, 1996, 1997).

Tilkicioglu & Winters (1989) identified three sources of emissions in the transportation of petroleum. These are emissions from loading Alaskan crude oil onto tankers, emissions from crude oil transfers to terminals, and ballast emissions.

Step 4.1: Loading Alaskan Crude Oil onto Tankers

The net amount of crude oil transported by tankers was determined by subtracting Alaskan refinery capacity from Alaskan crude oil production. This net amount was multiplied by an emission factor from Tilkicioglu & Winters (1989) to estimate emissions. The activity data and emissions estimates are shown in Table F-4.

Step 4.2: Crude Oil Transfers to Terminals

Methane emissions from crude oil transfers were taken from the total domestic crude oil transferred to terminals. This amount was assumed to be 10 percent of total domestic crude oil production less Alaskan crude oil production.

To estimate emissions, this transferred amount was multiplied by an emission factor from Tilkicioglu & Winters (1989). The activity data and emissions estimates are shown in Table F-5.

Step 4.3: Ballast Emissions

Ballast emissions are emitted from crude oil transported on marine vessels. This amount was calculated from the sum of Alaskan crude oil on tankers, the amount of crude oil transferred to terminals, and all crude oil imports less Canadian imports. Ballast volume was assumed to be 17 percent of this sum (Tilkicioglu & Winters 1989). This amount was then multiplied by an emission factor to estimate emissions. The activity data and emissions estimates are shown in Table F-6.

Total emissions from tanker operations are shown in Table F-7.

Step 5: Venting and Flaring

Methane emissions from venting and flaring were based on 1990 emissions estimates from EPA (1993) and were held constant through 1996 due to the lack of data available to assess the change in emissions.

Table F-1: Emissions from Petroleum Production Field Operations

Activity	Units	1990	1991	1992	1993	1994	1995	1996
Total Oil Wells		587,762	610,204	594,189	583,879	581,657	574,483	574,419
% Not Assoc. w/ Natural Gas	%	55.6%	56.4%	56.7%	56.7%	56.6%	56.7%	56.5%
Oil Wells in Analysis		326,982	343,873	336,749	330,843	329,366	325,451	324,362
Emission Factors								
Fugitive	kg/well/yr	72						
Routine Maintenance	kg/well/yr	0.15						
Emissions								
Fugitive	mill kg/yr	23.5	24.8	24.3	23.9	23.7	23.4	23.4
Routine Maintenance	mill kg/yr	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table F-2: Emissions from Petroleum Storage

Activity	Units	1990	1991	1992	1993	1994	1995	1996
Total Crude Stocks	1000 barrels/yr	908,387	893,102	892,864	922,465	928,915	894,968	849,669
Strategic Petroleum Stocks	1000 barrels/yr	585,692	568,508	574,724	587,080	591,670	591,640	566,000
Crude Oil Storage	1000 barrels/yr	322,695	324,594	318,140	335,385	337,245	303,328	283,669
Emission Factors								
Breathing	kg CH_4/brl/yr	0.002612						
Working	kg CH_4/brl/yr	0.002912						
Fugitive	kg CH_4/brl/yr	4.99×10^{-5}						
Emissions								
Breathing	kg/yr	842,892	847,853	830,994	876,039	880,897	792,305	740,955
Working	kg/yr	939,602	945,131	926,339	976,552	981,968	883,210	825,969
Fugitive	kg/yr	16,118	16,213	15,891	16,752	16,845	15,151	14,169
Total Emissions	**mill. kg/yr**	**1.80**	**1.81**	**1.77**	**1.87**	**1.88**	**1.69**	**1.58**

Table F-3: Emissions from Petroleum Refining

Activity (Jan 1)	Units	1990	1991	1992	1993	1994	1995	1996
Total Refinery Storage Capacity	1000 barrels/yr	174,490	171,366	167,736	170,823	164,364	161,305	158,435
Storage Emission Factor	Mg CH_4/brl/yr	5.9×10^{-5}						
Emissions	mill. kg/yr	10.29	10.10	9.89	10.07	9.69	9.51	9.34

Table F-4: Emissions from Petroleum Transportation: Loading Alaskan Crude Oil onto Tankers (Barrels/day*)

Activity	1990	1991	1992	1993	1994	1995	1996
Alaskan Crude	1,773,452	1,798,216	1,718,690	1,582,175	1,558,762	1,484,000	1,393,000
Alaskan Refinery Crude Capacity	229,850	239,540	222,500	256,300	261,000	275,152	283,350
Net Tankered	1,543,602	1,558,676	1,496,190	1,325,875	1,297,762	1,208,848	1,109,650
Conversion Factor (gal oil/ barrel oil)	42						
Emission factor (lbs/gallon)	0.001						
Emissions @ Loading AK (lbs/day)	64,831	65,464	62,840	55,687	54,506	50,772	46,605
Methane Content of Gas (%)	20.80%						
Emissions @ Loading AK (mill kg/yr)	2.23	2.26	2.17	1.92	1.88	1.75	1.61

* Unless otherwise noted

Table F-5: Emissions from Petroleum Transportation: Crude Oil Transfers to Terminals (Barrels/day*)

Activity	1990	1991	1992	1993	1994	1995	1996
US Crude Production	7,355,307	7,416,545	7,190,773	6,846,666	6,661,578	6,560,000	6,465,000
AK Crude Production	1,773,452	1,798,216	1,718,690	1,582,175	1,558,762	1,484,000	1,393,000
US Crude - AK Crude	5,581,855	5,618,329	5,472,082	5,264,490	5,102,816	5,076,000	5,072,000
10% transported to terminals	558,185	561,833	547,208	526,449	510,282	507,600	507,200
Conversion Factor (gal oil/ barrel oil)	42						
Emission factor (lbs/gallon)	0.001						
Emissions from Transfers (lbs/day)	23,444	23,597	22,983	22,111	21,432	21,319	21,302
Methane Content of Gas (%)	20.80%						
Emissions from Transfers (mill kg/yr)	0.81	0.81	0.79	0.76	0.74	0.73	0.73

* Unless otherwise noted

Table F-6: Emissions from Petroleum Transportation: Ballast Emissions (Barrels/day*)

Activity	1990	1991	1992	1993	1994	1995	1996
Crude Imports (less Canadian)	5,251,701	5,038,786	5,300,616	5,886,921	6,079,773	6,125,482	6,909,429
Alaskan Crude (Net Tankered)	1,543,602	1,558,676	1,496,190	1,325,875	1,297,762	1,208,848	1,109,650
10% Crude Prod. Transported to terminals	558,185	561,833	547,208	526,449	510,282	507,600	507,200
Conversion Factor (gal oil/ barrel oil)	42						
Emission factor (lbs/1000 gallons)	1.4						
Crude Oil Unloaded	7,353,489	7,159,296	7,344,015	7,739,245	7,887,816	7,841,930	8,526,279
Ballast Volume (17% of Crude Unloaded)	1,250,093	1,217,080	1,248,483	1,315,672	1,340,929	1,333,128	1,449,467
Ballast Emissions (lbs/day)	73,505	71,564	73,411	77,361	78,847	78,388	85,229
Methane Content of Gas (%)	20.80%						
Ballast Emissions (mill kg/yr)	2.53	2.47	2.53	2.67	2.72	2.70	2.94

* Unless otherwise noted

Table F-7: Total Methane Emissions from Petroleum Transportation

Year	Million kg/yr
1990	5.6
1991	5.5
1992	5.5
1993	5.4
1994	5.3
1995	5.2
1996	5.3

Annex G

Methodology for Estimating Methane Emissions from Enteric Fermentation

Step 1: Collect Livestock Population Data

All livestock population data, except for horses, was taken from U.S. Department of Agriculture (USDA) statistical reports. For each animal category, the USDA publishes monthly, annual, and multi-year livestock population and production estimates. Multi-year reports include revision to earlier published data. Recent reports were obtained from the USDA Economics and Statistics System website, at <http://www.mannlib.cornell.edu/usda/>, while historical data were downloaded from the USDA-National Agricultural Statistics Service (NASS) website at <http://www.usda.gov/nass/pubs/dataprd1.htm>.

The Food and Agriculture Organization (FAO) publish horse population data. These data were accessed from the FAOSTAT database at <http://apps.fao.org/>. Table G-1 summarizes the published population data by animal type.

Step 2: Estimate Emission Factors for Dairy Cows

Regional dairy cow emission factors from the 1993 Report to Congress (EPA 1993) were used as the starting point for the analysis. These emission factors were used to calibrate a model of methane emissions from dairy cows. The model applies revised regional emission factors that reflect changes in milk production per cow over time. Increases in milk production per cow, in theory, require increases in feed intake, which lead to higher methane emissions per cow. Table G-2 presents the emission factors per head by region used for dairy cows and milk production. The regional definitions are from EPA (1993).

Step 3: Estimate Methane Emissions from Dairy Cattle

Dairy cow emissions for each state were estimated by multiplying the published state populations by the regional emission factors, as calculated in Step 2. Dairy replacement emissions were estimated by multiplying national replacement populations by a national emission factor. The USDA reported the number of replacements 12 to 24 months old as "milk heifers." It is assumed that the number of dairy cow replacements 0 to 12 months old was equivalent to the number 12 to 24 months old replacements.

Step 4: Estimate Methane Emissions from Beef Cattle

Beef cattle methane emissions were estimated by multiplying published cattle populations by emission factors. Emissions from beef cows and replacements were estimated using state population data and regional emission developed in EPA (1993), as shown in Table G-3. Emissions from slaughter cattle and bulls were estimated using national data and emission factors. The emission factors for slaughter animals represent their entire life, from birth to slaughter. Consequently, the emission factors were multiplied by the national data on total steer and heifer slaughters rather than live populations of calves, heifers, and steers grown for slaughter. Slaughter population numbers were taken from and USDA datasets. The Weanling and Yearling mix was unchanged from earlier estimates derived from discussions with industry representatives.

Step 5: Estimate Methane Emissions from Other Livestock

Methane emissions from sheep, goats, swine, and horses were estimated by multiplying published national population estimates by the national emission factor for each year.

A summary of emissions is provided in Table G-4. Emission factors, national average or regional, are shown by animal type in Table G-5.

Table G-1: Livestock Population (thousand head)

Animal Type	1990	1991	1992	1993	1994	1995	1996
Dairy							
Cows	10,007	9,883	9,714	9,679	9,514	9,494	9,409
Replacements 0-12	4,135	4,097	4,116	4,088	4,072	4,021	3,902
Replacements 12-24	4,135	4,097	4,116	4,088	4,072	4,021	3,902
Beef							
Cows	32,677	32,960	33,453	34,132	35,325	35,628	35,414
Replacements 0-12	5,141	5,321	5,621	5,896	6,133	6,087	5,839
Replacements 12-24	5,141	5,321	5,621	5,896	6,133	6,087	5,839
Slaughter-Weanlings	5,199	5,160	5,150	5,198	5,408	5,612	5,580
Slaughter-Yearlings	20,794	20,639	20,600	20,794	21,632	22,450	22,322
Bulls	2,180	2,198	2,220	2,239	2,304	2,395	2,346
Other							
Sheep	11,356	11,174	10,797	10,201	9,742	8,886	8,454
Goats	2,545	2,475	2,645	2,605	2,595	2,495	2,495
Horses	5215	5650	5650	5850	5900	6000	6,000
Hogs	54,014	56,478	58,532	57,999	60,018	59,792	56,716

Table G-2: Dairy Cow Emission Factors and Milk Production Per Cow

Region	1990	1991	1992	1993	1994	1995	1996
Dairy Cow Emission Factors (kg/head)							
North Atlantic	116.2	118.8	121.3	121.0	122.3	124.7	124.8
South Atlantic	127.7	128.7	132.3	132.2	134.5	134.4	132.9
North Central	105.0	105.7	107.8	107.6	109.8	111.2	110.0
South Central	116.2	116.1	117.9	119.2	121.1	122.2	120.9
West	130.4	129.4	132.7	132.3	135.6	134.8	137.3
Milk Production (kg/year)							
North Atlantic	6,574	6,811	7,090	7,055	7,185	7,424	7,440
South Atlantic	6,214	6,300	6,622	6,608	6,813	6,792	6,673
North Central	6,334	6,413	6,640	6,627	6,862	6,987	6,881
South Central	5,696	5,687	5,849	5,971	6,148	6,248	6,128
West	8,339	8,255	8,573	8,530	8,874	8,789	9,047

Table G-3: Emission factors Beef Cows and Replacements (kg/head/yr)

Region	Replacements (0-12)	Replacements (12-24)	Mature Cows
North Atlantic	19.2	63.8	61.5
South Atlantic	22.7	67.5	70.0
North Central	20.4	60.8	59.5
South Central	23.6	67.7	70.9
West	22.7	64.8	69.1

Table G-4: Emissions from Livestock Enteric Fermentation (Tg)

Animal Type	1990	1991	1992	1993	1994	1995	1996
Dairy	1.47	1.46	1.47	1.47	1.47	1.47	1.46
Cows	1.15	1.14	1.15	1.15	1.15	1.16	1.15
Replacements 0-12	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Replacements 12-24	0.24	0.24	0.24	0.24	0.24	0.24	0.23
Beef	3.95	3.98	4.04	4.12	4.27	4.34	4.29
Cows	2.18	2.20	2.23	2.28	2.36	2.38	2.36
Replacements 0-12	0.11	0.12	0.13	0.13	0.14	0.14	0.13
Replacements 12-24	0.33	0.35	0.37	0.38	0.40	0.40	0.38
Slaughter-Weanlings	0.12	0.12	0.12	0.12	0.12	0.13	0.13
Slaughter-Yearlings	0.98	0.98	0.97	0.98	1.02	1.06	1.06
Bulls	0.22	0.22	0.22	0.22	0.23	0.24	0.23
Other	0.28	0.29	0.29	0.29	0.29	0.28	0.27
Sheep	0.09	0.09	0.09	0.08	0.08	0.07	0.07
Goats	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Horses	0.09	0.10	0.10	0.11	0.11	0.11	0.11
Hogs	0.08	0.08	0.09	0.09	0.09	0.09	0.09
Total	**5.70**	**5.73**	**5.80**	**5.88**	**6.03**	**6.10**	**6.02**

Table G-5: Enteric Fermentation Emission Factors

Animal Type	kg/head/year
Dairy	
Cows	regional
Replacements 0-12	19.6
Replacements 12-24	58.8
Beef	
Cows	regional
Replacements 0-12	regional
Replacements 12-24	regional
Slaughter-Weanlings	23.1
Slaughter-Yearlings	47.3
Bulls	100.0
Other	
Sheep	8.0
Goats	5.0
Horses	18.0
Hogs	1.5

Annex H

Methodology for Estimating Methane Emissions from Manure Management

Step 1: Collect Livestock Population Data

All livestock population data, except for horses, were taken from U.S. Department of Agriculture (USDA) statistical reports. For each animal category, the USDA publishes monthly, annual, and multi-year livestock population and production estimates. Multi-year reports include revisions to earlier published data. Recent reports were obtained from the USDA Economics and Statistics System website, at <http://www.mannlib.cornell.edu/usda/>, while historical data were downloaded from the USDA National Agricultural Statistics Service (NASS) website at <http://www.usda.gov/nass/pubs/dataprd1.htm>.

