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Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1999

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For Further Information

Contact Mr. Michael Gillenwater, Environmental Protection Agency, (202) 564-4092, gillenwater.michael@epa.gov.

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Non-Energy Uses of Fossil Fuels

The products and production processes pictured on the front and back cover of this report depict non-energy uses of fossil fuels. Rather than being combusted for energy, fuels consumed for non-energy purposes act as building blocks or reagents in fabricating other materials. These fossil fuel-derived materials are important from an emissions perspective since they often provide long-term storage of a portion of the fuel's carbon.

Refinery: Crude oil is a mixture of many hydrocarbon chains of various lengths. Refineries process crude oil by distillation, separating the fuel into its hydrocarbon components according to their boiling points and molecular weights. The oil "fractions" are further reacted through such processes as catalytic cracking and hydroprocessing to form the petrochemical feedstocks that serve as the building blocks of synthetic products.

Plastics: Monomers derived from oil and natural gas are reacted to form polymeric resins for use as plastics. Plastics store this fossil fuel carbon during their lifetime and, if recycled or landfilled, they can continue to act to store carbon.

Asphalt: Asphalt is a product of the crude oil fractions with high boiling points and molecular weights. These "heavy" fractions are mixed with rock aggregate when laid on roads and highways, storing the fossil fuel carbon.

Textiles: Like plastics, synthetic fibers such as polyester, nylon, and acrylic are made from polymeric resins derived from fossil fuels. The resins are spun into fibers that can be used in clothing, furniture, safety equipment, and building materials. These products can also act to store their fossil fuel carbon.

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U.S. Environmental Protection Agency
Office of Atmospheric Programs (6202N)
1200 Pennsylvania Avenue, NW
Washington, DC 20460
USA

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Other government agencies have contributed data as well, including the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, the National Agricultural Statistics Service, the Federal Aviation Administration, and the Department of Defense.

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Preface

The United States Environmental Protection Agency (EPA) prepares the official *U.S. Inventory of Greenhouse Gas Emissions and Sinks* to comply with existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC).[1] Under a decision of the UNFCCC Conference of the Parties, national inventories for most UNFCCC Annex I parties should be provided to the UNFCCC Secretariat each year by April 15.

In an effort to engage the public and researchers across the country, the EPA has instituted an annual public review and comment process for this document. The availability of the draft document is announced via Federal Register Notice and is posted on the EPA web page.[2] Copies are also mailed upon request. The public comment period is generally limited to 30 days; however, comments received after the closure of the public comment period are accepted and considered for the next edition of this annual report. The EPA's policy is to allow at least 60 days for public review and comment when proposing new regulations or documents supporting regulatory development—unless statutory or judicial deadlines make a shorter time necessary—and 30 days for non-regulatory documents of an informational nature such as the Inventory document.

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[1] See http://www.unfccc.de

[2] See http://www.epa.gov/globalwarming/emissions/national

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Changes in This Year's Inventory Report

Each year the EPA not only recalculates and revises the emission and sink estimates for all years that are presented in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* but also attempts to improve the analyses themselves through the use of better methods or data as well as the overall usefulness of the report. A summary of this year's changes is presented in the following sections and includes updates to historical data in addition to changes in methodology. The magnitude of each change is also described. Table Changes-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and Table Changes-2 summarizes the quantitative effect on U.S. sinks, both relative to the previously published U.S. Inventory (i.e., 1990-1998 report). These tables present the magnitude of these changes in units of teragrams of carbon dioxide (CO_2) equivalents (Tg CO_2 Eq.). (See Box Changes-1.)

Changes in historical data are generally the result of changes in statistical data supplied by other agencies. Data sources are provided for further reference.

For methodological changes, differences between the previous Inventory report and this report are explained. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 1998) has been recalculated to reflect the change.

Box Changes - 1: Emission Reporting Nomenclature

The Global Warming Potential (GWP) weighted emissions of all direct greenhouse gases in this report are presented in terms of equivalent emissions of carbon dioxide (CO_2), using units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.). In previous year's inventories emissions were reported in terms of carbon—versus carbon dioxide—equivalent emissions, using units of million metric tons of carbon equivalents (MMTCE). This change of units for reporting was implemented so that the U.S. Inventory would be more consistent with international practices, which are to report emissions in carbon dioxide equivalent units.

In order to convert the emission estimates presented in this report to those provided previously, the following equation can be employed:

$$\text{Tg } CO_2 \text{ Eq.} = \text{MMTCE} \times ({}^{44}/_{12})$$

There are two elements to the conversion. The first element is simply nomenclature, since one teragram is equal to one million metric ton:

$$\text{Tg} = 10^9 \text{ kg} = 10^6 \text{ metric tons} = \text{megaton} = 1 \text{ million metric tons}$$

The second element is the conversion, by weight, from carbon to carbon dioxide. The molecular weight of carbon is 12, and the molecular weight of oxygen is 16; therefore, the molecular weight of CO_2 is 44 (i.e., $12+[16\times2]$), as compared to 12 for carbon alone. Thus, carbon comprises $12/44^{ths}$ of carbon dioxide by weight.

Table Changes -1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CO_2	**(1.4)**	**(1.1)**	**9.4**	**0.7**	**18.0**	**26.0**	**27.1**	**28.7**	**11.7**
Waste Combustion	7.2	8.3	8.9	9.7	10.7	12.0	12.5	13.1	12.3
Fossil Fuel Combustion	(4.8)	(5.5)	4.2	(5.4)	11.2	17.4	18.1	19.0	3.3
Natural Gas Flaring	(4.0)	(4.0)	(3.9)	(3.7)	(3.6)	(3.6)	(3.5)	(3.5)	(3.4)
Other[a]	0.1	0.1	0.1	0.1	(0.2)	0.2	0.1	+	(0.5)
CH_4	**(7.7)**	**(8.7)**	**(9.4)**	**(17.1)**	**(19.5)**	**(24.6)**	**(33.5)**	**(41.7)**	**(38.6)**
Manure Management	(28.5)	(29.4)	(31.0)	(34.7)	(38.6)	(41.4)	(44.2)	(48.5)	(48.6)
Wastewater Treatment	8.0	8.1	8.2	8.3	8.4	8.5	8.5	8.6	8.7
Enteric Fermentation	9.5	8.6	10.2	6.0	9.1	8.3	5.5	4.2	3.9
Landfills	3.7	4.3	3.5	3.9	3.3	1.0	(1.5)	(2.9)	(2.0)
Other[a]	(0.4)	(0.4)	(0.4)	(0.6)	(1.8)	(1.2)	(1.8)	(3.2)	(0.7)
N_2O	**+**	**(0.8)**	**0.1**	**(1.3)**	**(2.4)**	**(3.8)**	**(4.0)**	**(4.8)**	**(4.0)**
Manure Management	3.7	3.5	3.4	3.3	3.0	2.7	2.8	2.8	2.5
Mobile Sources	3.9	4.1	4.2	4.1	3.6	2.9	1.2	1.8	1.2
Agricultural Soil Management	(7.2)	(8.1)	(7.1)	(8.3)	(8.7)	(9.6)	(7.6)	(9.0)	(7.2)
Other[a]	(0.4)	(0.4)	(0.4)	(0.4)	(0.3)	0.2	(0.4)	(0.3)	(0.5)
HFCs, PFCs, and SF_6	**(1.5)**	**(1.8)**	**(2.7)**	**(3.6)**	**(5.1)**	**(7.3)**	**(7.8)**	**(6.3)**	**(9.2)**
Magnesium Production and Processing	(0.7)	(1.7)	(2.6)	(3.7)	(4.9)	(5.5)	(5.4)	(3.5)	(4.7)
Substitution of Ozone Depleting Substances	NC	NC	NC	NC	(0.1)	(1.6)	(2.4)	(2.9)	(3.5)
Other[a]	(0.8)	(0.1)	(0.1)	0.1	(0.1)	(0.3)	+	0.1	(1.0)
Net Change in Total Emissions[b]	**(10.6)**	**(12.5)**	**(2.6)**	**(21.3)**	**(8.9)**	**(9.7)**	**(18.2)**	**(24.2)**	**(40.2)**
Percent Change	**-0.2%**	**-0.2%**	**+%**	**-0.3%**	**-0.1%**	**-0.2%**	**-0.3%**	**-0.4%**	**-0.6%**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Includes other source categories with only minor or no versions made to emission estimates.

[b] Excludes emissions from international bunker fuels and carbon sinks.

NC (No Change)

Note: Totals may not sum due to independent rounding.

Changes in Historical Data

- In the CO_2 Emissions from Fossil Fuel Combustion section of the Energy chapter, energy consumption data have been updated by the Energy Information Administration (EIA 2000a, 2000b, 2000c) for selected years (see below for detail on methodological changes). For example, the amount of coal combusted in the industrial end-use sector by nonutility generators of electricity was reused upward, resulting in an average 31.1 Tg CO_2 Eq. increase in emissions. In addition, the carbon content coefficients for motor gasoline blend components, unfinished oils, and miscellaneous petroleum products were revised from static to annually variable coefficients, based on EIA (2000b). The annually variable carbon content coefficients for coal (i.e., residential, commercial, industrial coking, industrial other, and utility coal) were expanded to include more significant digits, also based on EIA (2000b). These data changes, combined with the methodological changes described below, resulted in an average increase of 6.4 Tg of CO_2 Eq. (0.1 percent) in annual CO_2 emissions from fossil fuel combustion for 1990 through 1998.
- In the Stationary Combustion (excluding CO_2) section of the Energy chapter, two revisions to the energy consumption data were made. First, the EIA has provided estimates for commercial wood energy consumption for 1990 through 1992, which were previously not provided, and has revised the wood energy consumption data for the remaining years. Second, wood biomass has been reported separately

Table Changes-2: Revisions to Net CO_2 Sequestration from Land-Use Change and Forestry (Tg CO_2 Eq.)

Component	1990	1991	1992	1993	1994	1995	1996	1997	1998
Forests	140.5	152.6	204.3	(174.3)	(180.9)	(173.6)	(178.0)	(138.8)	(132.5)
Agricultural Soils	(40.4)	(39.7)	(40.9)	(70.0)	(69.3)	(68.8)	(68.9)	(69.0)	(77.3)
Landfilled Yard Trimmings	NC	NC	NC	NC	NC	NC	NC	NC	(0.5)
Total Change in Land-Use Change and Forestry Sequestration	**100.1**	**112.9**	**163.4**	**(244.3)**	**(250.2)**	**(242.4)**	**(246.9)**	**(207.8)**	**(210.3)**
Percent Change	**-8.6%**	**-11.2%**	**-15.6%**	**29.4%**	**30.4%**	**31.2%**	**31.9%**	**26.8%**	**27.2%**

NC (No Change)

Note: Numbers in parentheses indicate an *increase* in estimated net sequestration, or a decrease in net flux of CO_2 to the atmosphere. In the "percent change" row, negative numbers indicate that the sequestration estimate has decreased, and positive numbers indicate that the sequestration estimate has increased. These percents are based on sequestration estimates that were rounded to the nearest 10^2 gigagram CO_2. The previously published U.S. Inventory did not include agricultural soils in the total flux estimates for land-use change and forestry, so the data in the "agricultural soils" row are equal to the agricultural soil sequestration estimates presented in this Inventory. Totals may not sum due to independent rounding.

from wood wastes, liquors, municipal solid waste, tires, etc., in EIA's estimates of consumption for fuel combustion (EIA 2000a). Only estimates of wood consumption were used to calculate non-CO_2 emissions from stationary combustion. These revisions resulted in average decrease of 0.2 Tg CO_2 Eq. (2.8 percent) in annual stationary combustion methane emissions for 1990 through 1998. The average decrease in N_2O emissions was 0.4 Tg CO_2 Eq. (2.9 percent) for 1990 through 1998.

- In the Mobile Combustion (excluding CO_2) section of the Energy Chapter, estimates of 1996 to 1998 vehicle miles traveled were revised by the Federal Highway Administration (FHWA 1999). This data change, combined with the methodological changes described below, resulted in an average decrease of 0.4 Tg CO_2 Eq. (7.1 percent) in annual methane emissions for 1990 through 1998. Average N_2O emissions increased by 3.0 Tg CO_2 Eq. (5.2 percent) annually for 1990 through 1998.
- In the Coal Mining section of the Energy chapter, data on underground emissions have been revised and State gas sales data and coal production totals have been updated by DOE's Energy Information Administration (EIA 2000e). Due to improvements in the data, this year's inventory includes 5 additional coal mines for the 1998 data. Each year, States provide gas sales data, which are used to estimate emissions avoided from gas recovery projects. Previously, gas sales data for 1998 were not available, but this inventory reflects the final data from the States. Finally, DOE's EIA reports surface and underground production in the Coal Industry Annual (EIA 1999a). Although total production was available for 1998, the apportionment to surface and underground mining was not available. The total coal production values remain unchanged. These revisions result in an annual increase in CH_4 emissions of 1.3 Tg CO_2 Eq. (2.0 percent) for 1998.
- In the Natural Gas Systems section of the Energy chapter, methane emission estimates have been revised to incorporate new activity driver data on gas wells for 1997 and 1998 (AGA 1998, 1999a, 1999b, 2000, IPAA 1999). These data changes, combined with the methodological changes described below, resulted in an average decrease of 0.6 Tg CO_2 Eq. (0.5 percent) in annual methane emissions from natural gas systems from 1990 through 1998.
- In the Natural Gas Flaring and Criteria Pollutant Emissions in the Oil and Gas Activities section of the Energy chapter, a conversion factor accounting for the vented gas from petroleum systems has been corrected from previous reports. The amount of natural gas flared is calculated by subtracting the vented gas emissions from the total gas reported by EIA as combined vented and flared gas (EIA 2000d). Previ-

ously, the conversion value for vented gas was miscalculated, causing the amount of gas vented to appear negligible. Correction of the conversion factor caused the estimate of natural gas vented to increase to between 20 and 40 percent of the total gas vented and flared. This caused an associated average decrease in annual CO_2 emissions from natural gas flaring of 3.7 Tg CO_2 Eq. (29 percent) from 1990 through 1998. The EPA (2000b) has also revised estimates for criteria pollutants from oil and gas activities for 1990 through 1998. These revisions resulted in average increases of 3.5 percent in annual NO_x emissions, and 3.1 percent in annual CO emissions, and an average annual decrease of 0.1 percent in NMVOC emissions from 1990 through 1998.