Dairy cow and swine population data by farm size for each state, used in Step 2, were found in the *1992 Census of Agriculture* published by the U.S. Department of Commerce (DOC). This census is conducted every five years. Data from the census were obtained from the USDA NASS website at <http://www.nass.usda.gov/census/>.

The Food and Agriculture Organization (FAO) publishes horse population data. These data weree accessed from the FAOSTAT database at <http://apps.fao.org/>. Table H-1 summarizes the published population data by animal type.

Step 2: Estimate State Methane Conversion Factors for Dairy Cows and Swine

Data from EPA (1993) were used for assessing dairy and swine manure management practices by farm size. Based on this assessment, an average methane conversion factor (MCF) was assigned to each farm size category for dairy and swine farms, indicating the portion of the methane producing potential realized. Because larger farms tend to use liquid manure management systems, which produce more methane, the MCFs applied to them were higher for smaller farm sizes.

Using the dairy cow and swine populations by farm size in the DOC *Census of Agriculture* for each state, weighted average dairy and swine MCFs were calculated for each state. The MCF value for each state reflected the distribution of animals among farm sizes within the state. Table H-2 provides estimated MCF values.

Step 3: Estimate Methane Emissions from Swine

For each state, the total swine population was multiplied by volatile solids (VS) production rates to determine total VS production. Estimated state level emissions were calculated as the product of total VS production multiplied by the maximum methane production potential for swine manure (B_o), and the state MCF. Total U.S. emissions are the sum of the state level emissions. The VS production rate and maximum methane production potential are shown in Table H-3.

Step 4: Estimate Methane Emissions from Dairy Cattle

Methane emissions from dairy cow manure were estimated using the same method as emissions from swine (Step 3), but with an added analysis to estimate changes in manure production associated with changes in feed intake, or dry matter intake (DMi). It is assumed that manure and VS production will change linearly with changes in dry matter intake (DMi).

Changes in DMi were calculated reflecting changes in feed intake associated with changes in milk production per cow per year. To estimate the changes in feed intake, a simplified emission factor model was used for dairy cow enteric fermentation emissions (see Annex G). This model estimates the change in DMi over time relative to 1990, which was used to calculate VS production by dairy cows by state, as summarized in the following equation: (Dairy cow population) x (VS produced per cow) x (DMi scaling factor). Methane emissions were then calculated as follows:

(VS produced) x (Maximum methane production potential for dairy cow manure) x (State-specific MCF). Total emissions were finally calculated as the sum of the state level emissions. The 1990 VS production rate and maximum methane production potential are shown in Table H-3.

Step 5: Estimate Methane Emissions for Other Animals

The 1990 methane emissions for the other animal types were estimated using the detailed method described above for dairy cows and swine (EPA 1993). This process was not repeated for subsequent years for these other animal types. Instead, national populations of each of the animal types were used to scale the 1990 emissions estimates to the period 1991 through 1996.

Emission estimates are summarized in Table H-4.

Table H-1: Livestock Population (1000 head)

	1990	1991		1993	1994		1996
Dairy Cattle		**13,980**	**13,830**		**13,686**	**13,514**	
Dairy Cows	10,007		9,714	9,679		9,493	9,408
	4,135	4,097		4,088	4,072		3,902
Swine		**56,478**	**58,532**		**60,018**	**59,792**	
Beef Cattle	**86,065**		**88,546**	**90,317**		**94,364**	**93,683**
	7,252	7,927		7,838	8,063		7,822
Feedlot Heifers		4,144	3,884		4,088	3,934	
Feedlot Cow/Other	88		92	95		97	96
	2,180	2,198		2,239	2,304		2,346
NOF Calves		23,854	24,118		24,692	25,184	
NOF Heifers	8,740		9,261	9,727		10,790	10,800
	7,554	7,356		8,081	8,108		8,594
NOF Cows		32,860	33,359		35,227	35,531	
Sheep	**11,356**		**10,797**	**10,201**		**8,886**	**8,454**
	7,961	7,799		7,140	6,775		5,875
Rams/Weth>1yr		361	350		314	282	
Ewes<1yr	1,491		1,432	1,349		1,167	1,107
	381	373		348	332		282
Sheep on Feed		1,177	1,093		1,044	957	
Goats	**2,545**		**2,645**	**2,605**		**2,495**	**2,495**
	1,703,037	**1,767,513**		**1,895,851**	**1,971,404**		**2,091,364**
Hens>1yr		117,178	121,103		134,876	133,767	
Pullets laying	153,916		163,397	158,938		164,526	165,304
	34,222	34,272		33,833	32,808		31,316
Pullets<3mo		42,344	45,160		44,875	45,494	
Chickens	6,546		7,113	7,240		7,641	7,243
	1,172,830	1,227,430		1,338,862	1,403,508		1,519,640
Other (Lost)		7,278	7,025		12,744	8,152	
Other (Sold)	41,672		41,538	39,606		40,917	39,588
	128,384	129,505		130,750	131,375		137,595
Horses		**5,650**	**5,850**		**6,000**	**6,000**	

Table H-2: Dairy Cow and Swine Methane Conversion Factors

State	Dairy Cow	Swine	State	Dairy Cow	Swine
AK	0.35	0.35	MT	0.16	0.39
AL	0.23	0.28	NC	0.20	0.65
AR	0.45	0.59	ND	0.05	0.22
AZ	0.09	0.68	NE	0.08	0.34
CA	0.44	0.44	NH	0.12	0.36
CO	0.31	0.46	NJ	0.13	0.26
CT	0.19	0.01	NM	0.42	0.47
DE	0.21	0.29	NV	0.36	0.50
FL	0.41	0.23	NY	0.11	0.22
GA	0.27	0.35	OH	0.07	0.30
HI	0.40	0.40	OK	0.13	0.31
IA	0.04	0.38	OR	0.25	0.35
ID	0.23	0.27	PA	0.06	0.35
IL	0.07	0.42	RI	0.07	0.59
IN	0.06	0.43	SC	0.29	0.40
KS	0.09	0.33	SD	0.06	0.26
KY	0.06	0.30	TN	0.14	0.28
LA	0.19	0.30	TX	0.31	0.30
MA	0.13	0.40	UT	0.21	0.34
MD	0.15	0.42	VA	0.17	0.34
ME	0.10	0.01	VT	0.11	0.09
MI	0.12	0.42	WA	0.29	0.29
MN	0.04	0.38	WI	0.05	0.27
MO	0.07	0.33	WV	0.11	0.11
MS	0.17	0.35	WY	0.12	0.20

Table H-3: Dairy Cow and Swine Constants

Description	Dairy Cow	Swine	Source
Typical Animal Mass (kg)	640	150	ASAE 1995
kg VS/day per 1000 kg mass	10	8.5	ASAE 1995
Maximum methane generation potential (B_o) m^3 methane/kg VS	0.24	0.47	EPA 1992

Animal Type	1990	1992	1993	1995
Dairy Cattle	**0.75**		**0.77**	**0.79**
Dairy Cows	0.59		0.61	0.63
Dairy Heifers	0.16		0.16	0.16
Swine	**1.44**		**1.51**	**1.60**
Beef Cattle	**0.20**		**0.21**	**0.22**
Feedlot Steers	0.03		0.03	0.03
Feedlot Heifers	0.02		0.02	0.02
Feedlot Cow/Other	0.00		0.00	0.00
NOF Bulls	0.01		0.01	0.01
NOF Calves	0.02		0.02	0.02
NOF Heifers	0.02		0.02	0.02
NOF Steers	0.01		0.02	0.02
NOF Cows	0.10		0.10	0.11
Sheep	**0.004**		**0.003**	**0.003**
Ewes > 1 yr	0.003		0.003	0.002
Rams/Weth > 1 yr	0.000		0.000	0.000
Ewes < 1 yr	0.000		0.000	0.000
Rams/Weth < 1 yr	0.000		0.000	0.000
Sheep on Feed	0.000		0.000	0.000
Goats	**0.001**		**0.001**	**0.001**
Poultry	**0.27**		**0.28**	**0.30**
Hens > 1 yr	0.05		0.06	0.06
Pullets laying	0.06		0.06	0.06
Pullets > 3 mo	0.01		0.01	0.01
Pullets < 3 mo	0.01		0.01	0.01
Chickens	0.00		0.00	0.00
Broilers	0.10		0.11	0.12
Other (Lost)	0.00		0.00	0.00
Other (Sold)	0.01		0.01	0.01
Turkeys	0.03		0.03	0.03
Horses	**0.03**		**0.03**	**0.03**

Annex I

Methodology for Estimating Methane Emissions from Landfills

Landfill methane is produced from a complex process of waste decomposition and subsequent fermentation under anaerobic conditions. The total amount of methane produced in a landfill from a given amount of waste and the rate at which it is produced depends upon the characteristics of the waste, the climate, and operating practices at the landfill. To estimate the amount of methane produced in a landfill in given year the following information is needed: quantity of waste in the landfill, the waste characteristics, the residence time of the waste in the landfill, and landfill management practices.

The amount of methane emitted from a landfill is less than the amount of methane produced in a landfill. If no measures are taken to extract the methane, a portion of the methane will oxidize as it travels through the top layer of the landfill cover. The portion of the methane that oxidizes turns primarily to carbon dioxide (CO_2). If the methane is extracted and combusted (e.g., flared or used for energy), then that portion of the methane produced in the landfill will not be emitted as methane, but again would be converted to CO_2. In general, the CO_2 emitted is of biogenic origin and primarily results from the decomposition—either aerobic or anaerobic—of organic matter such as food or yard wastes.[7]

To take into account the inter-related processes of methane production in the landfill and methane emission, this analysis relied on a simulation of the population of landfills and waste disposal. A starting population of landfills was initialized with characteristics from the latest survey of municipal solid waste (MSW) landfills (EPA 1988). Using actual national waste disposal data, waste was simulated to be placed in these landfills each year from 1990 to 1996. If landfills reach their design capacity, they were simulated to have closed. New landfills were simulated to open only if annual disposal capacity was less than total waste disposal. Of note is that closed landfills continue to produce and emit methane for many years. This analysis tracks these closed landfills throughout the analysis period, and includes their estimated methane production and emissions.

Using this approach, the age of the waste in each landfill was tracked explicitly. This tracking allowed the annual methane production in each landfill to be estimated. Methane produced in industrial landfills was also estimated. It was assumed to be 7 percent of the total methane produced in MSW landfills. Finally, methane recovered and combusted and methane oxidized were subtracted to estimate final methane emissions.

Using this approach, landfill population and waste disposal characteristics were simulated over time explicitly, thereby allowing the time-dependent nature of methane production to be modeled. However, the characteristics used to initialize the landfill population in the model were relatively old and may not represent the current set of operating landfills adequately. There is also uncertainty in the methane production equation developed in EPA (1993), as well as in the estimate of methane oxidation (10 percent).

Step 1: Estimate Municipal Solid Waste in Place Contributing to Methane Emissions

The landfill population model was initialized to define the population of landfills at the beginning of 1990. Waste was simulated to be placed into these landfills for the years 1990 through 1996 using data on the total waste landfilled from Biocycle (1997). The annual acceptance rates of the landfills were used to apportion the total waste by landfill. More waste was preferentially disposed in "Large" landfills (see Table I-3), reflecting the trend toward fewer and more centralized disposal facilities. The model updates the landfill characteristics each year, calculating the total waste in place and the full time profile of waste disposal. This time profile was used to estimate the portion of the waste that contributes to methane emissions. Table I-1 shows the amount of waste landfilled each year and the total estimated waste in place contributing to methane emissions.

[7] Emissions and sinks of biogenic carbon are accounted for under the Land-Use Change and Forestry sector.

Step 2: Estimate Landfill Methane Production

Emissions for each landfill were estimated by applying the emissions model (EPA 1993) to the landfill waste in place contributing to methane production. Total emission were then calculated as the sum of emissions from all landfills.

Step 3: Estimate Industrial Landfill Methane Production

Industrial landfills receive waste from factories, processing plants, and other manufacturing activities. Because there were no data available on methane generation at industrial landfills, the approach used was to assume that industrial methane production equaled about 7 percent of MSW landfill methane production (EPA 1993), as shown below in Table I-2.

Step 4: Estimate Methane Recovery

To estimate landfill gas (LFG) recovered per year, data on current and planned LFG recovery projects in the United States were obtained from Governmental Advisory Associates (GAA 1994). The GAA report, considered to be the most comprehensive source of information on gas recovery in the United States, has estimates for gas recovery in 1990 and 1992. Their data set showed that 1.20 and 1.44 teragrams (Tg) of methane were recovered nationally by municipal solid waste landfills in 1990 and 1992, respectively. In addition, a number of landfills were believed to recover and flare methane without energy recovery and were not included in the GAA database. To account for the amount of methane flared without energy recovery, the estimate of gas recovered was increased by 25 percent (EPA 1993). Therefore, net methane recovery from landfills was assumed to equal 1.50 Tg in 1990, and 1.80 Tg in 1992. The 1990 estimate of methane recovered was used for 1991 and the 1992 estimate was used for the period 1992 to 1996. EPA is currently reviewing more detailed information on LFG recovery projects and expects that the total recovery figure could be significantly higher.

Step 5: Estimate Methane Oxidation

As discussed above, a portion of the methane escaping from a landfill through its cover oxidizes in the top layer of the soil. The amount of oxidation that occurs is uncertain and depends upon the characteristics of the soil and the environment. For purposes of this analysis, it was assumed that 10 percent of the methane produced was oxidized in the soil.

Step 6: Estimate Total Methane Emissions

Total methane emissions were calculated by adding emissions from MSW and industrial waste, and subtracting methane recovered and oxidized, as shown in Table I-2.

Table I-1: Municipal Solid Waste (MSW) Contributing to Methane Emissions (Tg)

Description	1990	1991	1992	1993	1994	1995	1996
Total MSW Generated[a]	264	255	265	278	293	296	297
Percent of MSW Landfilled[a]	71%	76%	72%	71%	67%	63%	62%
Total MSW Landfilled	189	194	190	197	196	187	184
MSW Contributing to Emissions[b]	4,926	5,027	5,162	5,292	5,428	5,559	5,676

[a] Source: Biocycle (1997). The data, originally reported in short tons, are converted to metric tons.
[b] The EPA emissions model (EPA 1993) defines all waste younger than 30 years as contributing to methane emissions.