- In the International Bunker Fuels section of the Energy chapter, civil marine bunker fuel data for 1990 were revised with previously unavailable data provided by DOC (2000). In addition, activity data for foreign airlines at U.S. airports in 1998 have been adjusted (BEA 2000). Lastly, DESC (2000) revised their estimates of jet fuel and aviation gasoline consumption by the military for international bunkers for 1990 to 1994. These revisions resulted in a decrease in CO_2 emissions of 4.0 Tg CO_2 Eq. (3.4 percent) in 1990 and a decrease of 1.9 Tg CO_2 Eq. (1.7 percent) in 1998. The new civil marine bunker fuel data accounted for almost all of the decrease in CO_2 emissions for 1990. Methane emissions have decreased by less than 0.1 Tg CO_2 Eq. (1.9 percent) in 1990 and less than 0.1 Tg CO_2 Eq. (2.5 percent) in 1998. Nitrous oxide emissions have decreased by less than 0.1 Tg CO_2 Eq. (3.0 percent) in 1990 and less than 0.1 Tg CO_2 Eq. (1.9 percent) in 1998.
- In the Limestone and Dolomite Use section of the Industrial Processes chapter, the activity data used to calculate CO_2 emissions for have been revised to incorporate published 1994 limestone and dolomite consumption (USGS 1995). Previously, limestone and dolomite consumption for 1994 was interpolated using 1993 and 1995 data. Additionally, estimates of the amount of limestone used in glassmaking have been revised for 1996 through 1998. In previous inventories, limestone used in glass making for 1996 through 1998 was assumed to account for the same proportion of total crushed stone consumption as in 1995. However, the USGS published new data (USGS 1999) for 1998 limestone consumption. Now, limestone consumed for glass making in 1996 and 1997 is interpolated, using both the 1995 and 1998 data, and the 1998 data have been updated. Finally, the amount of limestone consumed in 1998 for flue gas desulfurization has been updated to reflect new data (EIA 1999b). These updates resulted in a decrease in annual CO_2 emissions from limestone and dolomite use in 1994 and 1996 through 1998. On average, emissions decreased by 0.4 Tg CO_2 Eq. (2.2 percent).
- In the Nitric Acid Production section of the Industrial Processes chapter, 1998 production data were revised using data from Chemical and Engineering News (C&EN 2000). The revision resulted in a decrease of 0.2 Tg CO_2 Eq. (1.0 percent) in annual nitrous oxide emissions from nitric acid production in 1998.
- In the Substitution of Ozone Depleting Substances section of the Industrial Processes chapter, a review of the current chemical substitution trends, together with input from industry representatives, resulted in updated assumptions for the Vintaging Model, particularly in the precision cleaning solvents, stationary refrigeration, and fire extinguishing sectors. These revisions resulted in an average decrease of 2.1 Tg CO_2 Eq. (19 percent) in HFC, PFC, and SF_6 emissions from substitution of ozone depleting substances for 1994 through 1998.
- In the Aluminum Production section of the Industrial Processes chapter, the smelter-specific emission factors used for estimating PFC emissions from aluminum production were revised to reflect recently reported data concerning smelter operating parameters and smelter emission measurements. These data were provided by the EPA's Climate Protection Division in cooperation with participants in the Voluntary Aluminum Industrial Partnership (VAIP) program. The revisions resulted in an average decrease of 0.2 Tg CO_2 Eq. (4.0 percent) in PFC emissions from aluminum production for 1990 through 1998.

- In the Manure Management section of the Agriculture chapter, two major data revisions occurred. Manure management system data were revised and updated for the entire time series based on data that has been gathered by various sources. These sources include EPA's Office of Water (ERG 2000, UEP 1999), USDA's Animal and Plant Health Inspection Service (USDA 1996b, 1998b, 2000d, 2000e), as well as personal communications with USDA and other experts (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, Wright 2000). Contacts at Cornell University provided survey data on dairy manure management practices in New York (Poe et al., 1999). The revisions made to the manure management system data account for changes that have occurred in the industry, including more dairies moving away from daily spread systems and installing on-site manure storage systems and layer operations moving from flush systems to high rise housing. The revised data also account for dairies, beef feedlots, swine, and poultry operations handling portions of their manure as a dry waste, either as separated solids or manure collected from scrape systems. In particular, the new data revised the previous assumptions of the number of dairy cattle housed on pasture, range, or paddock, and the amount of manure managed in daily spread systems. Previously, general assumptions had been made that all large dairies and swine operations handle their manure in a liquid system, and all dairies with less than 100 head and swine operations with less than 200 head were managed in pasture, range, or paddock systems. These revised data result in lower CH_4 emissions and higher N_2O emissions.

  Secondly, Census of Agriculture data, which are used to determine the distribution of animals by farm size, were updated for 1992 and 1997. These distributions were then combined with manure management system data to determine State-specific weighted emission factors. The revised data, made available to the public in June 1999, revised the swine farm distribution, which resulted in a decrease in CH_4 emissions, and an increase in N_2O emissions.

  These data changes, together with the methodological changes described below, resulted in annual CH_4 emission estimates from manure management decreasing by an average of 38.3 Tg CO_2 Eq. (56 percent). Additionally, average annual N_2O emission estimates increased by 3.1 Tg CO_2 Eq. (23 percent), due to significant increases in the dairy estimates.

- The estimates of nitrous oxide (N_2O) emissions from agricultural soil management have been updated for a variety of reasons, as described below: Two changes were made to the commercial fertilizer statistics. First, the fertilizer consumption data for 1998 were updated based on revised values published by the Association of American Plant Food Control Officials (AAPFCO 1999). The updated data were less than 1 percent lower than the original data. Second, the nitrogen content of commercial organic fertilizers (4.1 percent in the previous Inventory) was revised to reflect the annual weighted average nitrogen contents published in annual reports of commercial fertilizer statistics (TVA 1991-1994, AAPFCO 1995-1999). These new nitrogen contents varied from 2.3 to 3.9 percent (by mass).

  The annual estimates of livestock manure production were refined through personal communications with livestock experts (Anderson 2000, Deal 2000, Johnson 2000, Lange 2000, Miller 2000, Milton 2000, Safley 2000, Stettler 2000, Sweeten 2000, and Wright 2000). These refinements resulted in a decrease of about 30 percent in the estimates of manure nitrogen applied to soils, a decrease of about 13 percent in the estimates of manure deposited by pasture, range, and paddock animals, and a decrease of about 20 percent in total livestock manure. The fraction of poultry manure assumed to be used as a livestock feed supplement was reduced from 10 percent to 4.2 percent (Carpenter 1992).

  In the calculations of both nitrogen-fixing crop production and crop residue application, the 1998 crop production data for small grains and beans and pulses were changed based upon updated values from USDA (2000b). The updated data for all crops except peanuts were lower than the USDA estimates used in the previous Inventory; the updated production statistics for peanuts were higher. All changes were less than 1 percent of the original data.

In the calculations of nitrogen-fixing crop production, the crop production data for forage legumes (i.e., alfalfa, red clover, white clover, birdsfoot trefoil, arrowleaf clover, crimson clover, and hairy vetch) were revised to include more detailed crop information, especially about biomass densities and grass/legume mixtures. Hairy vetch was dropped from the calculations because the data used in the previous Inventory were found to be too uncertain. These revisions resulted in a 6 percent decrease in the annual total forage legume production estimates.

The calculation of crop residue applications was revised in several ways. First, the following grains were included in the calculations, in addition to those considered previously: rice, barley, sorghum, oats, rye, and millet. Second, instead of assuming that 100 percent of the residue was left on the field, it was assumed that 90 percent of the residues of all crop types, except rice, were left on the field. For rice residue, it was assumed that all of the unburned residue was left on the field. Third, the conversion factors used in calculating the amount of crop residue applied to soils were revised to more recent, and in many cases, U.S.-based, data. New values for residue dry matter content and residue nitrogen content for wheat, rice, corn, and barley were obtained from Turn et al. (1997), and new values for residue dry matter content and residue nitrogen content for peanuts, sorghum, oats, and rye were obtained from a computer model at Cornell University's Animal Science Department—the Cornell Net Carbohydrate and Protein System (Ketzis 1999). The new values for residue dry matter content and residue nitrogen content for millet, and residue dry matter content for soybeans, were obtained from Strehler and Stützle (1987). The new value for residue nitrogen content for soybeans was obtained from Barnard and Kristoferson (1985). Together, these changes resulted in a 2 to 3 percent decrease in the total annual crop residue nitrogen application estimates.

These revisions, together with the methodological modification described below, resulted in an average decrease of 8.1 Tg CO_2 Eq. (2.8 percent) in estimated annual N_2O emissions from agricultural soil management for 1990 through 1998.

- The estimates of emissions from agricultural residue burning include three changes, as described below:

— Revised USDA crop production data for 1998 from USDA (2000b) have been incorporated. For all crops except sugarcane and peanuts, production estimates were lower than previously reported; the updated production statistics for sugarcane and peanuts were higher. All changes were less than 1 percent of the original estimate.

— Data on the percentage of rice burned in California were updated as a result of conversations with an air pollution specialist with the California Air Resources Board (Najita 2000). More accurate estimates of rice acreage burned in Sacramento Valley were obtained from data collected by the Air Resources Board. These estimates are about 75 to 130 percent higher than the estimates used in the previous Inventory.

— The crop conversion factors, which served as key assumptions for estimating emissions, were revised in this report to reflect data from recent, U.S.-based sources. Updated values for dry matter content, carbon content, and nitrogen content of wheat, rice, corn, and barley were obtained from Turn et al. (1997), and revised values for dry matter content, carbon content, and nitrogen content of peanuts were obtained from a computer model at Cornell University's Animal Science Department—the Cornell Net Carbohydrate and Protein System (Ketzis 1999).

— These revisions, in combination with the methodological revision described below, resulted in an average decrease in agricultural residue burning CH_4 emissions of 0.1 Tg CO_2 Eq. (14 percent), and an average increase in N_2O emissions of less than 0.1 Tg CO_2 Eq. (4.9 percent), for 1990 through 1998.

- In the Land-Use Change and Forestry chapter, the following changes were made to the Forests, Agricultural Soils, and Landfilled Yard Trimmings sections:

— In the Forests section of the Land-Use Change and Forestry chapter, new data from a U.S. forest survey for 1997 (Smith and Sheffield 2000) were utilized. These 1997 data were used to estimate 1997 carbon stocks for forests and harvested wood, which were combined with the 1992 and 2000 carbon stock estimates to derive carbon flux estimates for intervening years. The flux estimates for 1993 through 1998 in last year's Inventory were derived using a 1992 stock and a projected stock for 2000, since the 1997 forest survey was not yet available.

— The Agricultural Soils section of the Land-Use Change and Forestry chapter includes two changes, as described below:

— New data from a preliminary version of USDA's 1997 National Resources Inventory (NRI) (USDA 2000a) were used to derive mineral and organic soil carbon flux estimates for 1993 through 1999. The previous Inventory included only a partial time series of agricultural soil carbon flux estimates, and these estimates were not included in the total net flux estimates presented in the chapter because USDA's 1997 NRI had not yet been completed. This Inventory includes a complete time series of agricultural soil carbon flux estimates, and these estimates are included in the total net flux estimates for land use, land-use change, and forestry.

The carbon dioxide emission estimates for liming were also changed. The input data for these calculations were revised based on the latest updates from publications of the Bureau of Mines and the U.S. Geological Survey.

— In the Landfilled Yard Trimmings section of the Land-Use Change and Forestry chapter, the 1998 estimate for yard trimmings disposed in landfills was revised using new data found in EPA (1999). Previously, the 1998 value had been projected.

These changes, combined with the methodological changes described below, resulted in an average decrease of 125.5 Tg CO_2 Eq. (11.8 percent) in annual carbon sequestration from land-use change and forestry for 1990 through 1992, and an average increase of 233.2 Tg CO_2 Eq. (29.4 percent) in annual carbon sequestration from land-use change and forestry for 1993 through 1998.

- In the Human Sewage section of the Waste chapter, revisions have been made to U.S. Census Bureau population data (2000). Additionally, this report reflects an updated 1998 per capita protein consumption estimate published by the Food and Agriculture Organization (FAO 2000). These revisions resulted in an average increase of 0.1 Tg CO_2 Eq. (1.4 percent) in annual N_2O emissions from human sewage, from 1990 through 1998.
- In the Wastewater Treatment section of the Waste chapter, revisions have been made to national population data for 1990 through 1998 that were supplied by the U.S. Census Bureau (2000). This change, combined with the methodological changes described below, resulted in an average increase of 8.4 Tg CO_2 Eq. (255 percent) in annual CH_4 emissions from wastewater treatment.