Table I-2: Methane Emissions from Landfills (Tg)

Activity	1990	1991	1992	1993	1994	1995	1996
MSW Generation	11.6	11.8	12.2	12.5	12.8	13.2	13.5
Large Landfills	4.53	4.62	4.76	4.91	5.11	5.29	5.45
Medium Landfills	5.79	5.91	6.07	6.23	6.36	6.53	6.62
Small Landfills	1.27	1.30	1.33	1.36	1.39	1.41	1.42
Industrial Generation	0.73	0.75	0.77	0.79	0.81	0.83	0.85
Potential Emissions	12.3	12.6	12.9	13.3	13.7	14.1	14.3
Recovery	(1.50)	(1.50)	(1.80)	(1.80)	(1.80)	(1.80)	(1.80)
Oxidation	(1.09)	(1.12)	(1.12)	(1.16)	(1.19)	(1.23)	(1.26)
Net Emissions	**9.82**	**10.0**	**10.1**	**10.4**	**10.8**	**11.1**	**11.4**

Note: Totals may not sum due to independent rounding.

Table I-3: Municipal Solid Waste Landfill Size Definitions (Tg)

Description	Waste in Place
Small Landfills	< 0.4
Medium Landfills	0.4 - 2.0
Large Landfills	> 2.0

Annex J
Global Warming Potentials

Table J-1: Global Warming Potentials and Atmospheric Lifetimes (years)

Gas	Atmospheric Lifetime	GWP[a]
Carbon dioxide (CO_2)	50-200	1
Methane (CH_4)[b]	12±3	21
Nitrous oxide (N_2O)	120	310
HFC-23	264	11,700
HFC-125	32.6	2,800
HFC-134a	14.6	1,300
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-227ea	36.5	2,900
HFC-236fa	209	6,300
HFC-4310mee	17.1	1,300
CF_4	50,000	6,500
C_2F_6	10,000	9,200
C_4F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

Source: (IPCC 1996)

[a] 100 year time horizon

[b] The 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.

Annex K
Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere[8], where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere[9], where it is the main component of anthropogenic photochemical "smog". Chlorofluorocarbons (CFCs) and other compounds that contain chlorine or bromine have been found to destroy ozone in the stratosphere, and are commonly referred to as ozone-depleting substances (ODSs). If left unchecked, ozone depletion could result in a dangerous increase of ultraviolet radiation reaching the earth's surface. In 1987, nations around the world signed the *Montreal Protocol on Substances that Deplete the Ozone Layer*. This landmark agreement created an international framework for limiting, and ultimately eliminating, the use and emission of most ozone depleting substances, which are used in a variety of industrial applications, including refrigeration and air conditioning, foam blowing, fire extinguishing, aerosol propellants, sterilization, and solvent cleaning.

In the United States, the Clean Air Act Amendments of 1990 provide the legal instrument for implementation of the *Montreal Protocol* controls. The Clean Air Act classifies ozone depleting substances as either Class I or Class II, depending upon the ozone depletion potential (ODP) of the compound.[10] The production of CFCs, halons, carbon tetrachloride, and methyl chloroform, all Class I substances, has already ended in the United States. However, because stocks of these chemicals remain available and in use, they will continue to be emitted for many years from applications such as refrigeration and air conditioning equipment, fire extinguishing systems, and metered dose inhalers. As a result, emissions of Class I compounds will continue, in ever decreasing amounts, into the early part of the next century. Class II substances, which are comprised of hydrochlorofluorocarbons (HCFCs), are being phased-out at a later date because of their lower ozone depletion potentials. These compounds are serving as interim replacements for Class I compounds in many industrial applications. The use and emissions of HCFCs in the United States is anticipated to increase over the next several years. Under current controls, the production of all HCFCs in the United States will end by the year 2030.

In addition to contributing to ozone depletion, CFCs, halons, carbon tetrachloride, methyl chloroform, and HCFCs are also significant greenhouse gases. The total impact of ozone depleting substances on global warming is not clear, however, because ozone is also a greenhouse gas. The depletion of ozone in the stratosphere by ODSs has an indirect negative radiative forcing, while most ODSs have a positive direct radiative forcing effect. The IPCC has prepared both direct GWPs and net (i.e., combined direct and indirect effects) GWP ranges for some of the most common ozone depleting substances (IPCC 1996). Direct GWPs account for the direct global warming impact of the emitted gas. Net GWP ranges account for both the direct impact of the emitted gas and the indirect effects resulting from the destruction of ozone.

Although the IPCC emission inventory guidelines do not include reporting emissions of ozone depleting substances, the United States believes that no inventory is complete without the inclusion of these emissions. Emission estimates for several ozone depleting substances are provided in Table K-1.

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[8] The stratosphere is the layer from the top of the troposphere up to about 50 kilometers. Approximately 90 percent of atmospheric ozone lies within the stratosphere. The greatest concentration of ozone occurs in the middle of the stratosphere, in a region commonly called the ozone-layer.

[9] The troposphere is the layer from the ground up to about 11 kilometers near the poles and 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere, where humans live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for weather processes including most of the water vapor and clouds.

[10] Substances with an ozone depletion potential of 0.2 or greater are classified as Class I. All other substances that may deplete stratospheric ozone but which do not have an ODP of 0.2 or greater, are classified as Class II.

Table K-1: 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 estimates
+ Does not exceed 10 Mg

Methodology and Data Sources

Emissions of ozone depleting substances were estimated using two simulation models: the Atmospheric and Health Effects Framework (AHEF) and EPA's Vintaging Model.

The Atmospheric and Health Effects Framework model contains estimates of U.S. domestic use of each of the ozone depleting substances. These estimates were based upon data that industry reports to EPA and other published material. The annual consumption of each compound was divided into various end-uses based upon historical trends and research into specific industrial applications. These end-uses include refrigerants, foam blowing agents, solvents, aerosol propellants, sterilants, and fire extinguishing agents.

With the exception of aerosols, solvents, and certain foam blowing agents, emissions of ozone depleting substances are not instantaneous, but instead occur gradually over time (i.e., emissions in a given year are the result of both ODS use in that year and use in previous years). Each end-use has a certain release profile, which gives the percentage of the compound that is released to the atmosphere each year until all releases have occurred. In refrigeration equipment, for example, the initial charge is released slowly over the lifetime of the equipment, which could be 20 or more years. In addition, not all of the refrigerant is ultimately emitted—some will be recovered when the equipment is retired from operation.

The AHEF model was used to estimate emissions of ODSs that were in use prior to the controls implemented under the *Montreal Protocol*. This included CFCs, halons, carbon tetrachloride, methyl chloroform, and HCFC-22. Certain HCFCs, such as HCFC-123, HCFC-124, HCFC-141b, HCFC-142b, HCFC-225ca and HCFC-225cb, have also entered the market as interim substitutes for ODSs. Emissions estimates for these compounds were taken from EPA's Vintaging Model.

The Vintaging Model was used to estimate the use and emissions of various ODS substitutes, including HCFCs. The name refers to the fact that the model tracks the use and emissions of various compounds by the annual "vintages" of new equipment that enter service in each end-use. The Vintaging Model is a "bottom-up" model. Information was collected regarding the sales of equipment that use ODS substitutes and the amount of the chemical required by each unit of equipment. Emissions for each end-use were estimated by applying annual leak rates and release profiles, as in the AHEF. By aggregating the data for more than 40 different end-uses, the model produces estimates of annual use and emissions of each compound.

Uncertainties

Uncertainties exist with regard to the levels of chemical production, equipment sales, equipment characteristics, and end-use emissions profiles that are used by these models.

Annex L
Sulfur Dioxide Emissions

Sulfur dioxide (SO_2) emitted into the atmosphere through natural and anthropogenic processes affects the Earth's radiative budget through 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 through the atmosphere, its radiative forcing impacts are highly uncertain. Sulfur dioxide emissions have been provided below in Table L-1.

The major source of SO_2 emissions in the United States was the burning of sulfur containing fuels, mainly coal. Metal smelting and other industrial processes also released significant quantities of SO_2. As a result, the largest contributors to overall U.S. emissions of SO_2 were electric utilities, accounting for 66 percent in 1996 (see Table L-2). Coal combustion accounted for approximately 96 percent of SO_2 emissions from electric utilities in the same year. The second largest source was industrial fuel combustion, which produced 18 percent of 1996 SO_2 emissions. Overall, sulfur dioxide emissions in the United States decreased by 19 percent from 1990 to 1996. Eighty-two percent of this decline came from reductions from electric utilities, primarily due to increased consumption of low sulfur coal from surface mines in western states.

Sulfur dioxide is important for reasons other than its effect on radiative forcing. It is a major contributor to the formation of urban smog and acid rain. As a contributor to urban smog, high concentrations of SO_2 can cause significant increases in acute and chronic respiratory diseases. In addition, once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to earth as the primary contributor to acid deposition, or acid rain. Acid rain has been found to accelerate the decay of building materials and paints, as well as cause the acidification of lakes and streams and damage trees. As a result of these harmful effects, the United States has regulated the emissions of SO_2 under the Clean Air Act. The EPA has also developed a strategy to control these emissions via four programs: (1) the National Ambient Air Quality Standards program,[11] (2) New Source Performance Standards,[12] (3) the New Source Review/Prevention of Significant Deterioration Program,[13] and (4) the sulfur dioxide allowance program.[14]

[11] [42 U.S.C § 7409, CAA § 109]
[12] [42 U.S.C § 7411, CAA § 111]
[13] [42 U.S.C § 7473, CAA § 163]
[14] [42 U.S.C § 7651, CAA § 401]

Table L-1: Emissions of SO_2 (Gg)

Sector/Source	1990	1991	1992	1993	1994	1995	1996
Energy	**20,034**	**19,524**	**19,327**	**18,973**	**18,444**	**16,006**	**16,174**
Stationary Sources	18,407	17,959	17,684	17,459	17,134	14,724	15,228
Mobile Sources	1,237	1,222	1,267	1,166	965	947	612
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**
Chemical Manufacturing	269	254	252	244	249	260	260
Metals Processing	658	555	558	547	510	481	481
Storage and Transport	6	9	8	4	1	2	2
Other Industrial Processes	362	360	360	355	361	365	371
Miscellaneous*	11	10	9	8	13	8	8
Solvent Use	**+**	**+**	**+**	**1**	**1**	**1**	**1**
Degreasing	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+
Dry Cleaning	NA	NA	+	NA	+	+	+
Surface Coating	+	+	+	+	+	+	+
Other Industrial	+	+	+	+	+	+	+
Non-industrial	NA	NA	NA	NA	NA	NA	NA
Agriculture	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
Waste	**38**	**40**	**40**	**65**	**54**	**43**	**43**
Waste Combustion	38	39	39	56	48	42	42
Landfills	+	+	+	+	+	+	+
Wastewater Treatment	+	+	+	+	+	1	1
Miscellaneous Waste	+	1	1	8	5	+	+
Total	**21,379**	**20,752**	**20,554**	**20,196**	**19,633**	**17,165**	**17,339**

Source: (EPA 1997)
* Miscellaneous includes other combustion and fugitive dust categories.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

Table L-2: Emissions of SO_2 from Electric Utilities (Gg)

Fuel Type	1990	1991	1992	1993	1994	1995	1996
Coal	13,807	13,687	13,448	13,179	12,985	10,526	10,990
Oil	580	591	495	555	474	375	373
Gas	1	1	1	1	1	8	19
Misc. Internal Combustion	45	41	42	45	48	50	52
Total	**14,432**	**14,320**	**13,986**	**13,779**	**13,507**	**10,959**	**11,434**

Source: (EPA 1997)
Note: Totals may not sum due to independent rounding.

Annex M
Complete List of Sources

Sector/Source	Gas(es)
Energy	
Carbon Dioxide Emissions from Fossil Fuel Combustion	CO_2
Stationary Source Fossil Fuel Combustion (excluding CO_2)	CH_4, N_2O, CO, NO_x, NMVOC
Mobile Source Fossil Fuel Combustion (excluding CO_2)	CH_4, N_2O, CO, NO_x, NMVOC
Coal Mining	CH_4
Natural Gas Systems	CH_4
Petroleum Systems	CH_4
Natural Gas Flaring and Criteria Pollutant Emissions from Oil and Gas Activities	CO_2, CO, NO_x, NMVOC
Wood Biomass and Ethanol Consumption	CO_2
Industrial Processes	
Cement Manufacture	CO_2
Lime Manufacture	CO_2
Limestone and Dolomite Use	CO_2
Soda Ash Manufacture and Consumption	CO_2
Carbon Dioxide Manufacture	CO_2
Iron and Steel Production	CO_2
Ammonia Manufacture	CO_2
Ferroalloy Production	CO_2
Petrochemical Production	CH_4
Silicon Carbide Production	CH_4
Adipic Acid Production	N_2O
Nitric Acid Production	N_2O
Substitution of Ozone Depleting Substances	HFCs, PFCs[a]
Aluminum Production	CF_4, C_2F_6
HCFC-22 Production	HFC-23
Semiconductor Manufacture	HFCs, PFCs, SF_6[b]
Electrical Transmission and Distribution	SF_6
Magnesium Production and Processing	SF_6
Industrial Sources of Criteria Pollutants	CO, NO_x, NMVOC
Solvent Use	CO, NO_x, NMVOC
Agriculture	
Enteric Fermentation	CH_4
Manure Management	CH_4, N_2O
Rice Cultivation	CH_4
Agricultural Soil Management	N_2O
Agricultural Residue Burning	CH_4, N_2O, CO, NO_x
Land-Use Change and Forestry	
Changes in Forest Carbon Stocks	CO_2
Changes in Non-Forest Soil Carbon Stocks	CO_2
Waste	
Landfills	CH_4
Wastewater Treatment	CH_4
Human Sewage	N_2O
Waste Combustion	N_2O
Waste Sources of Criteria Pollutants	CO, NO_x, NMVOC

[a] In 1996, included HFC-23, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-4310mee, C_4F_{10}, C_6F_{14}, PFC/PFPEs

[b] Included such gases as HFC-23, CF_4, C_2F_6, SF_6

Annex N
IPCC Reporting Tables

This annex contains a series of tables which summarize the emissions and activity data discussed in the body of this report. The data in these tables conform with guidelines established by the IPCC (IPCC/UNEP/OECD/IEA 1997; vol. 1) for consistent international reporting of greenhouse gas emissions inventories. The format of these tables does not always correspond directly with the calculations discussed in the body of the report. In these instances, the data have been reorganized to conform to IPCC reporting guidelines. As a result, slight differences may exist between the figures presented in the IPCC tables and those in the body of the report. These differences are merely an artifact of variations in reporting structures; total U.S. emissions are unaffected.

Title of Inventory	*Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*
Contact Name	Wiley Barbour
Title	
Organisation	U.S. Environmental Protection Agency
Address	Climate Policy and Programs Division (2175) 401 M Street, SW Washington, DC 20460
Phone	(202) 260-6972
Fax	(202) 260-6405
E-Mail	barbour.wiley@epamail.epa.gov
Is uncertainty addressed?	Yes
Related documents filed with IPCC	Yes

IPCC Table 1: Sectoral Report for Energy (1996)

	Sectoral Report for National Greenhouse Gas Inventories (Gg)						
Greenhouse Gas Source and Sink Categories	**CO_2 [a]**	**CH_4**	**N_2O**	**NOx**	**CO**	**NMVOC**	**SO_2**
Total Energy	**5,330,574**	**10,188.5**	**242.92**	**20,123**	**67,596**	**8,470**	**16,173**
A Fuel Combustion Activities (Reference)	5,317,701						
A Fuel Combustion Activities (Sectoral)	5,317,843	667.1	242.92	20,024	67,280	8,014	15,839
1 Electric Utilities	1,895,156	23.3	26.13	5,991	341	41	11,434
Petroleum	57,236	-	-	-	-	-	-
Gas	147,859	-	-	-	-	-	-
Coal	1,689,925	-	-	-	-	-	-
Geothermal	135	-	-	-	-	-	-
2 Industry	1,125,708	141.6	16.56	2,794	972	188	3,084
Petroleum	383,708	-	-	-	-	-	-
Gas	524,213	-	-	-	-	-	-
Coal	217,787	-	-	-	-	-	-
3 Transport	1,631,090	238.4	195.44	10,656	61,931	7,048	612
Petroleum	1,592,519	-	-	-	-	-	-
Gas	38,570	-	-	-	-	-	-
Coal	0	-	-	-	-	-	-
4 Commercial	237,504	38.2	1.08	336	219	21	IE
Petroleum	56,184	-	-	-	-	-	
Gas	173,678	-	-	-	-	-	
Coal	7,642	-	-	-	-	-	
5 Residential	388,656	225.6	3.71	654	3,817	715	164
Petroleum	99,796	-	-	-	-	-	-
Gas	283,795	-	-	-	-	-	-
Coal	5,065	-	-	-	-	-	-
6 Agriculture / Forestry	IE	IE	IE	IE	IE	IE	IE
Petroleum							
Gas							
Coal							
7 Territories	39,730	NE	NE	NE	NE	NE	NE
Petroleum	38,794						
Gas							
Coal	936						
B Fugitive Emissions from Fuels	12,730	9,521.3	NE	100	316	456	334
1 Solid Fuels	NE	3,301.0	NE	NE	NE	NE	NE
a Coal Mining		3,301.0					
2 Petroleum and Natural Gas	12,730	6,220.3	NE	100	316	456	334
a Petroleum		270.6		-	-	-	-
b Natural Gas		5,949.7		-	-	-	-
c Venting and Flaring	12,730			-	-	-	-
Memo Items*:							
International Bunkers	82,443	NE	NE	IE	IE	IE	IE
Aviation	22,096						
Marine	60,346						
CO_2 Emissions from Biomass [b]	200,108	IE	IE	IE	IE	IE	IE
Wood	194,963						
Ethanol	5,145						

*Not included in energy totals
Note: Totals may not equal sum of components due to independent rounding.
"-" = Value is not estimated separately, but included in an aggregate figure.
NE = Not estimated
IE = Estimated but included elsewhere
[a] For CO_2 calculations a detailed bottom-up approach was implemented using activity data disaggregated by sector and fuel type.
[b] CO_2 emissions estimates from biomass consumption are from commercial, industrial, residential, transportation, and electric power production applications. Estimates of non-CO_2 emissions from these sources were calculated via U.S. EPA methodologies and are incorporated in sectoral estimates in section A.

IPCC Table 2a: Sectoral Report for Industrial Processes (1996)

	Sectoral Report for National Greenhouse Gas Inventories (Gg)									
Greenhouse Gas Source and Sink Categories	**CO_2**	**CH_4**	**N_2O**	**NOx**	**CO**	**NMVOC**	**SO_2**	**HFCs [b]**	**PFCs [b]**	**SF_6**
Total Industrial Processes	63,309	73.9	108.71	820	5,338	1,970	1,122	[b]	[b]	1.5342
A Mineral Products	62,169	NE	NE	IE	IE	IE	IE	NE	NE	NE
1 Cement Production	37,061									
2 Lime Production	14,092									
3 Limestone and Dolomite Use	6,743									
4 Soda Ash Production and Use	4,273									
5 Asphalt Roofing	NE			IE	IE	IE	IE			
6 Other	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B Chemical Industry	1,140	73.9	108.71	144	1,110	377	260	IE	IE	IE
1 Ammonia Production	23,138 [a]			-	-	-	-			
2 Nitric Acid Production			45.38	-	-	-	-			
3 Adipic Acid Production			63.32	-	-	-	-			
4 Silicon Carbide Production		0.9		-	-	-	-			
5 Carbon Dioxide Production	1,140			-	-	-	-			
6 Petrochemical Production		73.0		-	-	-	-			
C Metal Production	IE	NE	NE	89	2,157	64	481	NE	[b]	0.4603
1 Iron and Steel Production	79,040 [a]			-	-	-	-			
2 Ferroalloys Production	1,695 [a]			-	-	-	-			
3 Aluminum Production	5258 [a]			-	-	-	-		[b]	
4 SF_6 Used in Aluminum and Magnesium Foundries				-	-	-	-			0.4603
D Other Production	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
E Production of Halocarbons and SF_6	NE	NE	NE	NE	NE	NE	NE	IE [b]	IE [b]	IE
1 Byproduct Emissions								IE [b]		
2 Fugitive Emissions										
3 Other										
F Consumption of Halocarbons and SF_6	NE	NE	NE	NE	NE	NE	NE	IE [b]	IE [b]	1.0739
1 Refrigeration and Air Conditioning Equipment								-	-	
2 Foam Blowing								-	-	
3 Fire Extinguishers								-	-	
4 Aerosols								-	-	
5 Solvents								-	-	
6 Electrical Transmission and Distribution								-	-	1.0739
G Other	IE	IE	IE	587	2,071	1,529	381	NO	NO	NO
1 Storage and Transport				5	23	889	2			
2 Other Industrial Processes				366	576	391	371			
3 Miscellaneous				216	1,472	249	8			

Note: Totals may not equal sum of components due to independent rounding.
"-" = Value is not estimated separately, but included in an aggregate figure.
NE = Not estimated
IE = Estimated but included elsewhere
NO = Not known to be occurring
NA = Not applicable

[a] CO_2 emissions from aluminum, ammonia, ferroalloy, and iron & steel production are included in this table for informational purposes, but are not included in the national total in order to prevent double counting these emissions, which are included under non-fuel industrial uses under the Energy sector.
[b] Emissions of HFCs and PFCs are documented by gas in Table 2b.
[c] Includes cooling towers, fugitive dust, health services

IPCC Table 2b: Detailed Emissions of HFCs (1996)

	(MMTCE)	Sectoral Report for National Greenhouse Gas Inventories(Gg)							
Greenhouse Gas Source and Sink Categories	**Unspecified***	**HFC-23**	**HFC-125**	**HFC-134a**	**HFC-143a**	**HFC-152a**	**HFC-227ea**	**HFC-236fa**	**HFC-4310mee**
Total HFCs and PFCs	**1.4**	**2.690**	**3.172**	**13.605**	**0.226**	**1.08**	**2.063**	**0.079**	**1.030**
A Substitution of Ozone Depleting Substances		0.026	3.172	13.605	0.226	1.08	2.063	0.079	1.030
B Aluminum Production		NO	NO	NO	NO	NO	NO	NO	NO
C HCFC-22 Production		2.664	NO	NO	NO	NO	NO	NO	NO
D Semiconductor Manufacture	1.4	IE	NO	NO	NO	NO	NO	NO	NO

*Includes gases such as HFC-23, CF_4, C_2F_6, SF_6, and C_3F_8
IE = Estimated but included elsewhere
NO = Not known to be occurring

IPCC Table 2c: Detailed Emissions of PFCs (1996)

	Sectoral Report for National Greenhouse Gas Inventories (Gg)				
Greenhouse Gas Source and Sink Categories	**CF_4**	**C_2F_6**	**C_4F_{10}**	**C_6F_{14}**	**PFC/PFPEs [a]**
Total HFCs and PFCs	**1.434**	**0.143**	**0.064**	**0.006**	**0.990**
A Substitution of Ozone Depleting Substances	NO	NO	0.064	0.006	0.990
B Aluminum Production	1.434	0.143	NO	NO	NO
C HCFC-22 Production	NO	NO	NO	NO	NO
D Semiconductor Manufacture	IE	IE	NO	NO	NO

IE = Estimated but included elsewhere
NO = Not known to be occurring
[a] PFC/PFPEs are a proxy for many diverse PFCs and perfluoropolyethers (PFPEs) that are employed in solvent applications. The GWP and atmospheric lifetime of this aggregate category is based upon that of C_6F_{14}.

IPCC Table 3: Sectoral Report for Solvent and Other Product Use (1996)

	Sectoral Report for National Greenhouse Gas Inventories (Gg)			
Greenhouse Gas Source and Sink Categories	**NOx**	**CO**	**NMVOC**	**SO_2**
Total Solvent and Other Product Use	**3**	**5**	**5,691**	**1**
A Degreasing	[a]	[a]	599	[a]
B Dry Cleaning	[a]	1	172	[a]
C Graphic Arts	1	[a]	353	[a]
D Surface Coating (including paint)	2	1	2,613	[a]
E Other Industrial	[a]	3	48	[a]
F Non-Industrial	[a]	[a]	1,905	NO

[a] Less than 0.5 Gg

IPCC Table 4: Sectoral Report for Agriculture (1996)

	Sectoral Report for National Greenhouse Gas Inventories (Gg)						
Greenhouse Gas Source and Sink Categories	**CO_2**	**CH_4**	**N_2O**	**NOx**	**CO**	**NMVOC**	**SO_2**
Total Agriculture	**NE**	**9,381.5**	**847.94**	**34**	**783**	**NE**	**NE**
A Enteric Fermentation	NE	6,023.0	NE	NE	NE		
1 Dairy Cattle		1,456.0					
2 Beef Cattle		4,294.0					
3 Sheep		68.0					

4 Goats		12.0					
5 Horses, Mules and Asses		108.0					
6 Swine		85.0					
B Manure Management	NE	2,889.9	34.95	NE	NE		
1 Dairy Cattle		786.6	0.84				
2 Beef Cattle		226.1	14.46				
3 Sheep		2.8	0.27				
4 Goats		0.9	0.05				
5 Horses, Mules and Asses		30.8	0.59				
6 Swine		1,541.3	0.76				
7 Poultry		301.5	17.97				
C Rice Cultivation	NE	431.3	NE	NE	NE		
1 Irrigated		431.3					
2 Rainfed							
3 Deepwater							
D Agricultural Soils	NE	NE	811.56	NE	NE		
1 Direct Emission from Agricultural Cropping Practices			442.32				
2 Direct Emissions from Animal Production			128.21				
3 Indirect Emissions from Nitrogen Applied to Agricultural Soils			241.03				
E Prescribed Burning of Savannas	NE	NE	NE	NE	NE		
F Field Burning of Agricultural Residues	NE	37.3	1.42	34	783		
1 Cereals		27.5	0.67	16	578		
2 Pulse		8.7	0.74	17	183		
3 Tuber and Root		0.1	0.01	0	2		
4 Sugar Cane		0.9	0.01	0	19		

Note: Totals may not equal sum of components due to independent rounding.
NE = Not estimated

IPCC Table 5: Sectoral Report for Land-Use Change and Forestry (1996)

	Sectoral Report for National Greenhouse Gas Inventories (Gg)					
Greenhouse Gas Source and Sink Categories	**CO_2 Emissions**	**CO_2 Removals**	**CH_4**	**N_2O**	**NOx**	**CO**
Total Land-Use Change and Forestry		**-764,683**	**NE**	**NE**	**NE**	**NE**
A Changes in Forest and Other Woody Biomass Stocks		-311,667				
1 Forest Trees, Understory, Floor		-311,667				
B Forest and Grassland Conversion		NO				
C Abandonment of Managed Lands		NO				
D CO_2 Emissions and Removals from Soil		-316,250				
1 Forest Soils		-316,250				
2 Non-Forest Soils		NE				
E Other		-136,767				
1 Landfilled Wood Carbon Flux		-71,243				
2 Wood Product Flux		-65,523				

NE = Not estimated
NO = Not known to be occurring

IPCC Table 6: Sectoral Report for Waste (1996)

	Sectoral Report for National Greenhouse Gas Inventories (Gg)						
Greenhouse Gas Source and Sink Categories	**CO_2**	**CH_4**	**N_2O**	**NOx**	**CO**	**NMVOC**	**SO_2**
Total Waste	**IE**	**11,532**	**28**	**87**	**1,019**	**368**	**43**
A Solid Waste Disposal on Land	IE	11,372	NE	1	2	19	[a]
1 Managed Waste Disposal		11,372		1	2	19	[a]
B Wastewater Handling	NE	161	27	[a]	[a]	58	1
1 Domestic		161	NE	[a]	[a]	47	-
2 Industrial		NE	NE	[a]	[a]	11	-
3 Human Sewage		-	27	-			
C Waste Incineration	IE	NE	1	85	1,016	218	42
1 Waste Incineration			1	49	402	50	32
2 Open Burning				36	614	169	10
D Other	NE	NE	NE	1	1	73	[a]
1 Treatment Storage and Disposal Facility						41	-
2 Scrap and Waste Materials/Leaking Underground Storage Tanks				1	1	32	-

"-" = Value is not estimated separately, but included in an aggregate figure.
[a] Less than 0.5 Gg
NE = Not estimated
IE = Estimated but included elsewhere

IPCC Table 7 A: Summary Report for National Greenhouse Gas Inventories (1996)