Methodological Changes

Carbon Dioxide Emissions from Fossil Fuel Combustion [and] Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

The carbon storage factors used to estimate the carbon stored by the non-energy use of asphalt and road oil, liquefied petroleum gases (LPG), petrochemical feedstocks, pentanes plus, natural gas for other uses (i.e., not used for fertilizers), and lubricants were revised. The role of carbon storage in estimating emissions from the combustion of fossil fuels was explained in previous inventories only in Step 3 in the Methodology for the Carbon

Dioxide Emissions from Fossil Fuel Combustion section of the Energy chapter. For this inventory, the complete list of storage factors, the methods and data used to derive the factors, and the uncertainty involved with their estimation are discussed in a new source category section of the Energy chapter entitled, "Carbon Stored in Products from Non-Energy Uses of Fossil Fuels."

The storage factor revisions were made by examining the lifecycle of the various fuel products. The storage factor for asphalt and road oil remained 100 percent; LPG and pentanes plus were raised to 91 from 80 percent; naphtha petrochemical feedstocks were raised to 91 from 75 percent; other oil feedstocks were raised to 91 from 50 percent; natural gas for other uses was lowered to 91 percent from 100 percent; and lubricants were lowered to 9 percent from 50 percent. Details of the storage factor revisions can be found in Annex B, which has been added to document this new storage factor methodology.

Updated storage factors were developed for fuels according to the following three criteria:

- *Relative size of non-energy fuel consumption.* Nearly two-thirds of the carbon consumed for non-energy uses come from LPG (26 percent), petrochemical feedstocks (19 percent), and asphalt and road oil (19 percent). Combined, the fuels that have been selected represent approximately 305 Tg CO_2 Eq., nearly 64 percent of the total consumed for non-energy uses in 1999.
- *Ability to identify data for fuel products.* Data gathering is made efficient and the uncertainty is reduced when a fuel's uses are limited (i.e., there are only a few important end uses) or well characterized. Asphalt and road oil is a good example of a limited end use fuel, having only two major uses, asphalt paving and roofing. Lubricants are an example of a well-characterized non-energy use of fossil fuel—by virtue of analyses conducted to support rulemakings on used oils, the EPA maintains some data on their fate.
- *Uncertainty in previously used storage factor.* The previous storage factors for certain fuel types or products, and the assumptions upon which they are based, are not expected to be significantly altered through additional research. For example, special naphthas—a generic fuel category which covers highly purified organic compounds, usually containing 4 to 12 carbon atoms—are almost entirely used as solvents. Due to their volatility, they are generally emitted during use and are subsequently photo-oxidized to CO_2 in the atmosphere. Similarly, natural gas used in fertilizer is consumed for ammonia production, and nearly all the carbon is oxidized. The petrochemical feedstocks, on the other hand, lead to many products via a myriad of reaction pathways. In this case, the uncertainty in the storage factor could be reduced significantly by investigating the fuel's processing losses and end uses.

Overall, the storage factor revisions increased the carbon stored from non-energy uses of fossil fuels by an average of 26.9 Tg CO_2 Eq. for 1990 through 1998. These methodological changes, combined with the data changes described above, resulted in an average increase of 6.4 Tg CO_2 Eq. (0.1 percent) of CO_2 annual emissions from fossil fuel combustion for 1990 through 1998.

Mobile Combustion (excluding CO_2)

Annual vehicle mileage accumulation by vehicle age, provided by EPA (2000a), has been incorporated for this report. Previously, only the age distribution of highway vehicle registrations was accounted for when allocating vehicle miles traveled (VMT) to different model years. This change accounts for the fact that newer vehicles are generally driven more than older vehicles. This methodological change, combined with the data changes described above, resulted in an average decrease of 0.4 Tg CO_2 Eq. (7.1 percent) in annual CH_4 emissions from mobile combustion for 1990 through 1998. Average N_2O emissions increased by 3.0 Tg CO_2 Eq. (5.2 percent) annually for 1990 through 1998.

Natural Gas Systems

In the Natural Gas Systems section of the Energy chapter, a new source was added into the estimation of emissions from natural gas production for 1990 through 1999. Coalbed methane wells draw natural gas from deep deposits of coal, and in the course of producing gas, these wells can also produce large amounts of water, which has methane in solution. When the water reaches the surface, the dissolved methane volatilizes. Estimates of these emissions are small, and add approximately 0.15 Tg CO_2 Eq. per year to the total. This change, combined with the data changes mentioned above, resulted in an average decrease of 0.6 Tg CO_2 Eq. (0.5 percent) in annual CH_4 emissions from natural gas systems from 1990 through 1998.

Lime Manufacture

The method for estimating CO_2 emissions from lime manufacture was updated to adhere to IPCC Good Practice Guidance (IPCC 2000). Previously, gross emissions were calculated by multiplying total lime production by an emission factor of 0.73 metric ton CO_2/metric ton of lime. This emission factor was the product of the average CaO/CaO•MgO content of lime, 93 percent, and the stoichiometric ratio of CO_2 to CaO (0.785 metric ton CO_2/metric ton CaO). In this report, lime production was split into high-calcium lime and dolomitic lime, and the emission factors (0.75 and 0.86 metric ton CO_2/metric ton lime, respectively) were updated. Additionally, corrections were made for the amount of hydrated lime produced. These methodological revisions led to an average increase of 0.2 Tg CO_2 Eq. (1.6 percent) in annual CO_2 emissions from lime manufacture for 1990 through 1998.

Semiconductor Manufacturing

The estimates presented in the Semiconductor Manufacturing section of the Industrial Processes chapter in previous Inventories were estimated based on gas sales data from 1994, emission factors for the most commonly used gases, and projections—both backward and forward—regarding the growth of semiconductor sales and the effectiveness of emission reduction efforts. The methodology has been updated to use production data for 1990 through 1994, and reported data from semiconductor manufacturers for other years. These changes resulted in an average decrease of 0.1 Tg CO_2 Eq. (5.0 percent) in annual HFC, PFC, and SF_6 emissions from semiconductor manufacturing for 1990 through 1998.

Magnesium Production and Processing

Emission estimates for the magnesium production and processing industry have been revised to incorporate information provided by EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. These revisions resulted in an average decrease of 3.6 Tg CO_2 Eq. (37 percent) in annual SF_6 emissions from magnesium production and processing from 1990 through 1998.

Enteric Fermentation

Four major changes to the methodology used in estimating enteric fermentation emissions from cattle were completed in this report: 1) an enhanced population characterization method (i.e., IPCC Tier 2) was adopted for cattle only; 2) diet characterizations were expanded to apply to development of emission factors for the new population modeling structure; 3) certain DE and Y_m values were evaluated using a physiological model; and 4) new equations were implemented based on IPCC Good Practice Guidance (IPCC 2000).

For cattle, all historical emission estimates have been updated using the IPCC Good Practice Guidance Tier 2 approach. These methods for estimating methane emissions from enteric fermentation resulted in increased levels of detail, such as definitions of livestock sub-categories, livestock populations by sub-category, and feed intake estimates for the typical animal in each sub-category. Cattle populations were categorized in much more depth through the modeling of the populations by month. Factors such as weight gain, birth, pregnancy, feedlot placements, and slaughter were tracked to characterize the U.S. cattle population in greater detail than in previous inventories, in which only end of year population data were used.

Diets of beef, dairy, and feedlot animals were updated from the values presented in EPA (1993) by researching regional diets throughout the United States. A ruminant digestion model (Donovan and Baldwin 1999) and expert opinion (Johnson 1999) were used to derive DE and Y_m values for the selected animal categories using the results of the diet research. These estimates were used to develop new emission factors for all animal categories studied, with the exception of bulls.

The net energy and methane emission equations presented in IPCC (2000) were incorporated into a computer model that contains the population characterization to estimate emissions for each of the selected cattle population categories, both regionally and temporally. In previous Inventories, national emission factors recommended by IPCC/UNEP/OECD/IEA (1997) were used with static information relevant to broader classifications of the cattle industry to estimate total emissions. These methodological changes resulted in an average increase in annual CH_4 emissions from enteric fermentation of 7.3 Tg CO_2 Eq. (5.9 percent) from 1990 through 1998.

Manure Management

Several changes have been incorporated into the manure management emission estimates that affect estimates for all years. The major changes affecting the estimates are described below:

- *Swine Population Characterization Revisions.* Historically, swine population was broken into two groups: breeding swine (i.e., gestating sows, farrowing sows, and boars) and all market swine. For this report, the entire time series has been revised to account for different weight groups of market swine. Specifically, the market swine population was broken into four groups: swine less than 60 pounds (<27 kg), swine 60 to 119 pounds (27 to 54 kg), swine 120 to 179 pounds (54 to 81kg), and swine greater than 180 pounds (>82 kg). The population estimates for each size group were based on quarterly and annual population data available from USDA's National Agricultural Statistics Service (USDA 1998a, 2000c). The representative weight for each size group was set at the mid-point of the weight range, with the exception of the swine less than 60 pounds and swine greater than 180 pounds. The representative weight for these two size groups were based on expert judgment (Safley 2000).
- *Waste Characteristics Data Revisions.* Other animal waste characteristics were also revised to match data found in USDA's Agricultural Waste Management Field Handbook (USDA 1996a), in order to distinguish waste characteristics between various animal subgroups. For example, distinctions were made in the amount of volatile solids and nitrogen excreted by market swine in various stages of growth, beef cattle that are grazed versus beef cattle on high energy feed, and between lactating and dry dairy cows. The data source for waste characteristics for all livestock except sheep, goats, and horses was changed to the Agricultural Waste Management Field Handbook (USDA 1996a). The volatile solids and nitrogen excretion data for breeding swine are a combination of the types of animals that make up this animal group, namely gestating and farrowing swine and boars. It was assumed that a group of breeding swine is typically broken out as 80 percent gestating sows, 15 percent farrowing swine, and 5 percent boars (Safley 2000). In addition, B_o values used in previous estimates were reviewed and updated for dairy and beef cattle, swine, and poultry.

  Most significantly, volatile solids and nitrogen excretion data for immature swine were accessed from USDA's Agricultural Waste Management Field Handbook (USDA 1996a), and coupled with revised animal masses for the new population groups. Previously, the methodology for estimating these emissions assumed that all market swine generate volatile solids and nitrogen at a rate equal to a 255-pound (116 kg) swine. That methodology overestimated the amount of volatile solids and nitrogen generated, as well as the subsequent emissions of methane and nitrous oxide. These changes resulted in a roughly 70 percent drop in both volatile solids production and nitrogen excretion for swine operations.
- *Dairy Cow Volatile Solids Production Revisions.* The method for calculating volatile solids production from dairy cows was revised to better address

the relationship between milk production and volatile solids production. Cows that produce more milk per year also produce more volatile solids in their manure due to their increased feed. Data from the Agriculture Waste Management Field Handbook were used to determine the mathematical relationship between volatile solids production and milk production for a 1,400-pound dairy cow (USDA 1996a). Annual milk production data, published by USDA's National Agricultural Statistics Service (USDA 2000f), was accessed for each State and for each year 1990 through 1999. State-specific volatile solids production rates were then calculated and used instead of a national volatile solids constant.

- *Methane Conversion Factor (MCF) Revisions.* Historically, for the calculation of methane emissions, default MCFs from IPCC were used for all manure management systems. However, the IPCC Good Practice report (IPCC 2000) now provides a range of 0 to 100 percent as the MCF for anaerobic lagoons. Rather than choosing an MCF for all U.S. systems based solely on judgement, a methodology was developed to reflect the range in performance that is achieved by lagoon systems, and other liquid-based systems. Therefore, the entire time series was revised to incorporate a new method of calculating MCFs for liquid/slurry, deep pit, and anaerobic lagoon systems. The new calculation method is based on the mean ambient temperature of the location of the manure management system (Safley and Westerman 1990), represented by the State and the counties in which specific animal populations reside (USDA 1999). The calculation of the anaerobic lagoon MCF includes an additional approach to account for the timing and length of storage exhibited by these systems, which allows the organic matter to continue to break down over time, increasing the potential for methane production. This approach assesses the production of methane on a monthly basis, and accounts for residual volatile solids that are retained in the lagoon from previous months. In addition, the calculation includes an adjustment for the effect of management and design practices. This factor accounts for other mechanisms by which volatile solids are removed from the management system prior to conversion to methane, such as solids being removed from the lagoon for application to cropland. This factor, equal to 0.8, has been estimated using currently available methane measurement data from anaerobic lagoon systems in the United States (Safley and Westerman 1998 and 1992; Martin 2000). This methodology can be refined over time as new measurements and temperature data are gathered to reflect lagoon performance in the United States.

Nationally, the CH_4 emission estimates for the entire time series dropped between 50 to 60 percent. Swine estimates dropped most significantly (62 percent to 72 percent), followed by poultry (52 percent to 60 percent), dairy (38 percent to 44 percent), and beef (25 percent to 31 percent). Sheep emission estimates dropped by 19 percent across all years of the inventory due to a correction in animal weight and the related correction to volatile solids production. The combined effect of these changes, together with the data changes described above, resulted in a decrease in CH_4 emission estimates from manure management of 38.3 Tg CO_2 Eq. (56 percent) on average from 1990 through 1998.

The N_2O emission estimates for the entire time series increased between 17 to 27 percent primarily due to significant increases in the dairy estimates. Swine N_2O estimates for the time series dropped by 40 percent, while beef dropped about 5 percent. The combined effect of these changes, together with the data changes described above, resulted in an increase in the average annual N_2O emission estimates from manure management of 3.1 Tg CO_2 Eq. (23 percent).