	Summary Report for National Greenhouse Gas Inventories (Gg)										
Greenhouse Gas Source and Sink Categories	**CO_2 Emissions**	**CO_2 Removals**	**CH_4**	**N_2O**	**NO_x**	**CO**	**NMVOC**	**SO_2**	**HFCs**	**PFCs**	**SF_6**
Total National Emissions and Removals	**5,393,883**	**-764,683**	**31,176.1**	**1,227.11**	**21,067**	**74,741**	**16,499**	**17,339**	**[b]**	**[b]**	**1.5342**
1 Energy	5,330,574		10,188.5	242.92	20,123	67,596	8,470	16,173	NO	NO	NO
A Fuel Combustion Activities (Sectoral)	5,317,843		667.1	242.92	20,024	67,280	8,014	15,839			
1 Electric Utilities	1,895,156		23.3	26.13	5,473	341	41	11,434			
2 Industry	1,125,708		141.6	16.56	2,875	972	188	3,084			

3 Transport	1,631,090		238.4	195.44	10,656	61,931	7,048	612			
4 Commercial	237,504		38.2	1.08	336	219	21	546			
5 Residential	388,656		225.6	3.71	654	3,817	715	164			
6 Agriculture / Forestry	IE		IE	IE	IE	IE	IE	IE			
7 Territories	39,730		NE	NE	NE	NE	NE	NE			
B Fugitive Emissions from Fuels	12,730		9,521.3		100	316	456	334			
1 Solid Fuels	NE		3,301.0	NE	NE	NE	NE	NE			
2 Petroleum and Natural Gas	12,730		6,220.3	NE	100	316	456	334			
2 Industrial Processes	63,309		73.9	108.71	820	5,338	1,970	1,122	[b]	[b]	1.5342
A Mineral Products	62,169		NE	NE	IE	IE	IE	IE	NE	NE	NE
B Chemical Industry	1,140		73.9	108.71	144	1,110	377	260	IE	IE	IE
C Metal Production	IE		NE	NE	89	2,157	64	481	NE	[b]	0.4603
D Other Production	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA
E Production of Halocarbons and SF_6	NE		NE	NE	NE	NE	NE	NE	IE [b]	IE [b]	IE
F Consumption of Halocarbons and SF_6	NE		NE	NE	NE	NE	NE	NE	IE [b]	IE [b]	1.0739
G Other	IE		IE	IE	587	2,071	1,529	381	NO	NO	NO
3 Solvent and Other Product Use	NE		NE	NE	3	5	5,691	1	NO	NO	NO

*Not included in energy totals
Note: Totals may not sum due to independent rounding.
NE = Not estimated
IE = Estimated but included elsewhere
NO = Not known to be occurring
[a] CO_2 emissions estimates from biomass consumption are from commercial, industrial, residential, transportation, and electric power production applications. They are provided for informational purposes only and are not included in national totals. Estimates of non-CO_2 emissions from these sources were calculated via U.S. EPA methodologies and are incorporated in sectoral estimates in section 1A.
[b] Totaled by gas in Table 2b

IPCC Table 7 A (continued): Summary Report for National Greenhouse Gas Inventories (1996)

Summary Report for National Greenhouse Gas Inventories (Gg)											
Greenhouse Gas Source and Sink Categories	**CO_2 Emissions**	**CO_2 Removals**	**CH_4**	**N_2O**	**NO_x**	**CO**	**NMVOC**	**SO_2**	**HFCs**	**PFCs**	**SF_6**
4 Agriculture	NE		9,381.5	847.94	34	783	NE	NE	NO	NO	NO
A Enteric Fermentation	NE		6,023.0	NE	NE	NE					
B Manure Management	NE		2,889.9	34.95	NE	NE					
C Rice Cultivation	NE		431.3	NE	NE	NE					
D Agricultural Soils	NE		NE	811.56	NE	NE					
E Prescribed Burning of Savannas	NO		NO	NO	NO	NO					
F Field Burning of Agricultural Residues	NE		37.3	1.42	34	783					
5 Land-Use Change & Forestry		-764,683	NE	NE	NE	NE	NE	NE	NO	NO	NO
A Changes in Forest and Other Woody Biomass Stocks		-311,667									
B Forest and Grassland Conversion		NO									
C Abandonment of Managed Lands		NO									
D CO_2 Emissions and Removals from Soil		-316,250									
E Other		-136,767									
6 Waste	IE		11,532.3	27.55	87	1,019	368	43	NO	NO	NO
A Solid Waste Disposal on Land	IE		11,371.7	NE	1	2	19	0			
B Wastewater Handling	NE		160.6	26.66	0	0	58	1			
C Waste Incineration	IE		NE	0.89	85	1,016	218	42			
D Other	NE		NE	NE	1	1	73	0			
Memo Items*:											
International Bunkers	82,443		NE	NE	IE	IE	IE	IE	NO	NO	NO
Aviation	22,096										
Marine	60,346										
CO_2 Emissions from Biomass [a]	200,108		IE	IE	IE	IE	IE	IE	NO	NO	NO

*Not included in energy totals
Note: Totals may not sum due to independent rounding.
NE = Not estimated
IE = Estimated but included elsewhere
NO = Not known to be occurring
[a] CO_2 emissions estimates from biomass consumption are from commercial, industrial, residential, transportation, and electric power production applications. They are provided for informational purposes only and are not included in national totals. Estimates of non-CO_2 emissions from these sources were calculated via U.S. EPA methodologies and are incorporated in sectoral estimates in section 1A.
[b] Totaled by gas in Table 2b

IPCC Table 7B: Short Summary Report for National Greenhouse Gas Inventories (1996)

Summary Report for National Greenhouse Gas Inventories (Gg)											
Greenhouse Gas Source and Sink Categories	**CO_2 Emissions**	**CO_2 Removals**	**CH_4**	**N_2O**	**NOx**	**CO**	**NMVOC**	**SO_2**	**HFCs**	**PFCs**	**SF_6**
Total National Emissions and Removals	**5,393,883**	**-764,683**	**31,176.1**	**1,227.11**	**21,067**	**74,741**	**16,499**	**17,339**	**[b]**	**[b]**	**1.5342**
1 Energy (Reference Approach)	5,317,701										
1 Energy (Sectoral Approach)	5,330,574		10,188.5	242.92	20,123	67,596	8,470	16,173	NO	NO	NO
A Fuel Combustion Activities	5,317,843		667.1	242.92	20,024	67,280	8,014	15,839			
B Fugitive Emissions from Fuels	12,730		9,521.3	NE	100	316	456	334			
2 Industrial Processes	63,309		73.9	108.71	820	5,338	1,970	1,122	[b]	[b]	1.5342
3 Solvent and Other Product Use	NE		NE	NE	3	5	5,691	1	NO	NO	NO
4 Agriculture	NE		9,381.5	847.94	34	783	NE	NE	NO	NO	NO
5 Land-Use Change & Forestry		-764,683	NE	NE	NE	NE	NE	NE	NO	NO	NO
6 Waste	IE		11,532.3	27.55	87	1,019	368	43	NO	NO	NO
Memo Items*:											
International Bunkers	82,443		NE	NE	IE	IE	IE	IE	NO	NO	NO
Aviation	22,096										
Marine	60,346										
CO_2 Emissions from Biomass [a]	200,108		IE	IE	IE	IE	IE	IE	NO	NO	NO

*Not included in energy totals
Note: Totals may not sum due to independent rounding.
NE = Not estimated
IE = Estimated but included elsewhere
NO = Not known to be occurring
[a] CO_2 emissions estimates from biomass consumption are from commercial, industrial, residential, transportation, and electric power production applications. They are provided for informational purposes only and are not included in national totals. Estimates of non-CO_2 emissions from these sources were calculated via U.S. EPA methodologies and are incorporated in sectoral estimates in section 1A.
[b] Totaled by gas in Table 2b

IPCC Table 8A (part I): Overview Table for National Greenhouse Gas Inventories (1996)

Greenhouse Gas Source and Sink Categories	CO_2		CH_4		N_2O		NOx		CO		NMVOC	
	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality
Total National Emissions and Removals												
1 Energy												
A Fuel Combustion Activities (Reference)	ALL	H	NE		NE		NE		NE		NE	
A Fuel Combustion Activities (Sectoral)												
1 Electric Utilities	ALL	H	ALL	M	ALL	M	ALL	H	ALL	H	ALL	H
2 Industry	ALL	H	ALL	M	ALL	M	ALL	H	ALL	H	ALL	H
3 Transport	ALL	H	ALL	M	PART [b]	M	ALL	H	ALL	H	ALL	H
4 Commercial	ALL	H	ALL	M	ALL	M	ALL	H	ALL	H	ALL	H
5 Residential	ALL	H	ALL	M	ALL	M	ALL	H	ALL	H	ALL	H
6 Agriculture / Forestry	IE		IE		IE		IE		IE		IE	
7 Territories	ALL	H	NE		NE		NE		NE		NE	
B Fugitive Emissions from Fuels												
1 Solid Fuels	NE		ALL	M	NE		NE		NE		NE	
2 Petroleum and Natural Gas	PART [c]	M	ALL	M	NE		ALL	H	ALL	H	ALL	H
2 Industrial Processes												
A Mineral Products	ALL	H	NE		NE		IE		IE		IE	
B Chemical Industry	ALL	M	ALL	M	ALL	H	ALL	H	ALL	H	ALL	H
C Metal Production	IE		NE		NE		ALL	H	ALL	H	ALL	H
D Other Production	NA		NA		NA		NA		NA		NA	
E Production of Halocarbons and SF_6	NO		NO		NO		NO		NO		NO	
F Consumption of Halocarbons and SF_6	NO		NO		NO		NO		NO		NO	
G Other [f]	IE		IE		IE		ALL	H	ALL	H	ALL	H
3 Solvent and Other Product Use	NE		NE		NE		ALL	H	ALL	H	ALL	H

NE = Not estimated
IE = Estimated but included elsewhere
NO = Not known to be occurring
NA = Not applicable
PART = Partly estimated
ALL = Full estimate of all possible sources

Quality:
H = High Confidence in Estimation
M = Medium Confidence in Estimation
L = Low Confidence in Estimation

Documentation:
H = High (all background information included)
M = Medium (some background information included)
L = Low (only emission estimates included)

Disaggregation:
1 = Total emissions estimated
2 = Sectoral split
3 = Subsectoral split

[a] Non-forest soils are not included in this estimate.
[b] Estimate does not include nitrous oxide emissions from jet aircraft.
[c] Estimate excludes geologic carbon dioxide deposits released during petroleum and natural gas production.
[d] Estimate does not include emissions from industrial wastewater.
[e] Includes emissions from human sewage only
[f] From storage and transport; other industrial processes; and cooling towers, fugitive dust, and health services
[g] From landfilled wood and wood product flux
[h] From treatment, storage and disposal facilities: scrap and waste materials; and underground storage tanks

IPCC Table 8A (part II): Overview Table for National Greenhouse Gas Inventories (1996)

Greenhouse Gas Source and Sink Categories	CO_2		CH_4		N_2O		NOx		CO		NMVOC	
	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality
4 Agriculture												
A Enteric Fermentation	NE		ALL	M	NE		NE		NE		NE	
B Manure Management	NE		ALL	M	ALL	M	NE		NE		NE	
C Rice Cultivation	NE		ALL	M	NE		NE		NE		NE	
D Agricultural Soils	NE		NE		ALL	M	NE		NE		NE	
E Prescribed Burning of Savannas	NE		NE		NE		NE		NE		NE	
F Field Burning of Agricultural Residues	NE		ALL	M	ALL	M	ALL	M	ALL	M	NE	
5 Land-Use Change & Forestry												

A Changes in Forest and Other Woody Biomass Stocks	ALL	M	NE		NE		NE		NE		NE	
B Forest and Grassland Conversion	NO		NE		NE		NE		NE		NE	
C Abandonment of Managed Lands	NO		NE		NE		NE		NE		NE	
D CO_2 Emissions and Removals from Soil	PART [a]	L	NE		NE		NE		NE		NE	
E Other [g]	ALL	M	NE		NE		NE		NE		NE	
6 Waste												
A Solid Waste Disposal on Land	IE		ALL	H	NE		ALL	H	ALL	H	ALL	H
B Wastewater Handling	NE		PART [d]	M	PART [e]		ALL	H	ALL	H	ALL	H
C Waste Incineration	IE		NE		ALL	M	ALL	H	ALL	H	ALL	H
D Other [h]	NE		NE		NE	M	ALL	H	ALL	H	ALL	H
Memo Items:												
International Bunkers												
Aviation	ALL	M	NE		NE		IE		IE		IE	
Marine	ALL	M	NE		NE		IE		IE		IE	
CO_2 Emissions from Biomass [a]	ALL	M	IE		IE		IE		IE		IE	

NE = Not estimated
IE = Estimated but included elsewhere
NO = Not known to be occurring
NA = Not applicable
PART = Partly estimated
ALL = Full estimate of all possible sources

Quality:
H = High Confidence in Estimation
M = Medium Confidence in Estimation
L = Low Confidence in Estimation

Documentation:
H = High (all background information included)
M = Medium (some background information included)
L = Low (only emission estimates included)

Disaggregation:
1 = Total emissions estimated
2 = Sectoral split
3 = Subsectoral split

[a] Non-forest soils are not included in this estimate.
[b] Estimate does not include nitrous oxide emissions from jet aircraft.
[c] Estimate excludes geologic carbon dioxide deposits released during petroleum and natural gas production.
[d] Estimate does not include emissions from industrial wastewater.
[e] Includes emissions from human sewage only
[f] From storage and transport; other industrial processes; and cooling towers, fugitive dust, and health services
[g] From landfilled wood and wood product flux
[h] From treatment, storage and disposal facilities: scrap and waste materials; and underground storage tanks

IPCC Table 8A (part III): Overview Table for National Greenhouse Gas Inventories (1996)

Greenhouse Gas Source and Sink Categories	SO_2		HFCs		PFCs		SF_6		Documentation	Disaggregation	Footnotes
	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality			
Total National Emissions and Removals											
1 Energy											
A Fuel Combustion Activities (Reference)	NE		NE		NE		NE		H	3	
A Fuel Combustion Activities (Sectoral)									H	3	
1 Electric Utilities	ALL	H	NO		NO		NO				
2 Industry	ALL	H	NO		NO		NO				
3 Transport	ALL	H	NO		NO		NO				
4 Commercial	IE		NO		NO		NO				
5 Residential	IE		NO		NO		NO				
6 Agriculture / Forestry	NE		NO		NO		NO				
7 Territories	NE		NO		NO		NO				
B Fugitive Emissions from Fuels											
1 Solid Fuels	NE		NO		NO		NO		H	3	
2 Petroleum and Natural Gas	ALL	H	NO		NO		NO		H	3	
2 Industrial Processes											
A Mineral Products	IE		NE		NE		NE		H	3	
B Chemical Industry	ALL	H	IE		IE		IE		H	3	
C Metal Production	ALL	H	NE		ALL	M	ALL	M	M	3	
D Other Production	NA		NA		NA		NA				
E Production of Halocarbons and SF_6	NO		ALL	M	ALL	M	IE		M	2	
F Consumption of Halocarbons and SF_6	NO		ALL	M	ALL	M	ALL	M	M	2	
G Other [f]	ALL	H	NO		NO		NO		M	2	
3 Solvent and Other Product Use	ALL	H	NO		NO		NO		M	3	

NE = Not estimated
IE = Estimated but included elsewhere
NO = Not known to be occurring
NA = Not applicable
PART = Partly estimated
ALL = Full estimate of all possible sources

Quality:
H = High Confidence in Estimation
M = Medium Confidence in Estimation
L = Low Confidence in Estimation

Documentation:
H = High (all background information included)
M = Medium (some background information included)
L = Low (only emission estimates included)

Disaggregation:
1 = Total emissions estimated
2 = Sectoral split
3 = Subsectoral split

[a] Non-forest soils are not included in this estimate.
[b] Estimate does not include nitrous oxide emissions from jet aircraft.
[c] Estimate excludes geologic carbon dioxide deposits released during petroleum and natural gas production.
[d] Estimate does not include emissions from industrial wastewater.
[e] Includes emissions from human sewage only
[f] From storage and transport; other industrial processes; and cooling towers, fugitive dust, and health services
[g] From landfilled wood and wood product flux
[h] From treatment, storage and disposal facilities: scrap and waste materials; and underground storage tanks

IPCC Table 8A (part IV): Overview Table for National Greenhouse Gas Inventories (1996)

Greenhouse Gas Source and Sink Categories	SO_2		HFCs		PFCs		SF_6		Documentation	Disaggregation	Footnotes
	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality			
4 Agriculture											
A Enteric Fermentation	NE		NO		NO		NO		H	3	
B Manure Management	NE		NO		NO		NO		H	3	
C Rice Cultivation	NE		NO		NO		NO		H	3	
D Agricultural Soils	NE		NO		NO		NO		H	3	
E Prescribed Burning of Savannas	NE		NO		NO		NO				
F Field Burning of Agricultural Residues	NE		NO		NO		NO		H	3	
5 Land-Use Change & Forestry											
A Changes in Forest and Other Woody Biomass Stocks	NE		NO		NO		NO		M	2	
B Forest and Grassland Conversion	NE		NO		NO		NO				
C Abandonment of Managed Lands	NE		NO		NO		NO				
D CO_2 Emissions and Removals from Soil	NE		NO		NO		NO		M	2	
E Other [g]	NE		NO		NO		NO		M	2	
6 Waste											
A Solid Waste Disposal on Land	ALL	H	NO		NO		NO		H	3	
B Wastewater Handling	ALL	H	NO		NO		NO		H	2	
C Waste Incineration	ALL	H	NO		NO		NO		H	2	
D Other [h]	ALL	H	NO		NO		NO				
Memo Items:											
International Bunkers											
Aviation	IE		NO		NO		NO		H	1	
Marine	IE		NO		NO		NO		H	1	
CO_2 Emissions from Biomass [a]	IE		NO		NO		NO		H	2	

NE = Not estimated
IE = Estimated but included elsewhere
NO = Not known to be occurring
NA = Not applicable
PART = Partly estimated
ALL = Full estimate of all possible sources

Quality:
H = High Confidence in Estimation
M = Medium Confidence in Estimation
L = Low Confidence in Estimation

Documentation:
H = High (all background information included)
M = Medium (some background information included)
L = Low (only emission estimates included)

Disaggregation:
1 = Total emissions estimated
2 = Sectoral split
3 = Subsectoral split

[a] Non-forest soils are not included in this estimate.
[b] Estimate does not include nitrous oxide emissions from jet aircraft.
[c] Estimate excludes geologic carbon dioxide deposits released during petroleum and natural gas production.
[d] Estimate does not include emissions from industrial wastewater.
[e] Includes emissions from human sewage only
[f] From storage and transport; other industrial processes; and cooling towers, fugitive dust, and health services
[g] From landfilled wood and wood product flux
[h] From treatment, storage and disposal facilities: scrap and waste materials; and underground storage tanks

Annex O

IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion

It is possible to estimate carbon emissions from fossil fuel consumption using alternative methodologies and different data sources than those described in Annex A. For example, the IPCC requires countries in addition to their "bottom-up" sectoral methodology to complete a "top-down" Reference Approach for estimating carbon dioxide emissions from fossil fuel combustion. Section 1.3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reporting Instructions* states, "If a detailed, Sectoral Approach for energy has been used for the estimation of CO_2 from fuel combustion you are still asked to complete…the Reference Approach…for verification purposes" (IPCC/UNEP/OECD/IEA 1997). This reference method estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The basic principle is that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required. The following discussion provides the detailed calculations for estimating CO_2 emissions from fossil fuel combustion from the United States using the IPCC-recommended Reference Approach.

Step 1: Collect and Assemble Data in Proper Format

To ensure the comparability of national inventories, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention. National energy statistics were collected in physical units from several DOE/EIA documents in order to obtain the necessary data on production, imports, exports, and stock changes.[15] These data are presented in Table O-1.

The carbon content of fuel varies with the fuel's heat content. Therefore, for an accurate estimation of CO_2 emissions, fuel statistics should be provided on an energy content basis (e.g., BTU's or joules). Because detailed fuel production statistics are typically provided in physical units (as in Table O-1), they were converted to units of energy before carbon emissions can be calculated. Fuel statistics were converted to their energy equivalents by using conversion factors provided by DOE/EIA. These factors and their data sources are displayed in Table O-2. The resulting fuel data are provided in Table O-3.

Step 2: Estimate Apparent Fuel Consumption

The next step of the IPCC method is to estimate "apparent consumption" of fuels within the country. This requires a balance of primary fuels produced, plus imports, minus exports, and adjusting for stock changes. In this way, carbon enters an economy through energy production and imports (and decreases in fuel stocks) and is transferred out of the country through exports (and increases in fuel stocks). Thus, apparent consumption of primary fuels (including crude oil, natural gas liquids, anthracite, bituminous, subbituminous and lignite coal, and natural gas) can be calculated as follows:

Production + Imports - Exports - Stock Change

Flows of secondary fuels (e.g., gasoline, residual fuel, coke) should be added to primary apparent consumption. The production of secondary fuels, however, should be ignored in the calculations of apparent consumption since the carbon contained in these fuels is already accounted for in the supply of primary fuels from which they were derived

[15] For the United States, national aggregate energy statistics typically exclude data on the U.S. territories. As a result, national statistics were adjusted to include production, imports, exports, and stock changes within the United States territories. The territories include Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, Wake Island, and U.S. Pacific Islands.

(e.g., the estimate for apparent consumption of crude oil already contains the carbon from which gasoline would be refined). Flows of secondary fuels should therefore be calculated as follows:

Imports - Exports - Stock Change

Note that this calculation can result in negative numbers for apparent consumption. This is a perfectly acceptable result since it merely indicates a net export or stock increase in the country of that fuel when domestic production is not considered.

The IPCC Reference Approach calls for estimating apparent fuel consumption before converting to a common energy unit. However, certain primary fuels in the United States (e.g., natural gas and steam coal) have separate conversion factors for production, imports, exports, and stock changes. In these cases, it is not appropriate to multiply apparent consumption by a single conversion factor since each of its components have different heat contents. Therefore, United States fuel statistics were converted to their heat equivalents before estimating apparent consumption. The energy value of bunker fuels was subtracted before computing energy totals.[16] Results are provided in Table O-3.

Step 3: Estimate Carbon Emissions

Once apparent consumption is estimated, the remaining calculations are virtually identical to those for the "bottom-up" Sectoral Approach (see Annex A). That is:

- Potential carbon emissions were estimated using fuel-specific carbon coefficients (see Table O-4).[17]
- The carbon sequestered in non-fuel uses of fossil fuels (e.g., plastics or asphalt) was then estimated and subtracted from the total amount of carbon (see Table O-5).
- Finally, to obtain actual carbon emissions, net carbon emissions were adjusted for any carbon that remained unoxidized as a result of incomplete combustion (e.g., carbon contained in ash or soot).[18]

Step 4: Convert to CO_2 Emissions

Because the IPCC reporting guidelines recommend that countries report greenhouse gas emissions on a full molecular weight basis, the final step in estimating CO_2 emissions from fossil fuel consumption was converting from units of carbon to units of CO_2. Actual carbon emissions were multiplied by the molecular to atomic weight ratio of CO_2 to carbon (44/12) to obtain total carbon dioxide emitted from fossil fuel combustion in teragrams (Tg). The results are contained in Table O-6.

Comparison Between Sectoral and Reference Approaches

These two alternative approaches can both produce reliable estimates that are comparable within a few percent. The major difference between methodologies employed by each approach lies in the energy data used to derive carbon emissions (i.e., the actual reported consumption for the Sectoral Approach versus apparent consumption derived for the Reference Approach). In theory, both approaches should yield identical results. In practice, however, slight discrepancies occur. For the United States, these differences are discussed below.

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[16] Bunker fuels refer to quantities of fuels used for international transportation. The IPCC methodology accounts for these fuels as part of the energy balance of the country in which they were delivered to end-users. Carbon dioxide emissions from the combustion of these fuels were estimated separately and were not included in U.S. national totals. This is done to ensure that all fuel is accounted for in the methodology and so that the IPCC is able to prepare global emission estimates.

[17] Carbon coefficients from EIA were used wherever possible. Because EIA did not provide coefficients for coal, the IPCC-recommended emission factors were used in the top-down calculations for these fuels. See notes in Table O-4 for more specific source information.

[18] For the portion of carbon that is unoxidized during coal combustion, the IPCC suggests a global average value of 2 percent. However, because combustion technologies in the United States are more efficient, the United States inventory uses one percent in its calculations for petroleum and coal and 0.5 percent for natural gas.

Differences in Total Amount of Energy Consumed

Table O-7 summarizes the differences between the two methods in estimating total energy consumption in the United States. Although theoretically the two methods should arrive at the same estimate for U.S. energy consumption, the Sectoral Approach provides an energy total that is about 2.2 percent higher than the Reference Approach. The greatest difference lies in the higher estimate of petroleum consumption with the Sectoral Approach. There are several potential sources for these discrepancies:

- *Product Definitions.* The fuel categories in the Reference Approach are different from those used in the Sectoral Approach, particularly for petroleum. For example, the Reference Approach estimates apparent consumption for crude oil. Crude oil is not typically consumed directly, but refined into other products. As a result, the United States does not focus on estimating the energy content of crude oil, but rather estimating the energy content of the various products resulting from crude oil refining. The United States does not believe that estimating apparent consumption for crude oil, and the resulting energy content of the crude oil, is the most reliable method for the United States to estimate its energy consumption. Other differences in product definitions include using sector-specific coal statistics in the Sectoral Approach (i.e., residential, commercial, industrial coking, industrial other, and transportation coal), while the Reference Approach characterizes coal by rank (i.e. anthracite, bituminous, etc.). Also, the liquefied petroleum gas (LPG) statistics used in the bottom-up calculations are actually a composite category composed of natural gas liquids (NGL) and LPG.

- *Heat Equivalents.* It can be difficult to obtain heat equivalents for certain fuel types, particularly for categories such as "crude oil" where the key statistics are derived from thousands of producers in the United States and abroad. For heat equivalents by coal rank, it was necessary to refer back to EIA's *State Energy Data Report 1992* (1994) because this information is no longer published.

- *Possible inconsistencies in U.S. Energy Data.* The United States has not focused its energy data collection efforts on obtaining the type of aggregated information used in the Reference Approach. Rather, the United States believes that its emphasis on collection of detailed energy consumption data is a more accurate methodology for the United States to obtain reliable energy data. Therefore, top-down statistics used in the Reference Approach may not be as accurately collected as bottom-up statistics applied to the Sectoral Approach.

- *Balancing Item.* The Reference Approach uses *apparent* consumption estimates while the Sectoral Approach uses *reported* consumption estimates. While these numbers should be equal, there always seems to be a slight difference that is often accounted for in energy statistics as a "balancing item."

Differences in Estimated CO_2 Emissions

Given these differences in energy consumption data, the next step for each methodology involved estimating emissions of CO_2. Table O-8 summarizes the differences between the two methods in estimated carbon emissions.

As previously shown, the Sectoral Approach resulted in a 2.2 percent higher estimate of energy consumption in the United States than the Reference Approach, but the resulting estimates of carbon emissions are almost exactly the same. While the Reference Approach estimates of coal and gas emissions were slightly higher than the bottom-up numbers, top-down oil emission estimates were lower than the Sectoral Approach. Overall emissions balance out because of these differences. Potential reasons for these patterns may include:

- *Product Definitions.* Coal data is aggregated differently in each methodology, as noted above, with United States coal data typically collected in the format used the Sectoral Approach. This results in more accurate estimates than in the Reference Approach. Also, the Reference Approach relies on a "crude oil" category for determining petroleum-related emissions. Given the many sources of crude oil in the United States, it is not an easy matter to track potential differences in carbon content between different sources of crude, particularly since information on the carbon content of crude oil is not regularly collected.

- *Carbon Coefficients.* The Reference Approach relies on several default carbon coefficients provided by IPCC (IPCC/UNEP/OECD/IEA 1997), while the Sectoral Approach uses category-specific coefficients that are likely to be more accurate. Also, as noted above, the carbon coefficient for crude oil is not an easy value to obtain given the many sources and grades of crude oil consumed in the United States.

Although the two approaches produce similar results, the United States believes that the "bottom-up" Sectoral Approach provides a more accurate assessment of CO_2 emissions at the fuel level. This improvement in accuracy is largely a result of the data collection techniques used in the United States, where there has been more emphasis on obtaining the detailed products-based information used in the Sectoral Approach than obtaining the aggregated energy flow data used in the Reference Approach. However, the United States also believes that it is valuable to understand fully the reasons for the differences between the two methods.