Rice Cultivation

There was a calculation error in the rice cultivation spreadsheets used in the previous Inventory. This has been identified and corrected, resulting in a slightly lower emission estimate for 1996, and higher emission estimates for 1992 through 1995 and 1997 and 1998. This correction resulted in an average increase of 0.1 Tg CO_2 Eq. (0.9 percent) in annual methane emissions from rice cultivation for 1992 through 1998.

Agricultural Soil Management

The estimates of nitrous oxide (N_2O) emissions from the pasture, range, and paddock manure sub-source were derived by applying the emission factor to total pasture, range, and paddock manure nitrogen, rather than just the unvolatilized portion. In the previous Inventory, the emission factor was applied to the unvolatilized portion of pasture, range, and paddock manure.

This methodological change, in combination with the revisions to historical data, resulted in an average decrease of 8.1 Tg CO_2 Eq. (2.8 percent) in estimated annual N_2O emissions from agricultural soil management for 1990 through 1998.

Agricultural Residue Burning

The emission factor for methane from agricultural residue burning was revised to reflect the default value in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The default emission factor from the previous version of the IPCC Guidelines was used in the previous Inventory. This methodological change, in combination with the revisions to historical data described above, resulted in an average decrease in agricultural residue burning CH_4 emissions of 0.1 Tg CO_2 Eq. (14 percent), and an average increase in N_2O emissions of less than 0.1 Tg CO_2 Eq. (4.9 percent), for 1990 through 1998.

Land-Use Change and Forestry

The Land-Use Change and Forestry chapter comprises three sections: 1) Forests; 2) Agricultural Soils; and 3) Landfilled Yard Trimmings. The methodologies used in the first two sections have changed relative to the previous Inventory. The changes to each section are described below.

- *Forests*. First, the treatment of specific portions of the forest land base (i.e., Timberland, Reserved Forest Land, and Other Forest Land[27]) has changed. Previously, carbon stock and flux estimates for private Timberlands were estimated using the FORCARB model and associated forest sector models (Birdsey and Heath 1995). Carbon estimates for all other forestlands (i.e., public Timberlands, all Reserved Forest Land, and all Other Forest Land) were estimated by multiplying regional forest statistics resource data (e.g., Powell et al. 1993) by average regional carbon conversion factors obtained from information in the FORCARB model. In this Inventory, carbon estimates for both the private and public Timberlands are derived from the FORCARB modeling framework, i.e., using the method that was used for only private Timberlands previously. Carbon estimates for all Reserved Forest Land and Other Forest Land, regardless of ownership, are still calculated by multiplying regional forest statistics data by average regional carbon conversion factors. However, forest statistics data are available for 1997, and carbon conversion factors are updated on these lands. In this Inventory, Reserved Forests are assumed to contain the same carbon stock per acre as Timberlands of the same forest type, region, and owner group. For Other Forest Land, carbon stocks per acre were calculated for the lowest productivity class of Timberland, and multiplied by 80 percent to represent carbon stocks of these lower productivity lands.

Second, a preliminary model to estimate net logging residue flux was employed. Logging residues were not included in the previous Inventory.

And lastly, calculations for products and landfills are now based on estimates of the model constructed by Skog and Nicholson (1998). This model has a similar structure to the model by Heath et al. (1996) that was previously used; however, annual estimates are produced based on wood product surveys. Net storage of landfilled carbon is substantially greater in this model, based on work that indicates that current landfill management practices result in low decay rates.

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[27] Timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. It is the most productive type of forest land, growing at a rate of 20 cubic feet per acre per year or more. Reserved Forest Land is forest land withdrawn from timber use by statute or regulation. Other Forest Land is unreserved forest land, growing at a rate less than 20 cubic feet per acre per year.

- *Agricultural soils.* Three changes have been made to the methodologies used to estimate mineral and organic soil carbon flux. First, last year's Inventory included the total land base included in USDA's soil survey database. The data included in this year's Inventory only include land areas that are classified as cropland or grazing land in 1987, 1992, and/or 1997. Second, in estimating carbon stock changes for last year's Inventory, input data were aggregated prior to estimating stock changes (Eve et al. 2001). This resulted in an underestimate of stock changes for some land areas. For this year's Inventory, stock changes were estimated for each data point, and then aggregated (Eve et al. 2000), resulting in a more precise estimate of net flux. Third, an error in the computer code used in last year's Inventory was identified and corrected.

These changes, combined with the revisions to historical data, resulted in an average decrease of 125.5 Tg CO_2 Eq. (11.8 percent) in annual carbon sequestration from land-use change and forestry for 1990 through 1992, and an average increase of 233.2 Tg CO_2 Eq. (29.4 percent) in annual carbon sequestration from land-use change and forestry for 1993 through 1998.

Landfills

The methodology used to estimate recovered landfill gas has been updated in two ways. First, methane recovered for landfill gas-to-energy (LFGTE) electricity projects was estimated based on reported capacity (i.e., megawatts) rather than reported landfill gas flow. Although the data on electricity capacity are generally considered more reliable than the landfill flow data, capacity data tend to be underestimated. The main reason for this underestimation is the tendency of landfill owners/operators to undersize the units to ensure a sufficient and steady flow of gas to support the unit. Second, in order to avoid double counting, the estimate of methane emissions avoided due to flaring was reduced to adjust for LFGTE projects for which a vendor-specific flare could not be identified. These steps resulted in a downward revision of landfill gas recovered. Also, this report reflects flare data from an additional two vendors, resulting in the evaluation of 487 flares, as compared to 190 for the previous Inventory. Finally, this report includes data on 36 additional LFGTE projects. These methodological changes resulted in an average increase in annual methane emissions from landfills of 1.5 Tg CO_2 Eq. (0.7 percent). This increase is primarily due to a reduction in the estimate of methane emissions avoided at LFGTE projects, which is mainly a result of the use of a more conservative approach for estimating methane avoided.

Waste Combustion

The Waste Combustion section of the Waste chapter has been revised substantially. Formerly, only CO_2 emissions from the combustion of plastics and N_2O emissions from municipal solid waste were included. Carbon dioxide from the combustion of tires, synthetic rubber, synthetic fabrics, and hazardous waste have been added. These updates have increased the average emissions from waste combustion by 10.5 Tg CO_2 Eq. (91.5 percent) for 1990 through 1998.

Wastewater Treatment

The value for wastewater biological oxygen demand (BOD) produced per capita has been revised from 0.05 to 0.065 (kg/capita/day). The 0.05 value was referenced from IPCC/UNEP/OECD/IEA (1997). The revised value of 0.065 is the value given for the United States in EPA (1997). The IPCC Good Practice Guidance (IPCC 2000) has a default value of 0.06 for this parameter; however, that value represents an average for all countries. The wastewater BOD is slightly higher in the United States due to its use of garbage disposals, as stated in EPA (1997). Additionally, the emission factor has been changed from 0.22 kg CH_4/kg BOD to 0.6 kg CH_4/kg BOD to reflect the IPCC Good Practice Guidance (IPCC 2000). Additionally, an estimate of emissions from pulp and paper operations has been included for the first time under the wastewater category. These methodological revisions, together with the data changes described above, resulted in an average increase of 8.4 Tg CO_2 Eq. (255 percent) in annual methane emissions.

Executive Summary

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

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

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…"[3] The United States views this report as an opportunity to fulfill this commitment.

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 1999. To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC signatory countries, the estimates presented here were calculated using methodologies consistent with those recommended in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). For most source categories, the IPCC default methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as halons. CFCs, HCFCs, and halons are stratospheric ozone depleting substances and are therefore covered under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. The UNFCCC defers to

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

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

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

this earlier international treaty in addressing these ozone depleting substances; however, some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several gases that do not have a direct global warming effect but indirectly affect terrestrial radiation absorpon by influencing the formation and destruction of tropospheric and stratospheric ozone. These gases—referred to as ozone precursors—include carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane volatile organic compounds (NMVOCs).[4] 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.

Box ES-1: Emission Reporting Nomenclature

The Global Warming Potential (GWP) weighted emissions of all direct greenhouse gases presented throughout this report are presented in terms of equivalent emissions of carbon dioxide (CO_2), using units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.) In previous year's inventories emissions were reported in terms of carbon—versus carbon dioxide—equivalent emissions, using units of million metric tons of carbon equivalents (MMTCE). This change of units for reporting was implemented so that the U.S. Inventory would be more consistent with international practices, which are to report emissions in carbon dioxide equivalent units.

In order to convert the emission estimates presented in this report to those provided previously, the following equation can be employed:

Tg CO_2 Eq. = MMTCE × ($^{44}/_{12}$)

There are two elements to the conversion. The first element is simply nomenclature, since one teragram is equal to one million metric tons:

Tg = 10^9 kg = 10^6 metric tons = 1 megaton= 1 million metric tons

The second element is the conversion, by weight, from carbon to carbon dioxide. The molecular weight of carbon is 12, and the molecular weight of oxygen is 16; therefore, the molecular weight of CO_2 is 44 (i.e., 12+[16 × 2]), as compared to 12 for carbon alone. Thus, carbon comprises 12/44^{ths} of carbon dioxide by weight.

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

Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODSs) increased by nearly 10 percent per year until the mid-1980s, when international concern about ozone depletion led to the signing of the *Montreal Protocol*. Since then, a phase-out of the production of ODSs has been occurring. In recent years, use of ODS substitutes such as HFCs and PFCs has grown as they begin to be phased in as replacements for CFCs and HCFCs.

Recent Trends in U.S. Greenhouse Gas Emissions

Total U.S. greenhouse gas emissions rose in 1999 to 6,746.0 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.)[5] (11.7 percent above 1990 emissions). The single year increase in emissions from 1998 to 1999 was 0.9 percent (59.2 Tg CO_2 Eq.), less than the average annual rate of increase for 1990 through 1999 (1.2 percent). The lower than average increase in emissions, especially given the robust economic growth in 1999, was primarily attributable to the following factors: 1) warmer than normal summer and winter conditions; 2) significantly increased output from existing nuclear power plants; and 3) reduced CH_4 emissions from coal mines and HFC-23 by-product emissions from the chemical manufacture of HCFC-22. Figure ES-1 through Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute change since 1990. Table ES-1 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 1999.

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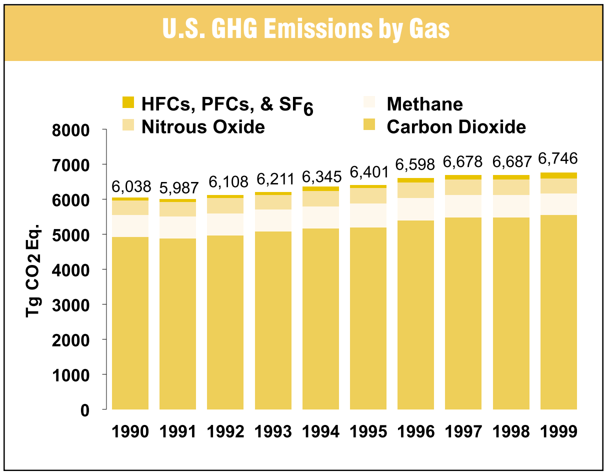
[4] Also referred to in the U.S. Clean Air Act as "criteria pollutants."

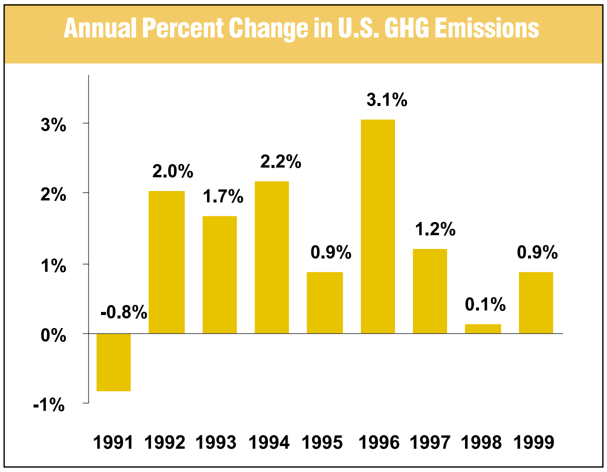
[5] Estimates are presented in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.), which weight each gas by its Global Warming Potential, or GWP, value. (see following section).

Figure ES-1



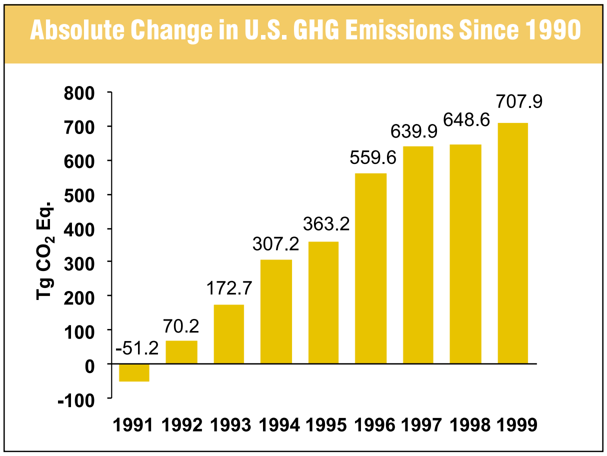
U.S. GHG Emissions by Gas

Figure ES-2



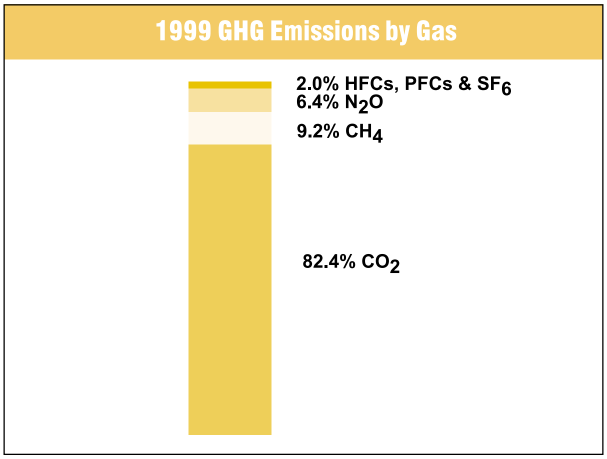
Annual Percent Change in U.S. GHG Emissions

Figure ES-3



Absolute Change in U.S. GHG Emissions Since 1990

Figure ES-4



1999 GHG Emissions by Gas

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 1999. The primary greenhouse gas emitted by human activities was CO_2. The largest source of CO_2, and of overall greenhouse gas emissions in the United States, was fossil fuel combustion. Methane emissions resulted primarily from decomposition of wastes in landfills, enteric fermentation associated with domestic livestock, natural gas systems, and coal mining. Emissions of N_2O were dominated by agricultural soil management and mobile source fossil fuel combustion. The emissions of substitutes for ozone depleting substances and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate HFC emissions. Electrical transmission and distribution systems emitted the majority of SF_6, while PFC emissions came mainly from primary aluminum production.

As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion accounted for a nearly constant 80 percent of global warming potential (GWP) weighted emissions in the 1990s.[6] Emissions from this source category grew by 13 percent (617.4 Tg CO_2 Eq.) from 1990 to 1999 and were responsible for the majority of the increase in national emissions during this period. The annual increase in CO_2 emissions from fossil fuel combustion was 1.2 percent in 1999, a figure close to the source's average annual rate of 1.4 percent during the 1990s. Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

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[6] If a full accounting of emissions from fossil fuel combustion is made by including emissions from the combustion of international bunker fuels and CH_4 and N_2O emissions associated with fuel combustion, then this percentage increases to a constant 82 percent during the 1990s.

Table ES-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999
CO_2	**4,913.0**	**5,219.8**	**5,403.2**	**5,478.7**	**5,489.7**	**5,558.1**
Fossil Fuel Combustion	4,835.7	5,121.3	5,303.0	5,374.9	5,386.8	5,453.1
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	39.9
Waste Combustion	17.6	23.1	24.0	25.7	25.1	26.0
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.4
Natural Gas Flaring	5.1	13.6	13.0	12.0	10.8	11.7
Limestone and Dolomite Use	5.1	7.0	7.3	8.3	8.1	8.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.3	4.4	4.3	4.2
Carbon Dioxide Consumption	0.8	1.0	1.1	1.3	1.4	1.6
Land-Use Change and Forestry (Sink)[a]	(1,059.9)	(1,019.1)	(1,021.6)	(981.9)	(983.3)	(990.4)
International Bunker Fuels[b]	114.0	101.0	102.2	109.8	112.8	107.3
CH_4	**644.5**	**650.5**	**638.0**	**632.0**	**624.8**	**619.6**
Landfills	217.3	222.9	219.1	217.8	213.6	214.6
Enteric Fermentation	129.5	136.3	132.2	129.6	127.5	127.2
Natural Gas Systems	121.2	124.2	125.8	122.7	122.1	121.8
Coal Mining	87.9	74.6	69.3	68.8	66.5	61.8
Manure Management	26.4	31.0	30.7	32.6	35.2	34.4
Petroleum Systems	27.2	24.5	24.0	24.0	23.3	21.9
Wastewater Treatment	11.2	11.8	11.9	12.0	12.1	12.2
Rice Cultivation	8.7	9.5	8.8	9.6	10.1	10.7
Stationary Combustion	8.5	8.9	9.0	8.1	7.6	8.1
Mobile Combustion	5.0	4.9	4.8	4.7	4.6	4.5
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7
Agricultural Residue Burning	0.5	0.5	0.6	0.6	0.6	0.6
Silicon Carbide Production	+	+	+	+	+	+
International Bunker Fuels[b]	+	+	+	+	+	+
N_2O	**396.9**	**431.9**	**441.6**	**444.1**	**433.7**	**432.6**
Agricultural Soil Management	269.0	285.4	294.6	299.8	300.3	298.3
Mobile Combustion	54.3	66.8	65.3	65.2	64.2	63.4
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.2
Manure Management	16.0	16.4	16.8	17.1	17.2	17.2
Stationary Combustion	13.6	14.3	14.9	15.0	15.1	15.7
Adipic Acid	18.3	20.3	20.8	17.1	7.3	9.0
Human Sewage	7.1	8.2	7.8	7.9	8.1	8.2
Agricultural Residue Burning	0.4	0.4	0.4	0.4	0.5	0.4
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2
International Bunker Fuels[b]	1.0	0.9	0.9	1.0	1.0	1.0
HFCs, PFCs, and SF_6	**83.9**	**99.0**	**115.1**	**123.3**	**138.6**	**135.7**
Substitution of Ozone Depleting Substances	0.9	24.0	34.0	42.1	49.6	56.7
HCFC-22 Production	34.8	27.1	31.2	30.1	40.0	30.4
Electrical Transmission and Distribution	20.5	25.7	25.7	25.7	25.7	25.7
Aluminum Production	19.3	11.2	11.6	10.8	10.1	10.0
Semiconductor Manufacture	2.9	5.5	7.0	7.0	6.8	6.8
Magnesium Production and Processing	5.5	5.5	5.6	7.5	6.3	6.1
Total Emissions	**6,038.2**	**6,401.3**	**6,597.8**	**6,678.0**	**6,686.8**	**6,746.0**
Net Emissions (Sources and Sinks)	**4,978.3**	**5,382.3**	**5,576.2**	**5,696.2**	**5,703.5**	**5,755.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data.

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

Note: Totals may not sum due to independent rounding.

Note: Parentheses indicate negative values (or sequestration).

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. On an annual basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams would be expected to have proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

Longer-term changes in energy consumption patterns, however, tend to be more a function of changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs) and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

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

Carbon dioxide emissions from fossil fuel combustion grew rapidly in 1996, due primarily to two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as colder winter conditions and the associated rise in demand for natural gas from residential, commercial, and industrial customers for heating caused gas prices to rise sharply; and 2) higher consumption of petroleum fuels for transportation. Milder weather conditions in summer and winter moderated the growth in emissions in 1997; however, the shut-down of several nuclear power plants lead electric utilities to increase their consumption of coal and other fuels to offset the lost capacity. In 1998, weather conditions were again a dominant factor in slowing the growth in emissions. Warm winter temperatures resulted in a significant drop in residential, commercial, and industrial natural gas consumption. This drop in emissions from natural gas used for heating was primarily offset by two factors: 1) electric utility emissions, which increased in part due to a hot summer and its associated air conditioning demand; and 2) increased motor gasoline consumption for transportation.

In 1999, the increase in emissions from fossil fuel combustion was driven largely by growth in petroleum consumption for transportation. In addition, heating fuel demand partially recovered in the residential, commercial, and industrial sectors as winter temperatures dropped relative to 1998, although temperatures were still warmer than normal. These increases were offset, in part, by a

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

Sector	Fuel Type	1995 to 1996		1996 to 1997		1997 to 1998		1998 to 1999	
Electric Utility	Coal	89.9	5.7%	52.0	3.1%	14.3	0.8%	-32.1	-1.8%
Electric Utility	Natural Gas	-25.3	-14.7%	13.1	9.0%	16.2	10.1%	-7.8	-4.4%
Electric Utility	Petroleum	5.1	10.0%	8.1	14.4%	26.7	41.6%	-17.4	-19.1%
Transportation[a]	Petroleum	38.8	2.5%	7.6	0.5%	34.1	2.1%	57.6	3.6%
Residential	Natural Gas	21.4	8.1%	-14.0	-4.9%	-24.0	-8.9%	8.5	3.4%
Commercial	Natural Gas	7.0	4.3%	3.1	1.8%	-11.1	-6.4%	2.9	1.8%
Industrial	Coal	-7.3	-2.7%	2.0	0.8%	-1.1	-0.4%	29.2	11.2%
Industrial	Natural Gas	17.8	3.4%	-0.5	-0.1%	-14.5	-2.7%	1.6	0.3%
All Sectors[b]	**All Fuels**	**181.7**	**3.5%**	**71.9**	**1.4%**	**11.9**	**0.2%**	**66.4**	**1.2%**

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

decline in emissions from electric utilities due primarily to: 1) an increase in net generation of electricity by nuclear plants (8 percent) to record levels, which reduced demand from fossil fuel plants; and 2) moderated summer temperatures compared to the previous year—thereby reducing electricity demand for air conditioning. Utilization of existing nuclear power plants, measured as a plant's capacity factor,[7] has increased from just over 70 percent in 1990 to over 85 percent in 1999.

Another factor that does not affect total emissions, but does affect the interpretation of emission trends is the allocation of emissions from nonutility power producers. The Energy Information Administration (EIA) currently includes fuel consumption by nonutilities with the industrial end-use sector. In 1999, there was a large shift in generating capacity from utilities to nonutilities, as restructuring legislation spurred the sale of 7 percent of utility generating capability (EIA 2000b). This shift is illustrated by the increase in industrial end-use sector emissions from coal and the associated decrease in electric utility emissions. However, emissions from the industrial end-use sector did not increase as much as would be expected even though net generation by nonutilities increased from 11 to 15 percent of total U.S. electricity production (EIA 2000b).[8]

Overall, from 1990 to 1999, total emissions of CO_2 and N_2O increased by 645.2 (13 percent) and 35.7 Tg CO_2 Eq. (9 percent), respectively, while CH_4 emissions decreased by 24.9 Tg CO_2 Eq. (4 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 51.8 Tg CO_2 Eq. (62 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because many of them have extremely high global warming potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests and in landfilled carbon, which were estimated to be 15 percent of total emissions in 1999.

Other significant trends in emissions from additional source categories over the nine year period from 1990 through 1999 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 55.8 Tg CO_2 Eq. This increase was partly offset, however, by reductions in PFC emissions from aluminum production (9.2 Tg CO_2 Eq. or 48 percent), and reductions in emissions of HFC-23 from the production of HCFC-22 (4.4 Tg CO_2 Eq. or 13 percent). Reductions in PFC emissions from aluminum production were the result of both voluntary industry emission reduction efforts and lower domestic aluminum production. HFC-23 emissions from the production of HCFC-22 decreased due to a reduction in the intensity of emissions from that source, despite increased HCFC-22 production.
- Emissions of N_2O from mobile combustion rose by 9.1 Tg CO_2 Eq. (17 percent), primarily due to increased rates of N_2O generation in highway vehicles.
- Methane emissions from coal mining dropped by 26 Tg CO_2 Eq. (30 percent) as a result of the mining of less gassy coal from underground mines and the increased use of methane from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 29.3 Tg CO_2 Eq. (11 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.
- By 1998, all of the three major adipic acid producing plants had voluntarily implemented N_2O abatement technology, and as a result, emissions fell by 9.3 Tg CO_2 Eq. (51 percent). The majority of this decline occurred from 1997 to 1998, despite increased production.

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

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[7] The capacity factor is defined as the ratio of the electrical energy produced by a generating unit for a given period of time to the electrical energy that could have been produced at continuous full- power operation during the same period (DOE/EIA 2000).

[8] It is unclear whether reporting problems for electric utilities and the industrial end-use sector have increased with the dramatic growth in nonutilities and the opening of the electric power industry to increased competition.

Box ES-2: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

There are several ways to assess a nation's greenhouse gas emitting intensity. The basis for measures of intensity can be 1) per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; 2) per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; 3) per unit of electricity consumption, because the electric power industry—utilities and nonutilities combined—were the largest sources of U.S. greenhouse gas emissions in 1999; 4) per unit of total gross domestic product as a measure of national economic activity; or 5) on a per capita basis. Depending upon the measure used, the United States could appear to have reduced or increased its national greenhouse gas intensity during the 1990s.