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Table O-1: 1996 U.S. Energy Statistics (physical units)

Fuel Category (Units)	Fuel Type	Production	Imports	Exports	Stock Change	Bunkers	U.S. Territories
Solid Fuels (1000 Short Tons)	Anthracite Coal	4,768	[1]	[1]	[1]		
	Bituminous Coal	630,741	[1]	[1]	[1]		
	Sub-bituminous Coal	340,291	[1]	[1]	[1]		
	Lignite	88,056	[1]	[1]	[1]		
	Coke		1,111	1,121	21		
	Unspecified Coal		6,476	90,473	(17,411)		460
Gas Fuels (Million Cubic Feet)	Natural Gas	19,289,254	2,844,207	151,262	(11,000)		
Liquid Fuels (Thousand Barrels)	Crude Oil	2,366,017	2,747,839	40,211	(45,299)		
	Nat Gas Liquids and LRGs	669,820	77,286	19,459	(7,620)		1,450
	Other Liquids	84,349	213,934	7,869	(7)		
	Motor Gasoline		123,099	38,127	(4,287)		17,853
	Aviation Gasoline		49	-	(72)		
	Kerosene		452	793	(178)		13,967
	Jet Fuel		40,561	17,673	(146)	54,983	
	Distillate Fuel		84,234	69,603	(3,485)	18,657	22,452
	Residual Fuel		90,854	37,165	8,732	104,370	24,143
	Naptha for Petrofeed		20,231	-	(1,041)		
	Petroleum Coke		510	104,359	272		
	Other Oil for Petrofeed		52,030	-	(8)		
	Special Napthas		3,457	7,598	(139)		
	Lubricants		4,185	12,506	(291)		219
	Waxes		468	1,002	57		
	Asphalt/Road Oil		9,833	2,448	(1,997)		
	Still Gas		-	-	-		
	Misc. Products		106	84	73		13,240

[1] Included in Unspecified Coal

Data Sources: Solid Fuels - EIA Coal Industry Annual 1996; Gas Fuels - EIA Annual Energy Review 1996; Liquid Fuels - EIA Petroleum Supply Annual 1996

Table O-2: Conversion Factors to Energy Units (heat equivalents)

Fuel Category (Units)	Fuel Type	Production	Imports	Exports	Stock Change	Bunkers	U.S. Territories
Solid Fuels (Million BTU/Short Ton)	Anthracite Coal	22.573					
	Bituminous Coal	23.89					
	Sub-bituminous Coal	17.14					
	Lignite	12.866					
	Coke		24.8	24.8	24.8		
	Unspecified		25.000	26.174	21.287		21.287
Natural Gas (BTU/Cubic Foot)		1,027	1,022	1,011	1,027		
Liquid Fuels (Million Btu/Barrel)	Crude Oil	5.800	5.935	5.800	5.800	5.800	5.800
	Nat Gas Liquids and LRGs	3.777	3.777	3.777	3.777	3.777	3.777
	Other Liquids	5.825	5.825	5.825	5.825	5.825	5.825
	Motor Gasoline		5.253	5.253	5.253	5.253	5.253
	Aviation Gasoline		5.048	5.048	5.048	5.048	5.048
	Kerosene		5.67	5.67	5.67	5.67	5.67
	Jet Fuel		5.67	5.67	5.67	5.67	5.67
	Distillate Fuel		5.825	5.825	5.825	5.825	5.825
	Residual Oil		6.287	6.287	6.287	6.287	6.287
	Naptha for Petrofeed		5.248	5.248	5.248	5.248	5.248
	Petroleum Coke		6.024	6.024	6.024	6.024	6.024
	Other Oil for Petrofeed		5.825	5.825	5.825	5.825	5.825
	Special Napthas		5.248	5.248	5.248	5.248	5.248
	Lubricants		6.065	6.065	6.065	6.065	6.065
	Waxes		5.537	5.537	5.537	5.537	5.537
	Asphalt/Road Oil		6.636	6.636	6.636	6.636	6.636
	Still Gas		6.000	6.000	6.000	6.000	6.000
	Misc. Products		5.796	5.796	5.796	5.796	5.796

Data Sources: Coal and lignite production - EIA State Energy Data Report 1992; Coke - EIA Annual Energy Review 1996; Unspecified Solid Fuels - EIA Monthly Energy Review, April 1998; Natural Gas - EIA Monthly Energy Review, April 1998; Crude Oil - EIA Monthly Energy Review, April 1998; Natural Gas Liquids and LRGs - EIA Petroleum Supply Annual 1996; all other Liquid Fuels - EIA Monthly Energy Review, April 1998

Table O-3: 1996 Apparent Consumption of Fossil Fuels (trillion Btu)

Fuel Category	Fuel Type	Production	Imports	Exports	Stock Change	Bunkers	U.S. Territories	Apparent Consumption
Solid Fuels	Anthracite Coal	107.6					-	107.6
	Bituminous Coal	15,068.4					-	15,068.4
	Sub-bituminous Coal	5,832.6					-	5,832.6
	Lignite	1,132.9					-	1,132.9
	Coke	-	27.6	27.8	0.5		-	(0.8)
	Unspecified	-	161.9	2,368.0	(370.6)		9.8	(1,825.7)
Gas Fuels	Natural Gas	19,810.1	2,906.8	152.9	(11.3)		-	22,575.2
Liquid Fuels	Crude Oil	13,722.9	16,308.4	233.2	(262.7)	-	-	30,060.8
	Nat Gas Liquids and LRGs	2,529.9	291.9	73.5	(28.8)	-	5.5	2,782.6
	Other Liquids	491.3	1,246.2	45.8	(0.0)	-	-	1,691.7
	Motor Gasoline	-	646.6	200.3	(22.5)	-	93.8	562.7
	Aviation Gasoline	-	0.2	-	(0.4)	-	-	0.6
	Kerosene	-	2.6	4.5	(1.0)	-	79.2	78.3
	Jet Fuel	-	230.0	100.2	(0.8)	311.8	-	(181.2)
	Distillate Fuel	-	490.7	405.4	(20.3)	108.7	130.8	127.6
	Residual Oil	-	571.2	233.7	54.9	656.2	151.8	(221.7)
	Naptha for Petrofeed	-	106.2	-	(5.5)	-	-	111.6
	Petroleum Coke	-	3.1	628.7	1.6	-	-	(627.2)
	Other Oil for Petrofeed	-	303.1	-	(0.0)	-	-	303.1
	Special Napthas	-	18.1	39.9	(0.7)	-	-	(21.0)
	Lubricants	-	25.4	75.8	(1.8)	-	1.3	(47.4)
	Waxes	-	2.6	5.5	0.3	-	-	(3.3)
	Asphalt/Road Oil	-	65.3	16.2	(13.3)	-	-	62.3
	Still Gas	-	-	-	-	-	-	-
	Misc. Products	-	0.6	0.5	0.4	-	76.7	76.4
Total		**58,695.8**	**23,408.3**	**4,612.1**	**(682.0)**	**1,076.6**	**548.9**	**77,646.3**

Note: Totals may not sum due to independent rounding.

Table O-4: 1996 Potential Carbon Emissions

Fuel Category	Fuel Type	Apparent Consumption (QBTU)	Carbon Coefficients (MMTCE/QBTU)	Potential Carbon Emissions (MMTCE)
Solid Fuels	Anthracite Coal	0.11	26.86	2.9
	Bituminous Coal	15.07	25.86	389.7
	Sub-bituminous Coal	5.83	26.26	153.2
	Lignite	1.13	27.66	31.3
	Coke	(0.00)	25.56	(0.0)
	Unspecified	(1.83)	25.74	(47.0)
Gas Fuels	Natural Gas	22.58	14.47	326.7
Liquid Fuels	Crude Oil	30.06	20.23	608.1
	Nat Gas Liquids and LRGs	2.78	16.99	47.3
	Other Liquids	1.69	20.23	34.2
	Motor Gasoline	0.56	19.38	10.9
	Aviation Gasoline	0.00	18.87	0.0
	Kerosene	0.08	19.72	1.5
	Jet Fuel	(0.18)	19.33	(3.5)
	Distillate Fuel	0.13	19.95	2.5
	Residual Oil	(0.22)	21.49	(4.8)
	Naptha for Petrofeed	0.11	18.14	2.0
	Petroleum Coke	(0.63)	27.85	(17.5)
	Other Oil for Petrofeed	0.30	19.95	6.0
	Special Napthas	(0.02)	19.86	(0.4)
	Lubricants	(0.05)	20.24	(1.0)
	Waxes	(0.00)	19.81	(0.1)
	Asphalt/Road Oil	0.06	20.62	1.3
	Still Gas	0.00	17.51	0.0
	Misc. Products	0.08	19.81	1.5
Total				**1545.0**

Data Sources: Coal and Lignite - *Revised 1996 IPCC Guidelines Reference Manual*, Table 1-1; Coke - EIA *Monthly Energy Review*, April 1998 Table C1; Unspecified Solid Fuels - EIA *Monthly Energy Review*, April 1998 Table C1 (U.S. Average); Natural Gas and Liquid Fuels - EIA *Emissions of Greenhouse Gases in the United States 1996.*

Note: Totals may not sum due to independent rounding.

Table O-5: 1996 Carbon Stored in Products

	Consumption for Non-Fuel Use (Trillion BTU)	Carbon (MMTCE/QBTU)	Carbon (MMTCE)	Fraction	Carbon Sequestered (MMTCE)
	27.8	25.53		0.75	0.5
	381.4	14.47		1.00	5.5
	1175.9	20.62		1.00	24.2
	1698.7	16.99		0.80	23.1
	335.5	20.24		0.50	3.4
	319.0	18.24		0.80	4.7
	[1]	[1]		[1]	13.8
	208.0	27.85		0.50	2.9
	74.5	19.86		0	0.0
	[1]	[1]		[1]	3.4
	[1]	[1]		[1]	0.2
					81.7

[1] Values for Misc. U.S. Territories Petroleum, Petrochemical Feedstocks and Waxes/Misc. are not shown because these categories are aggregates of numerous smaller components.

Table O-6: Reference Approach CO_2 Emissions from Fossil Fuel Consumption (MMTCE unless otherwise noted)

Fuel Category	Potential Carbon Emissions	Carbon Sequestered	Net Carbon Emissions	Fraction Oxidized (percent)	CO_2 Emissions (MMTCE)	CO_2 Emissions (Tg)
Coal	530.0	0.5	529.5	99.0%	524.2	1922.1
Petroleum	688.3	75.7	612.7	99.0%	606.5	2223.9
Natural Gas	326.7	5.5	321.1	99.5%	319.5	1171.6
Total	**1,545.0**	**81.7**	**1463.3**	**-**	**1450.3**	**5317.7**

Note: Totals may not sum due to independent rounding.

Table O-7: 1996 Energy Consumption in the United States: Sectoral vs. Reference Approaches (trillion BTU)

Approach	Coal	Natural Gas	Petroleum	Total
Sectoral[a]	20,570	22,508	36,340	79,419
Reference (Apparent)[a]	20,315	22,575	34,756	77,646
Difference	**-1.2%**	**0.3%**	**-4.4%**	**-2.2%**

[a] Includes U.S. territories

Note: Totals may not sum due to independent rounding.

Table O-8: 1996 CO_2 Emissions from Fossil Fuel Combustion by Estimating Approach (MMTCE)

Approach	Coal	Natural Gas	Petroleum	Total
Sectoral[a]	524.0	318.6	607.7	1450.3
Reference[a]	524.2	319.5	606.5	1450.3
Difference	**0.0%**	**0.3%**	**-0.2%**	**0.0%**

[a] Includes U.S. territories

Note: Totals may not sum due to independent rounding.

Annex P

Preliminary 1997 Estimates of U.S. Greenhouse Gas Emissions and Sinks

This annex provides preliminary 1997 estimates of greenhouse gas emissions and sinks. Although these calculations are not final, large changes are not expected, and therefore, this annex allows the reader to evaluate the trend in U.S. emissions.

The following trends are evident based on a comparison of these preliminary 1997 estimates and 1990 through 1996 estimates found in the body of this report. In 1997, total U.S. emissions appear to have grown by 180 MMTCE (11.0 percent) since 1990. From 1996 to 1997, emissions rose by 1.4 percent, or 25 MMTCE. Table P-1 below shows preliminary estimates in teragrams (Tg) of gas and MMTCE.

Specifically, emissions of CO_2 increased by 10.6 percent over the 8 year period, and by 1.4 percent in the last year. Increases in emissions from coal and natural gas combustion by utilities and petroleum consumption by industry were responsible for the majority of this increase in emissions.

Methane emissions grew by 5.5 percent over the 1990 to 1997 period, and by 0.4 percent in the last year. From 1996 to 1997, most CH_4 sources experienced small increases or decreases. Emissions from rice cultivation grew the most in terms of percentage (10.1 percent), while landfill emissions grew the most absolutely (1.6 MMTCE).

Nitrous oxide emissions rose 13.8 percent over the 1990 to 1997 period. However, from 1996 to 1997, N_2O emissions increased by only 1.2 percent or 1.3 MMTCE. In the last year, emissions from adipic acid production dropped by 37 percent due to improved industrial controls. As a percentage increase, emissions from manure management rose the most (25.7 percent). The source contributing the most to the total N_2O increase was agricultural soil management (1.6 MMTCE).

Emissions of HFCs, PFCs, and SF_6 showed a 6.4 percent increase from 1996 to 1997. Over the 1990 to 1997 period, emissions from this sector increased by 66.4 percent or 14.7 MMTCE. In the last year, emissions from HCFC-22 production and semiconductor manufacture showed a slight decrease. However, increased emissions of 2.6 MMTCE from the substitution of ozone depleting substances offset this trend.