Table ES-3 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.2 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption—thereby indicating an improved or lower greenhouse gas emitting intensity—and much slower than that for either electricity consumption or overall gross domestic product. Emissions, however, are growing faster than national population, thereby indicating a worsening or higher greenhouse gas emitting intensity on a per capita basis (see Figure ES-5). Overall, global atmospheric CO_2 concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

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

Variable	1991	1992	1993	1994	1995	1996	1997	1998	1999	Growth Rate[f]
GHG Emissions[a]	99	101	103	105	106	109	111	111	112	1.2%
Energy Consumption[b]	100	101	104	106	108	111	112	112	115	1.5%
Fossil Fuel Consumption[b]	99	101	103	105	107	110	112	112	113	1.4%
Electricity Consumption[b]	102	102	105	108	111	114	116	119	120	2.1%
GDP[c]	100	103	105	110	112	116	122	127	132	3.2%
Population[d]	101	102	103	104	105	106	107	108	109	1.0%
Atmospheric CO_2 Concentration[e]	100	101	101	101	102	102	103	104	104	0.4%

[a] GWP weighted values

[b] Energy content weighted values. (EIA 2000a)

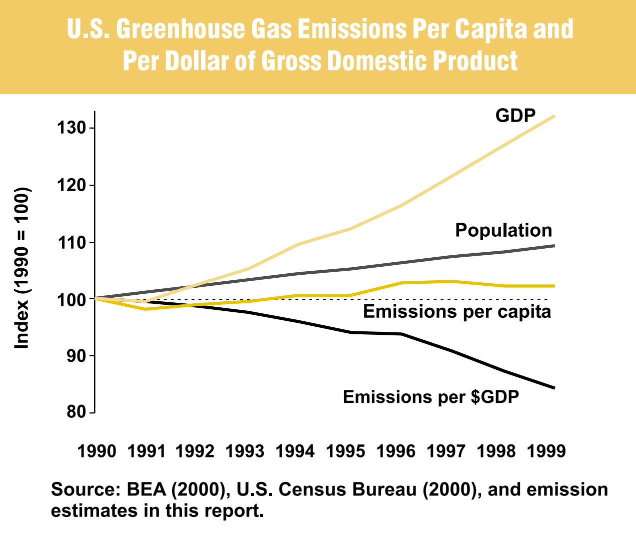
[c] Gross Domestic Product in chained 1996 dollars (BEA 2000)

[d] (U.S. Census Bureau 2000)

[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 2000)

[f] Average annual growth rate

Figure ES-5



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

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

Box ES- 3: Weather and Non-Fossil Energy Adjustments to CO_2 from Fossil Fuel Combustion Trends

An analysis was performed using EIA's Short-Term Integrated Forecasting (STIFS) model to examine the effects of variations in weather and output from nuclear and hydroelectric generating plants on U.S. energy-related CO_2 emissions.[9] Weather conditions affect energy demand because of the impact they have on residential, commercial, and industrial end-use sector heating and cooling demands. Warmer winters tend to reduce demand for heating fuels—especially natural gas—while cooler summers tend to reduce air conditioning-related electricity demand. Changes in electricity output from hydroelectric and nuclear power plants do not necessarily affect final energy demand, but increased output from these plants does offset electricity generation by fossil fuel power plants, and therefore leads to reduced CO_2 emissions.

The results of this analysis show that CO_2 emissions from fossil fuel combustion would have been roughly 1.9 percent higher (102 Tg CO_2 Eq.) if weather conditions and hydroelectric and nuclear power generation had remained at normal levels (see Figure ES-6). Similarly, emissions in 1997 and 1998 would have been roughly 0.5 and 1.2 percent (7 and 17 Tg CO_2 Eq.) greater under normal conditions, respectively.

In addition to the absolute level of emissions being greater, the growth rate in CO_2 emissions from fossil fuel combustion from 1998 to 1999 would have been 2.0 percent instead of the actual 1.2 percent if both weather conditions and nonfossil electricity generation had been normal (see Figure ES-7). Similarly, emissions in 1998 would have increased by 0.9 percent under normal conditions versus the actual rate of 0.2 percent.

Figure ES-6

Percent Difference in Adjusted and Actual Energy-Related CO_2 Emissions

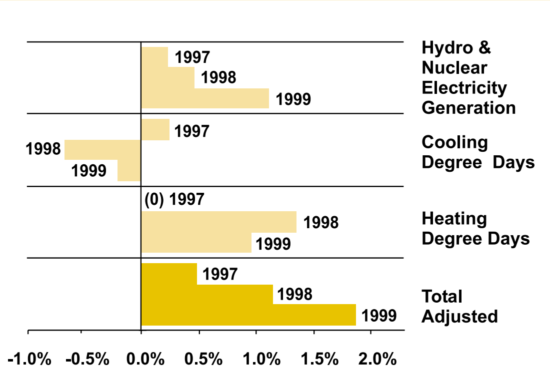
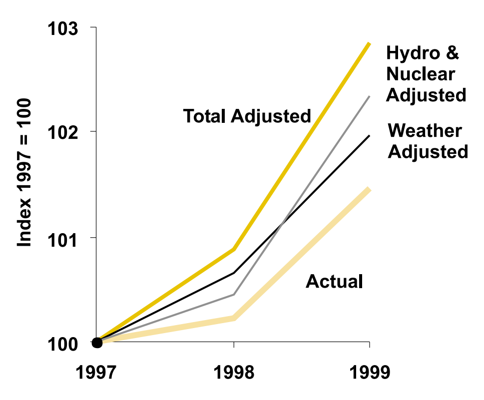


Figure ES-7

Recent Trends in Adjusted and Actual Energy-Related CO_2 Emissions



Warmer winter conditions in both 1998 and 1999 had a significant effect on U.S. CO_2 emissions by reducing demand for heating fuels. Heating degree days in the United States in 1998 and 1999 were 14 and 7 percent below normal, respectively (see Figure ES-8).[10] These warm winters, however, were partially countered by increased electricity demand that resulted from hotter summers. Cooling degree days in 1998 and 1999 were 18 and 3 percent above normal, respectively (see Figure ES-9).

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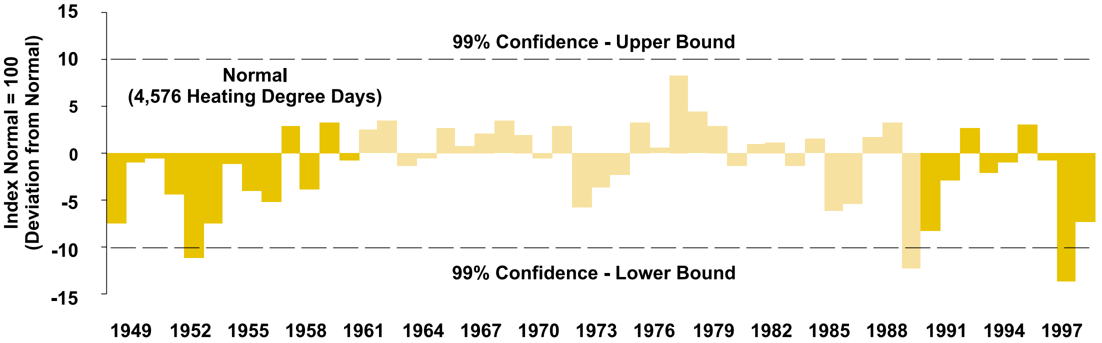
[9] The STIFS model is employed in producing EIA's *Short-Term Energy Outlook* (DOE/EIA-0202). Complete model documentation can be found at < http://www.eia.doe.gov/emeu/steo/pub/contents.html>. A variety of other factors that influence energy-related CO_2 emissions were also examined such as: changes in output from energy intensive manufacturing industries, and changes in fossil fuel prices. These additional factors, however, were not found to have a significant effect on emission trends.

[10] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F, while cooling degree days are deviations of the mean daily temperature above 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990. The variation in these normals during this time period was ±10 percent and ±14 percent for heating and cooling degree days, respectively (99 percent confidence interval).

Figure ES-8

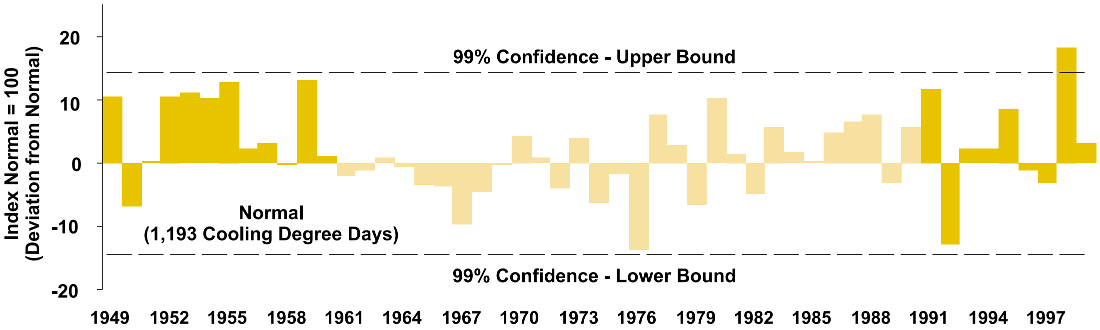
Annual Deviations from Normal Heating Degree Days for the United States (1949-1999)



Note: Climatological normal data is highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.
Source: NOAA (2000b)

Figure ES-9

Annual Deviations from Normal Cooling Degree Days for the United States (1949-1999)



Note: Climatological normal data is highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.
Source: NOAA (2000b)

Although no new U.S. nuclear power plants have been constructed in many years, the utilization (i.e., capacity factors[11]) of existing plants reached record levels in 1998 and 1999, approaching 90 percent. This increase in utilization translated into an increase in electricity output by nuclear plants of slightly more than 7 percent in both years. This increase in nuclear plant output, however, was partially offset by reduced electricity output by hydroelectric power plants, which declined by 10 and 4 percent in 1998 and 1999, respectively. Electricity generated by nuclear plants provides approximately twice as much of the energy consumed in the United States as hydroelectric plants. Nuclear and hydroelectric power plant capacity factors since 1973 are shown in Figure ES-10.

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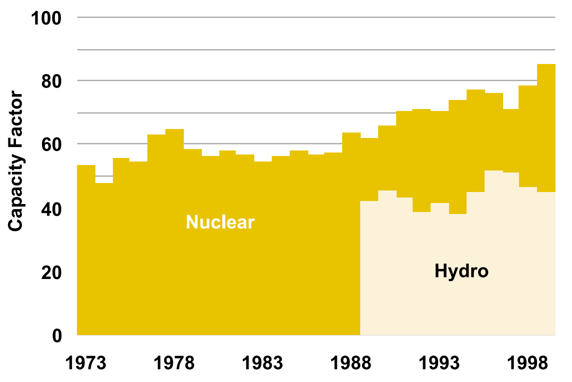
[11] The capacity factor is defined as the ratio of the electrical energy produced by a generating unit for a given period of time to the electrical energy that could have been produced at continuous full- power operation during the same period (DOE/EIA 2000).

Figure ES-10

Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1973-1999)



Box ES-4: 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 (FHWA). Likewise, the number of miles driven—up 13 percent from 1990 to 1999—and gallons of gasoline consumed each year in the United States have increased steadily since the 1980s, according to the FHWA and Energy Information Administration, respectively. These increases in motor vehicle usage are the result of a confluence of factors including population growth, economic growth, urban sprawl, low fuel prices, and increasing popularity of sport utility vehicles and other light-duty trucks that tend to have lower fuel efficiency.[12] A similar set of social and economic trends has led to a significant increase in air travel and freight transportation—by both air and road modes—during the 1990s.

One of the unintended consequences of these changes is a slowing of progress toward cleaner air in both urban and rural parts of the country. Passenger cars, trucks, motorcycles, and buses emit significant quantities of air pollutants with local, regional, and global effects. Motor vehicles are major sources of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nonmethane volatile organic compounds (NMVOCs), nitrogen oxides (NO_x), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). Motor vehicles are also important contributors to many serious air pollution problems, including ground-level ozone (i.e., smog), acid rain, fine particulate matter, and global warming. Within the United States and abroad, government agencies have taken actions to reduce these emissions. Since the 1970s, the EPA has required the reduction of 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. New vehicles are now equipped with advanced emissions controls, which are designed to reduce emissions of NO_x, hydrocarbons, and CO.

Table ES-4 summarizes greenhouse gas emissions from all transportation-related activities. Overall, transportation activities—excluding international bunker fuels—accounted for an almost constant 26 percent of total U.S. greenhouse gas emissions from 1990 to 1999. These emissions were primarily CO_2 from fuel combustion, which increased by 16 percent from 1990 to 1999. However, because of larger increases in N_2O and HFC emissions during this period, overall emissions from transportation activities actually increased by 18 percent.

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[12] The average miles per gallon achieved by the U.S. highway vehicle fleet actually decreased by slightly less than one percent in both 1998 and 1999.

Table ES-4: Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Vehicle Type	1990	1995	1996	1997	1998	1999
CO_2	**1,474.4**	**1,581.8**	**1,621.2**	**1,631.4**	**1,659.0**	**1,716.4**
Passenger Cars	620.0	641.9	654.1	660.2	674.5	688.9
Light-Duty Trucks	283.1	325.3	333.5	337.3	356.9	364.8
Other Trucks	206.0	235.9	248.1	257.0	257.9	269.7
Buses	10.7	13.5	11.3	12.0	12.3	12.9
Aircraft[a]	176.7	171.5	180.2	179.0	183.0	184.6
Boats and Vessels	59.4	66.9	63.8	50.2	47.9	65.6
Locomotives	28.4	31.5	33.4	34.4	33.6	35.1
Other[b]	90.1	95.3	96.7	101.4	93.0	94.9
International Bunker Fuels[c]	114.0	101.0	102.2	109.8	112.8	107.3
CH_4	**5.0**	**4.9**	**4.8**	**4.7**	**4.6**	**4.5**
Passenger Cars	2.4	2.0	2.0	2.0	2.0	1.9
Light-Duty Trucks	1.6	1.9	1.6	1.6	1.5	1.4
Other Trucks and Buses	0.4	0.5	0.7	0.7	0.7	0.7
Aircraft	0.2	0.1	0.1	0.2	0.1	0.2
Boats and Vessels	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	+	+
Other[d]	0.2	0.2	0.2	0.2	0.2	0.2
International Bunker Fuels[c]	+	+	+	+	+	+
N_2O	**54.3**	**66.8**	**65.3**	**65.2**	**64.2**	**63.4**
Passenger Cars	31.0	33.0	32.7	32.4	32.1	31.5
Light-Duty Trucks	17.8	27.1	23.9	24.0	23.3	22.7
Other Trucks and Buses	2.6	3.6	5.6	5.8	5.9	6.1
Aircraft[a]	1.7	1.7	1.8	1.7	1.8	1.8
Boats and Vessels	0.4	0.5	0.4	0.3	0.3	0.4
Locomotives	0.3	0.3	0.3	0.2	0.2	0.2
Other[d]	0.6	0.6	0.6	0.6	0.6	0.6
International Bunker Fuels[c]	1.0	0.9	0.9	1.0	1.0	1.0
HFCs	**+**	**9.5**	**13.5**	**17.2**	**20.6**	**23.7**
Mobile Air Conditioners[e]	+	9.5	13.5	17.2	20.6	23.7
Total[c]	**1,533.7**	**1,663.0**	**1,704.8**	**1,718.5**	**1,748.4**	**1,808.0**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

[a] Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.