Table P-1: Preliminary 1997 Estimates of U.S. Greenhouse Gas Emissions and Sinks

Gas/Source	Tg	MMTCE
CO_2	**5,469.3**	**1,491.6**
Fossil Fuel Combustion	5,391.4	1,470.4
Natural Gas Flaring	12.4	3.4
Cement Manufacture	38.8	10.6
Lime Manufacture	14.2	3.9
Limestone and Dolomite Use	7.0	1.9
Soda Ash Manufacture and Consumption	4.4	1.2
Carbon Dioxide Manufacture	1.1	0.3
Land-Use Change and Forestry (Sink)[a]	(764.7)	(208.6)
CH_4	**31.3**	**179.3**
Stationary Sources	0.39	2.24
Mobile Sources	0.2	1.2
Coal Mining	3.3	18.7
Natural Gas Systems	5.9	33.5
Petroleum Systems	0.3	1.6
Petrochemical Production	0.1	0.4
Silicon Carbide Production	+	+
Enteric Fermentation	6.0	34.2
Manure Management	3.0	17.0
Rice Cultivation	0.5	2.7
Agricultural Residue Burning	+	0.2
Landfills	11.7	66.7
Wastewater Treatment	0.2	0.9
N_2O	**876.7**	**105.0**
Stationary Sources	+	4.13
Mobile Sources	0.2	16.9
Adipic Acid	+	3.4
Nitric Acid	0.1	4.2
Manure Management	43.9	3.7
Agricultural Soil Management	830.8	70.2
Agricultural Residue Burning	1.6	0.1
Human Sewage	+	2.3
Waste Combustion	+	0.1
HFCs, PFCs, and SF_6	**M**	**36.9**
Substitution of Ozone Depleting Substances	M	14.5
Aluminum Production	M	2.9
HCFC-22 Production[b]	+	8.2
Semiconductor Manufacture	M	1.3
Electrical Transmission and Distribution[c]	+	7.0
Magnesium Production and Processing[c]	+	3.0
Total Emissions	**NA**	**1812.9**
Net Emissions	**NA**	**1604.4**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 Tg or 0.05 MMTCE
M (Mixture of multiple gases)
NA (Not Applicable)
[a] Sinks are not included in CO_2 emissions total.
[b] HFC-23 emitted
[c] SF_6 emitted

Annex Q
Sources of Greenhouse Gas Emissions Excluded

Although this report is intended to be a comprehensive assessment of anthropogenic sources and sinks of greenhouse gas emissions for the United States, certain sources have been identified yet excluded from the estimates presented for various reasons. Before discussing these sources, however, it is important to note that processes or activities that are not *anthropogenic in origin* or do not result in a *net source or sink* of greenhouse gas emissions are intentionally excluded from a national inventory of greenhouse gas emissions. In general, processes or activities that are not anthropogenic are considered natural (i.e., not directly influenced by human activity) in origin and, as an example, would include the following:

- Volcanic eruptions
- CO_2 exchange (i.e., uptake or release) by oceans
- Natural forest fires[19]
- CH_4 emissions from wetlands not affected by human induced land-use changes

Some activities or process may be anthropogenic in origin but do not result in net emissions of greenhouse gases, such as the respiration of CO_2 by living organisms. Given a source category that is both anthropogenic and results in net greenhouse gas emissions, reasons for excluding a source related to an anthropogenic activity include one or more of the following:

- There is currently insufficient scientific understanding to develop a reliable method for estimating emissions at a national level.
- Although an estimating method has been developed, data was not adequately available to calculate emissions.
- Emissions were implicitly accounted for within another source category (e.g., CO_2 from fossil fuel combustion).

It is also important to note that the United States believes the exclusion of the sources discussed below introduces only a minor bias in its overall estimate of U.S. greenhouse gas emissions.

N_2O from the Combustion of Jet Fuel

The combustion of jet fuel by aircraft results in N_2O emissions. The N_2O emissions per mass of fuel combusted during landing/take-off (LTO) operations differ significantly from those during aircraft cruising. Accurate estimation of these N_2O emissions requires a detailed accounting of LTO cycles and fuel consumption during cruising by aircraft model (e.g., Boeing 747-400). Sufficient data for calculating such N_2O emissions were not available for this report. (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 1.93 - 1.96)

Emissions from Bunker Fuels and Fossil Fuels Combusted Abroad by the U.S. Military

Emissions from fossil fuels combusted in military vehicles (i.e., ships, aircraft, and ground vehicles) may or may not be included in U.S. energy statistics. Domestic fuel sales to the military are captured in U.S. energy statistics; however, fuels purchased abroad for base operations and refueling of vehicles are not. It is not clear to what degree fuels purchased domestically are exported by the military to bases abroad.

[19] In some cases forest fires that are started either intentionally or unintentionally are viewed as mimicking natural burning processes which have been suppressed by other human forest management activities. The United States does not consider forest fires within its national boundaries to be a net source of greenhouse emissions.

Fuels combusted by military ships and aircraft while engaged in international transport or operations in international waters or airspace (i.e., flying or cruising in international airspace or waters) that is purchased domestically is included in U.S. energy statistics. Therefore, the United States currently under reports its emissions of CO_2 from international bunker fuels, and most likely over reports its CO_2 emissions from transportation related fossil fuel combustion by the same amount. At this time, fuel consumption statistics from the Department of Defense are not adequately detailed to correct for this bias.[20]

CO_2 from Burning in Coal Deposits and Waste Piles

Coal is periodically burned in deposits and waste piles. It has been estimated that the burning of coal in deposits and waste piles would represent less than 1.3 percent of total U.S. coal consumption (averaged over ten-years). Because there is currently no known source of data on the quantity of coal burned in waste piles and there is uncertainty as to the fraction of coal which is oxidized during such burnings, these CO_2 emissions are not currently estimated. Further research would be required to develop accurate emission factors and activity data for these emissions to be estimated. (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 1.112 - 1.113)

Fossil CO_2 from Petroleum and Natural Gas Wells, CO_2 Separated from Natural Gas, and CO_2 from Enhanced Oil Recovery (EOR)

Petroleum and natural gas well drilling, petroleum and natural gas production, and natural gas processing—including removal of CO_2—may result in emissions of CO_2 that was at one time stored in underground formations. Sufficient methodologies for estimating emissions of this "fossil" CO_2 at the national level have not been adequately developed.

Carbon dioxide is also injected into underground deposits to increase crude oil reservoir pressure in a field technique known as enhanced oil recovery (EOR). It is thought that much of the injected CO_2 may be effectively and permanently sequestered, but the fraction of injected CO_2 which is re-released remains uncertain. The fraction re-released varies from well to well depending upon the field geology and the gas capture/re-injection technology employed at the wellhead. Further research into EOR is required before the resulting CO_2 emissions can be adequately quantified. (see the discussion of the Carbon Dioxide Manufacture source category in the Industrial Processes sector)

Carbon Sequestration in Underground Injection Wells

Organic hazardous wastes are injected into underground wells. Depending on the source of these organic substances (e.g., derived from fossil fuels) the carbon in them may or may not be included in U.S. CO_2 emission estimates. Sequestration of carbon containing substances in underground injection wells may be an unidentified sink. Further research is required to if this potential sink is to be quantified.

CH_4 from Abandoned Coal Mines

Abandoned coal mines are a source of CH_4 emissions. In general, many of the same factors that affect emissions from operating coal mines will affect emissions from abandoned mines such as the permeability and gassiness of the coal, the mine's depth, geologic characteristics, and whether it has been flooded. A few gas developers have recovered methane from abandoned mine workings; therefore, emissions from this source may not be insignificant. Further research and methodological development is needed if these emissions are to be estimated.

CO_2 from Unaccounted for Natural Gas

There is a discrepancy between the amount of natural gas sold by producers and that reported as purchased by consumers. This discrepancy, known as unaccounted for or unmetered natural gas, was assumed to be the sum of

[20] See the Defense Energy Support Center (formerly the Defense Fuel Supply Center), *Fact Book 1997*. [http://www.desc.dla.mil/main/pulicati.htm]

leakage, measurement errors, data collection problems, undetected non-reporting, undetected overreporting, and undetected underreporting. Historically, the amount of gas sold by producers has always exceeded that reportedly purchased by consumers; therefore, some portion of unaccounted for natural gas was assumed to be a source of CO_2 emissions. (It was assumed that consumers were underreporting their usage of natural gas.) In DOE/EIA's energy statistics for 1996, however, reported consumption of natural gas exceeded the amount sold by producers. Therefore, the historical explanation given for this discrepancy has lost credibility and unaccounted for natural gas is no longer used to calculate CO_2 emissions. (see section on Changes in the U.S. Greenhouse Gas Inventory Report)

CO_2 from Shale Oil Production

Oil shale is shale saturated with kerogen.[21] It can be thought of as the geological predecessor to crude oil. Carbon dioxide is released as a by-product of the process of producing petroleum products from shale oil. As of now, it is not cost-effective to mine and process shale oil into usable petroleum products. The only identified large-scale oil shale processing facility in the U.S. was operated by Unocal during the year of 1985 to 1990. There have been no known emissions from shale oil processing in the United States since 1990 when the Unocal facility closed.

CH_4 from the Production of Carbides other than Silicon Carbide

Methane may be emitted from the production of carbides because the petroleum coke used in the process contains volatile organic compounds which form methane during thermal decomposition. Methane emissions from the production of silicon carbide were estimated and accounted for, but emissions from the production of calcium carbide and other carbides were not. Further research is needed to estimate CH_4 emissions from the production of calcium carbide and other carbides other than silicon carbide. (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.20 - 2.21)

CO_2 from Calcium Carbide and Silicon Carbide Production

Carbon dioxide is formed by the oxidation of petroleum coke in the production of both calcium carbide and silicon carbide. These CO_2 emissions are implicitly accounted for with emissions from the combustion of petroleum coke under the Energy sector. There is currently not sufficient data on coke consumption to estimate emissions from these sources explicitly. (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.20 - 2.21)

CO_2 from Graphite Consumption in Ferroalloy and Steel Production

The CO_2 emissions from the three reducing agents used in ferroalloy and steel production—coke, wood (or biomass), and graphite—are accounted for as follows:

- Emissions resulting from the use of coke are accounted for in the Energy sector under fossil fuel combustion.
- Estimating emissions from the use of wood or other biomass materials is unnecessary because these emissions should be accounted for under Land-Use Change and Forestry sector if the biomass is harvested on an unsustainable basis.
- The CO_2 emissions from the use of graphite, which is produced from petroleum by-products, may be accounted for in the Energy sector (further analysis is required to determine if these emissions are being properly estimated). The CO_2 emissions from the use of natural graphite, however, have not been accounted for in the estimate.

Emissions from graphite electrode consumption—versus its use as a reducing agent—in ferroalloy and steel production may at present only be accounted for in part under fossil fuel combustion if the graphite used was derived from a fossil fuel substrate (versus natural graphite ore). Further research into the source and total consumption of

[21] Kerogen is fossilized insoluble organic material found in sedimentary rocks, usually shales, which can be converted to petroleum products by distillation.

graphite for these purposes is required to explicitly estimate emissions. (see Iron and Steel Production and Ferroalloy Production in the Industrial Processes sector)

N_2O from Caprolactam Production

Caprolactam is a widely used chemical intermediate, primarily to produce nylon-6. All processes for producing caprolactam involve the catalytic oxidation of ammonia, with N_2O being produced as a by-product. Caprolactam production could be a significant source of N_2O—it has been identified as such in the Netherlands. More research is required to determine this source's significance because there is currently insufficient information available on caprolactam production to estimate emissions in the United States. (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.22 - 2.23)

N_2O from Cracking of Certain Oil Fractions

In order to improve the gasoline yield in crude oil refining, certain oil fractions are processed in a catcracker. Because crude oil contains some nitrogen, N_2O emissions may result from this cracking process. There is currently insufficient data to develop a methodology for estimating these emissions. (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.23)

CH_4 from Coke Production

Coke production may result in CH_4 emissions. Detailed coke production statistics were not available for the purposes of estimating CH_4 emissions from this minor source. (see Petrochemical Production under the Industrial Processes sector and the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.23)

CO_2 from Metal Production

Coke is used as a reducing agent in the production of some metals from their ores, including magnesium, chromium, lead, nickel, silicon, tin, titanium, and zinc. Carbon dioxide may be emitted during the metal's production from the oxidization of the coke used as a reducing agent and, in some cases, from the carbonate ores themselves (e.g., some magnesium ores contain carbonate). The CO_2 emissions from coke oxidation are accounted for in the Energy sector under Fossil Fuel Combustion. The CO_2 emissions from the carbonate ores are not presently accounted for, but their quantities are thought to be minor. (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.37 - 2.38)

N_2O from Acrylonitrile Production

Nitrous oxide may be emitted during acrylonitrile production. No methodology was available for estimating these emissions, and therefore further research is needed if these emissions are to be included. (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.22)

Miscellaneous SF_6 Uses

Sulfur hexafluoridemay be used in gas-filled athletic shoes, in foam insulation, for dry etching, in laser systems, as an atmospheric tracer gas, for indoor air quality testing, for laboratory hood testing, for chromatography, in tandem accelerators, in sound-insulating windows, in tennis balls, in loudspeakers, in shock absorbers, and for certain biomedical applications. Data need to be gathered and methodologies developed if these emissions are to be estimated.

CO_2 from Solvent Incineration

CO_2 may be released during the incineration of solvents. Although emissions from this source are believed to be minor, data need to be gathered and methodologies developed if these emissions are to be estimated.

CO_2 from Non-Forest Soils

Non-forest soils emit CO_2 from decaying organic matter and carbonate minerals—the latter may be naturally present or mined and later applied to soils as a means to adjust their acidity. Soil conditions, climate, and land-use practices interact to affect the CO_2 emission rates from non-forest soils. The U.S. Forest Service has developed a model to estimate CO_2 emissions from forest soils, but no such model has been adequately developed for non-forest soils. Further research and methodological development is needed if these emissions are to be accurately estimated. (see Changes in Non-Forest Carbon Stocks under the Land-Use Change and Forestry sector)

CH_4 from Land-Use Changes Including Wetlands Creation or Destruction

Wetlands are a known source of CH_4 emissions. When wetlands are destroyed, CH_4 emissions may be reduced. Conversely, when wetlands are created (e.g., during the construction of hydroelectric plants), CH_4 emissions may increase. Grasslands and forest lands may also be weak sinks for CH_4 due to the presence of methanotrophic bacteria that use CH_4 as an energy source (i.e., they oxidize CH_4 to CO_2). Currently, an adequate scientific basis for estimating these emissions and sinks does not exist, and therefore further research and methodological development is required.

CH_4 from Septic Tanks and Drainfields

Methane is produced during the biodegradation of organics in septic tanks if other suitable electron-acceptors (i.e., oxygen, nitrate, or sulfate) besides CO_2 are unavailable. Such conditions are called methanogenic. There were insufficient data and methodological developments available to estimate emissions from this source.

N_2O from Wastewater Treatment

As a result of nitrification and denitrification processes, N_2O may be produced and emitted from wastewater treatment plants. Nitrogen-containing compounds are found in wastewater due to the presence of both human excrement and other nitrogen-containing constituents (e.g. garbage, industrial wastes, dead animals, etc.). The portion of emitted N_2O which originates from human excrement is currently estimated under the Human Sewage source category—based upon average dietary assumptions. The portion of emitted N_2O which originates from other nitrogen-containing constituents is not currently estimated. Further research and methodological development is needed if these emissions are to be accurately estimated.

CH_4 from Industrial Wastewater

Methane may be produced during the biodegradation of organics in wastewater treatment if other suitable electron-acceptors (i.e. oxygen, nitrate, or sulfate) besides CO_2 are unavailable. Such conditions are called methanogenic. Methaneproduced from domestic wastewater treatment plants is accounted for under the Waste sector. These emissions are estimated by assuming an average 5-day biological oxygen demand (BOD_5) per capita contribution in conjunction with the approximation that 15 percent of wastewater's BOD_5 is removed under methanogenic conditions. This method itself needs refinement. It is not clear if industrial wastewater sent to domestic wastewater treatment plants, which may contain biodegradable material, would be accounted for in the average BOD_5 per capita number. Additionally, CH_4 emissions from methanogenic processes at industrial wastewater treatment plants are not currently estimated. Further research and methodological development is needed if these emissions are to be accurately estimated. (see Wastewater Treatment under the Waste sector)

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