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

[c] Emissions from International Bunker Fuels include emissions from both civilian and military activities, but are not included in totals.

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

[e] Includes primarily HFC-134a.

Box ES- 5: Greenhouse Gas Emissions from Electric Utilities

Like transportation, activities related to the generation, transmission, and distribution of electricity in the United States resulted in a significant fraction of total U.S. greenhouse gas emissions. The electric power industry in the United States is composed of traditional electric utilities as well as other entities, such as power marketers and nonutility power producers. Table ES-5 presents emissions from electric utility-related activities. Aggregate emissions from electric utilities of all greenhouse gases increased by 11 percent from 1990 to 1999, and accounted for a relatively constant 29 percent of U.S. emissions during the same period. Emissions from nonutility generators are not included in these estimates. Nonutilities were estimated to have produced about 15 percent of the electricity generated in the United States in 1999, up from 11 percent in 1998 (EIA 2000c). Therefore, a more complete accounting of greenhouse gas emissions from the electric power industry (i.e., utilities and nonutilities combined) would account for roughly 40 percent of U.S. CO_2 emissions (EIA 2000d).

The majority of electric utility-related emissions resulted from the combustion of coal in boilers to produce steam that is passed through a turbine to generate electricity. Overall, the generation of electricity—especially when nonutility generator are included—results in a larger portion of total U.S. greenhouse gas emissions than any other activity.

Table ES-5: Electric Utility-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Fuel Type or Source	1990	1995	1996	1997	1998	1999
CO_2	**1,757.3**	**1,810.6**	**1,880.3**	**1,953.5**	**2,010.7**	**1,953.4**
Coal	1,509.3	1,587.7	1,677.7	1,729.7	1,744.0	1,711.9
Natural Gas	151.1	171.8	146.5	159.6	175.8	168.0
Petroleum	96.8	51.0	56.0	64.1	90.8	73.4
Geothermal	0.2	0.1	0.1	0.1	0.1	+
CH_4	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Stationary Combustion (Utilities)	0.5	0.5	0.5	0.5	0.5	0.5
N_2O	**7.4**	**7.8**	**8.2**	**8.5**	**8.7**	**8.6**
Stationary Combustion (Utilities)	7.4	7.8	8.2	8.5	8.7	8.6
SF_6	20.5	25.7	25.7	25.7	25.7	25.7
Electrical Transmission and Distribution	20.5	25.7	25.7	25.7	25.7	25.7
Total	**1,785.7**	**1,844.5**	**1,914.7**	**1,988.2**	**2,045.6**	**1,988.2**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding. Excludes emissions from non-utilities, which are currently accounted for under the industrial end-use sector.

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, when a gas influences the atmospheric lifetimes of other gases, and/or when a gas affects other atmospheric processes that alter the radiative balance of the earth (e.g., affect cloud formation or albedo). The concept of a Global Warming Potential (GWP) has been developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. Carbon dioxide (CO_2) was chosen as the reference gas to be consistent with IPCC guidelines.

Global Warming Potentials are not provided for the criteria pollutants CO, NO_x, NMVOCs, and SO_2 because there is no agreed upon method to estimate the contribution of gases that are short-lived in the atmosphere and have only indirect effects on radiative forcing (IPCC 1996).

All gases in this executive summary are presented in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.) The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

$$\text{Tg CO}_2\ \text{Eq.} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000\ \text{Gg}}\right)$$

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

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

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

Source: IPCC (1996)

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

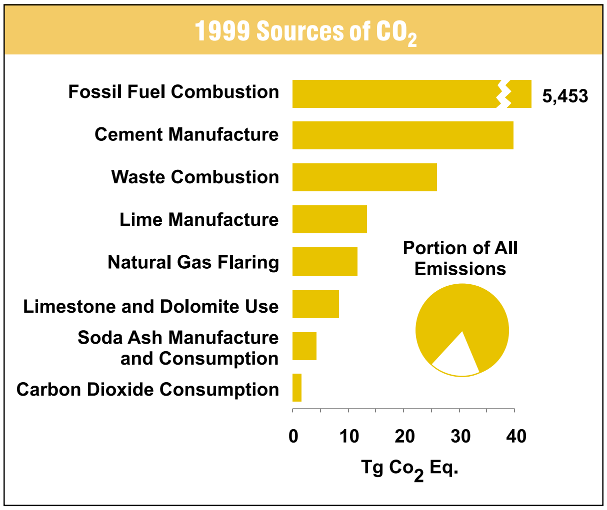
Carbon Dioxide Emissions

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

Since the Industrial Revolution, this equilibrium of atmospheric carbon has been altered. Atmospheric concentrations of CO_2 have risen about 28 percent (IPCC 1996), principally because of fossil fuel combustion, which accounted for 98 percent of total U.S. CO_2 emissions in 1999. Changes in land use and forestry practices can also emit CO_2 (e.g., through conversion of forest land to agricultural or urban use) or can act as a sink for CO_2 (e.g., through net additions to forest biomass).

Figure ES-11 and Table ES-7 summarize U.S. sources and sinks of CO_2. The remainder of this section then discusses CO_2 emission trends in greater detail.

Figure ES-11



1999 Sources of CO_2

Energy

Energy-related activities accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 1999. Carbon dioxide from fossil fuel combustion was the dominant contributor. In 1999, approximately 84 percent of the energy consumed in the United States was produced through the combustion of fossil fuels. The remaining 16 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar (see Figure ES-12 and Figure ES-13). A discussion of specific trends related to CO_2 emissions from energy consumption is presented below.

Fossil Fuel Combustion

As fossil fuels are combusted, the carbon stored in them is almost entirely emitted as CO_2. The amount of carbon in fuels per unit of energy content varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of energy, while petroleum has about 25 percent less carbon than coal, and natural gas about 45 percent less. From 1990 through 1999, petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent of total energy consumption. Natural gas and coal followed in order of importance, accounting for an average of 24 and 23 percent of total energy consumption, respectively. Most

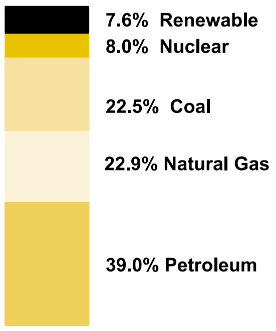
Table ES-7: U.S. Sources of CO_2 Emissions and Sinks (Tg CO_2 Eq.)

Source or Sink	1990	1995	1996	1997	1998	1999
Fossil Fuel Combustion	4,835.7	5,121.3	5,303.0	5,374.9	5,386.8	5,453.1
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	39.9
Waste Combustion	17.6	23.1	24.0	25.7	25.1	26.0
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.4
Natural Gas Flaring	5.1	13.6	13.0	12.0	10.8	11.7
Limestone and Dolomite Use	5.1	7.0	7.3	8.3	8.1	8.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.3	4.4	4.3	4.2
Carbon Dioxide Consumption	0.8	1.0	1.1	1.3	1.4	1.6
Land-Use Change and Forestry (Sink)[a]	(1,059.9)	(1,019.1)	(1,021.6)	(981.9)	(983.3)	(990.4)
International Bunker Fuels[b]	114.0	101.0	102.2	109.8	112.8	107.3
Total Emissions	**4,913.0**	**5,219.8**	**5,403.2**	**5,478.7**	**5,489.7**	**5,558.1**
Net Emissions (Sources and Sinks)	**3,853.0**	**4,200.8**	**4,381.6**	**4,496.8**	**4,506.4**	**4,567.8**

[a] Sinks are only included in net emissions total, and are based partially on projected activity data.
[b] Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.
Note: Parentheses indicate negative values (or sequestration).

Figure ES-12

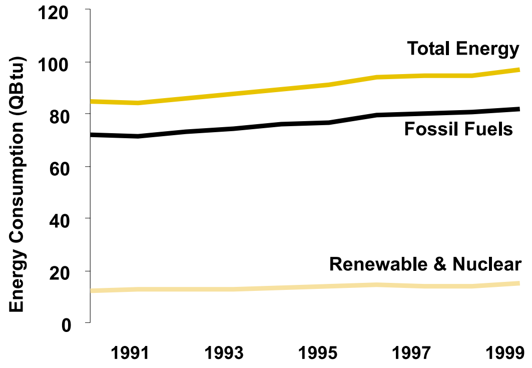
1999 U.S. Energy Consumption by Energy Source



Source: DOE/EIA-0384(99), Annual Energy Review 1998, Table 1.3, July 2000

Figure ES-13

U.S. Energy Consumption (Quadrillion Btu)



Note: Expressed as gross calorific values.
Source: DOE/EIA-0384(97), Annual Energy Review 1999, Table 1.3, July 2000

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

Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.4 percent from 1990 to 1999. The fundamental factors behind this trend include (1) a robust domestic economy, (2) relatively low energy prices as compared to 1990, (3) fuel switching by electric utilities, and (4) heavier reliance on nuclear energy. After 1990, when CO_2 emissions from fossil fuel combustion were 4,835.7 Tg CO_2 Eq., there has been a relatively steady increase to 5,453.1 Tg CO_2 Eq. in 1999. Overall, CO_2 emissions from fossil fuel combustion increased by 13 percent over the ten year period.

In 1999, fossil fuel emission trends were primarily driven by a strong economy and an increased reliance on carbon-neutral nuclear power for electricity generation. Although the price of crude oil increased over 40 percent from 1998 and relatively mild weather conditions moderated energy consumption for heating and cooling, emissions from fossil fuels still rose 1.2 percent from 1998. Emissions from the combustion of petroleum products in 1999 grew the most (64 Tg CO_2 Eq. or about 3 percent), although emissions from the combustion of petroleum by electric utilities decreased 19 percent. That decrease was offset by increased emissions from petroleum combustion in the residential, commercial, industrial, and especially transportation end-use sectors. Emissions from the combustion of natural gas in 1999 increased slightly (5 Tg CO_2 Eq. or 0.4 percent) and emissions from coal consumption decreased slightly (3 Tg CO_2 Eq. or 0.1 percent) as the industrial end-use sector substituted more natural gas for coal in 1999.

As introduced above, 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, electric utility emissions have been distributed to each end-use sector based upon their fraction of aggregate electricity consumption. This method of distributing emissions assumes that each end-use sector consumes electricity that is generated with the national average mix of fuels according to their carbon intensity. In reality, sources of electricity vary widely in carbon intensity. By giving equal carbon-intensity weight to each sector's electricity consumption, for example, emissions attributed to the residential sector may be overestimated, while emissions attributed to the industrial sector may be underestimated. Emissions from electric utilities are addressed separately after the end-use sectors have been discussed.

It is important to note, though, that all emissions resulting from the generation of electricity by the growing number of nonutility power plants are currently allocated to the industrial sector. Nonutilities supplied 15 percent of the electricity consumed in the United States in 1999. Emissions from U.S. territories are also calculated separately due to a lack of end-use-specific consumption data. Table ES-8, Figure ES-14, and Figure ES-15 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Industrial End-Use Sector. Industrial CO_2 emissions resulting from direct fossil fuel combustion and from the generation of electricity by utilities consumed by industry accounted for 33 percent of CO_2 from fossil fuel combustion in 1999. About two-thirds of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes or by non-utilities to generate electricity, the latter of which is growing rapidly. The remaining third of emissions resulted from consuming electricity from electric utilities for motors, electric furnaces, ovens, lighting, and other applications.

Transportation End-Use Sector. Transportation activities—excluding international bunker fuels—accounted for 31 percent of CO_2 emissions from fossil fuel combustion in 1999.[13] Virtually all of the energy consumed in this end-use sector came from petroleum products. Just under two thirds of the emissions resulted from gasoline consumption in motor vehicles. The remaining emissions came from other transportation activities, including the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircraft.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 19 and 16 percent, respectively, of CO_2 emissions from fossil fuel con-

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

End-Use Sector	1990		1995	1996	1997	1998	1999
Industrial	1,636.0		1,709.5	1,766.0	1,783.6	1,758.8	1,783.9
Transportation	1,474.4		1,581.8	1,621.2	1,631.4	1,659.0	1,716.4
Residential	930.7		988.7	1,047.5	1,044.2	1,040.9	1,035.8
Commercial	760.8		797.2	828.2	872.9	880.2	864.0
U.S. Territories	33.7		44.0	40.1	42.8	47.9	53.0
Total	**4,835.7**		**5,121.3**	**5,303.0**	**5,374.9**	**5,386.8**	**5,453.1**

* Emissions from electric utilities are allocated based on aggregate electricity consumption in each end-use sector.

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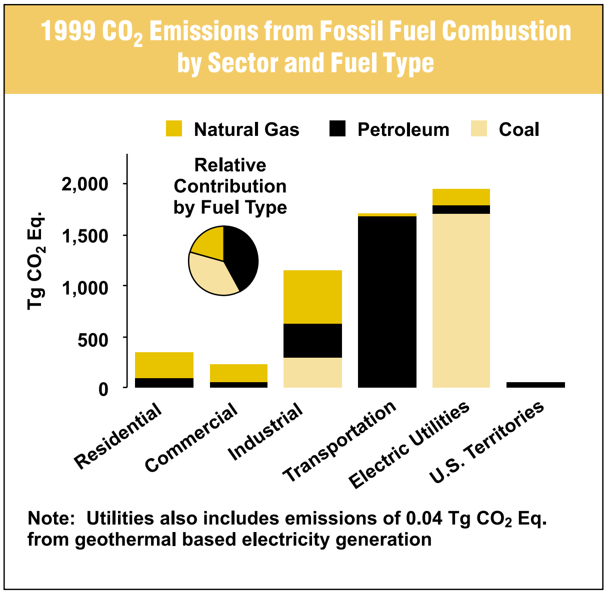
[13] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 33 percent of U.S. emissions from fossil fuel combustion in 1999.

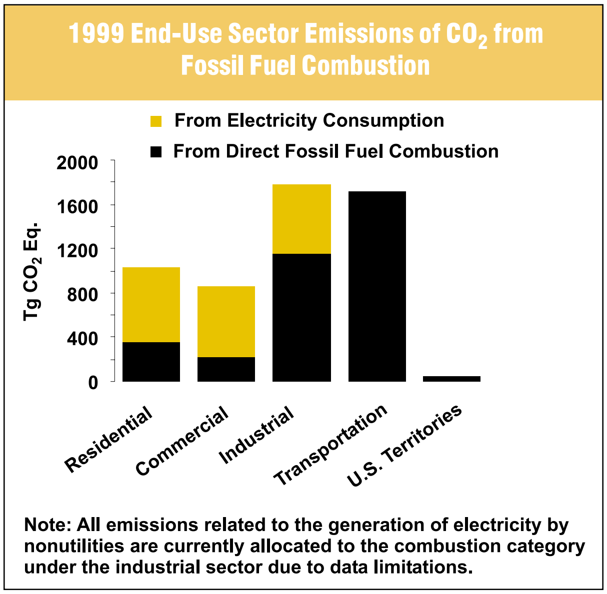
Figure ES-14



1999 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Note: Utilities also includes emissions of 0.04 Tg CO_2 Eq. from geothermal based electricity generation

Figure ES-15



1999 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

Note: All emissions related to the generation of electricity by nonutilities are currently allocated to the combustion category under the industrial sector due to data limitations.

sumption in 1999. Both sectors relied heavily on electricity for meeting energy needs, with 66 and 74 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were largely due to the consumption of natural gas and petroleum, primarily for meeting heating and cooking needs.

Electric Utilities. The United States relies on electricity to meet a significant portion of its energy demands, especially for lighting, electric motors, heating, and air conditioning. Electric utilities are responsible for consuming 27 percent of U.S. energy from fossil fuels and emitted 36 percent of the CO_2 from fossil fuel combustion in 1999. 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 85 percent of all coal consumed in the United States in 1999. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions. Note, again, that all emissions resulting from the generation of electricity by nonutility plants are currently allocated to the industrial end-use sector.

Natural Gas Flaring

Carbon dioxide is produced when natural gas from oil wells is flared (i.e., combusted) to relieve rising pressure or to dispose of small quantities of gas that are not commercially marketable. In 1999, flaring activities emitted approximately 11.7 Tg CO_2 Eq., or about 0.2 percent of U.S. CO_2 emissions.

Biomass Combustion

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

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

Gross CO_2 emissions from biomass combustion were 234.1 Tg CO_2 Eq. in 1999, with the industrial sector accounting for 81 percent of the emissions, and the residential sector 14 percent. Ethanol consumption by the transportation sector accounted for only 3 percent of CO_2 emissions from biomass combustion.

Industrial Processes

Emissions are produced as a by-product of many non-energy-related activities. For example, industrial processes can chemically transform raw materials. This transformation often releases greenhouse gases such as CO_2. The major production processes that emit CO_2 include cement manufacture, lime manufacture, limestone and dolomite use (e.g., in iron and steel making), soda ash manufacture and consumption, and CO_2 consumption. Total CO_2 emissions from these sources were approximately 67.4 Tg CO_2 Eq. in 1999, 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 has remained relatively constant.

Cement Manufacture (39.9 Tg CO_2 Eq.)

Carbon dioxide is produced primarily during the production of clinker, an intermediate product from which finished Portland and masonry cement are made. 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 (13.4 Tg CO_2 Eq.)

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

Limestone and Dolomite Use (8.3 Tg CO_2 Eq.)

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 (4.2 Tg CO_2 Eq.)

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

Carbon Dioxide Consumption (1.6 Tg CO_2 Eq.)

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

Land-Use Change and Forestry

Land-Use Change and Forestry (Sink) (990.4 Tg CO_2 Eq.)

When humans alter the terrestrial biosphere through land use, changes in land-use, and forest management practices, they alter the natural carbon flux between biomass, soils, and the atmosphere. Forest management practices, the management of agricultural soils, and landfilling of yard trimmings have resulted in a net uptake (sequestration) of carbon in the United States that is equivalent to about 15 percent of total U.S. gross emissions. Forests (including vegetation, soils, and harvested wood) accounted for approximately 91 percent of the total sequestration, agricultural soils (including mineral and organic soils and the application of lime) accounted for 8 percent, and landfilled yard trimmings accounted for less than 1 percent of the total sequestration. The net forest sequestration is largely a result of improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting. In agricultural soils, mineral soils account for a net carbon sink that is more than three times larger than the sum of emissions from organic soils and liming. Net sequestration in agricultural mineral soils is largely due to improved cropland and grazing land management practices, especially the adoption of conservation tillage practices and leaving residues on the field after harvest, and to taking erodable lands out of production and planting them with grass or trees through the Conservation Reserve Program. The landfilled yard trimmings net sequestration is due to the long-term accumulation of yard trimming carbon in landfills.

Waste

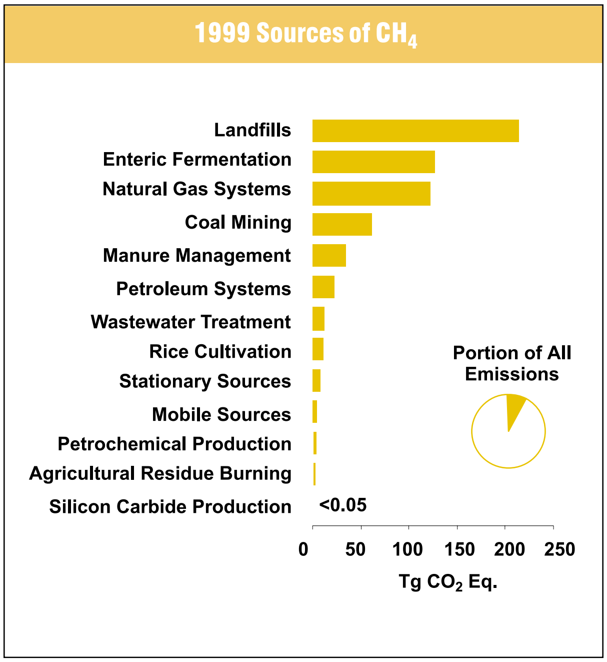
Waste Combustion (26.0 Tg CO_2 Eq.)

Waste combustion involves the burning of garbage and non-hazardous solids, referred to as municipal solid waste (MSW), as well as the burning of hazardous waste. Carbon dioxide emissions arise from the organic (i.e., carbon) materials found in these wastes. Within MSW, many products contain carbon of biogenic origin, and the CO_2 emissions from their combustion are reported under the Land-Use Change and Forestry Chapter. However, several components of MSW—plastics, synthetic rubber, synthetic fibers, and carbon black—are of fossil fuel origin, and are included as sources of CO_2 emissions.

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 has been estimated to be 21 times more effective at trapping heat in the atmosphere than CO_2 (i.e., the GWP value of methane is 21). Over the last two centuries, methane's concentration in the atmosphere has more than doubled (IPCC 1996). Experts believe these atmospheric increases were due largely to increasing emissions from anthropogenic sources, such as landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes (see Figure ES-16 and Table ES-9).

Figure ES-16



1999 Sources of CH_4

Landfills

Landfills are the largest source of anthropogenic methane emissions in the United States. In an environment where the oxygen content is low or nonexistent, organic materials, such as yard waste, household waste, food waste, and paper, can be 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 1999 were 214.6 Tg CO_2 Eq., down 1 percent since 1990. The relatively constant emission estimates are a result of two offsetting trends: (1) the amount of municipal solid waste 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. Emissions from U.S. municipal solid waste landfills accounted for 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 28 percent of the methane generated

Table ES-9: U.S. Sources of Methane Emissions (Tg CO_2 Eq.)

Source	1990	1995	1996	1997	1998	1999
Landfills	217.3	222.9	219.1	217.8	213.6	214.6
Enteric Fermentation	129.5	136.3	132.2	129.6	127.5	127.2
Natural Gas Systems	121.2	124.2	125.8	122.7	122.1	121.8
Coal Mining	87.9	74.6	69.3	68.8	66.5	61.8
Manure Management	26.4	31.0	30.7	32.6	35.2	34.4
Petroleum Systems	27.2	24.5	24.0	24.0	23.3	21.9
Wastewater Treatment	11.2	11.8	11.9	12.0	12.1	12.2
Rice Cultivation	8.7	9.5	8.8	9.6	10.1	10.7
Stationary Combustion	8.5	8.9	9.0	8.1	7.6	8.1
Mobile Combustion	5.0	4.9	4.8	4.7	4.6	4.5
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7
Agricultural Residue Burning	0.5	0.5	0.6	0.6	0.6	0.6
Silicon Carbide Production	+	+	+	+	+	+
International Bunker Fuels*	+	+	+	+	+	+
Total*	**644.5**	**650.5**	**638.0**	**632.0**	**624.8**	**619.6**

+ Does not exceed 0.05 Tg CO_2 Eq.
* Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.

in U.S. landfills in 1999 was recovered and combusted, often for energy.

A regulation promulgated in March 1996 requires the largest U.S. landfills to begin collecting and combusting their landfill gas to reduce emissions of 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 conditions. In 1999, methane emissions from U.S. natural gas systems were estimated to be 121.8 Tg CO_2 Eq., accounting for approximately 20 percent of U.S. methane emissions.

Petroleum is found in the same geological structures as natural gas, and the two are retrieved together. Methane is also saturated in crude oil, and volatilizes as the oil is exposed to the atmosphere at various points along the system. Methane emissions from the components of petroleum systems—including crude oil production, crude oil refining, transportation, and distribution—generally occur as a result of system leaks, disruptions, and routine maintenance. In 1999, emissions from petroleum systems were estimated to be 21.9 Tg CO_2 Eq., or just under 4 percent of U.S. methane emissions.

From 1990 to 1999, combined methane emissions from natural gas and petroleum systems decreased by 3 percent. Emissions from natural gas systems have remained fairly constant, while emissions from petroleum systems have declined gradually since 1990 primarily due to production declines.

Coal Mining

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

Methane from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed. Because methane in underground mines is explosive at concentrations of 5 to 15 percent in air, most active underground mines are required to vent this methane, typically to the atmosphere. At some mines, methane-recovery systems may supplement these ventilation systems. Recovery of methane in the United States has increased in recent years. During 1999, coal mining activities emitted 61.8 Tg CO_2 Eq. of methane, or 10 percent of U.S. methane emissions. From 1990 to 1999, emissions from this source decreased by 30 percent due to increased use of the methane collected by mine degasification systems.

Agriculture

Agriculture accounted for 28 percent of U.S. methane emissions in 1999, with enteric fermentation in domestic livestock, manure management, and rice cultivation accounting for the majority. Agricultural waste burning also contributed to methane emissions from agricultural activities.

Enteric Fermentation (127.2 Tg CO_2 Eq.)

During animal digestion, methane is produced through the process of enteric fermentation, in which microbes residing in animal digestive systems break down the feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest 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 1999, enteric fermentation was the source of about 21 percent of U.S. methane emissions, and more than half of the methane emissions from agriculture. From 1990 to 1999, emissions from this source decreased by 2 percent. Emissions from enteric fermentation have been generally decreasing since 1995, primarily due to declining dairy cow and beef cattle populations.

Manure Management (34.4 Tg CO_2 Eq.)

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 6 percent of U.S. methane emissions in 1999, and 20 percent of the methane emissions from agriculture. From 1990 to 1999, emissions from this source increased by 8.0 Tg CO_2 Eq.—the largest absolute increase of all the methane source categories. The bulk of this increase was from swine and dairy cow manure, and is attributed to the shift in the composition of the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use liquid management systems.

Rice Cultivation (10.7 Tg CO_2 Eq.)

Most of the world's rice, and all of the rice in the United States, is grown on flooded fields. When fields are flooded, anaerobic conditions develop and the organic matter in the soil decomposes, releasing methane to the atmosphere, primarily through the rice plants. In 1999, rice cultivation was the source of 2 percent of U.S. methane emissions, and about 6 percent of U.S. methane emissions from agriculture. Emission estimates from this source have increased about 23 percent since 1990, due to an increase in the area harvested.

Agricultural Residue Burning (0.6 Tg CO_2 Eq.)

Burning crop residue releases a number of greenhouse gases, including methane. Because field burning is not common in the United States, it was responsible for only 0.1 percent of U.S. methane emissions in 1999.

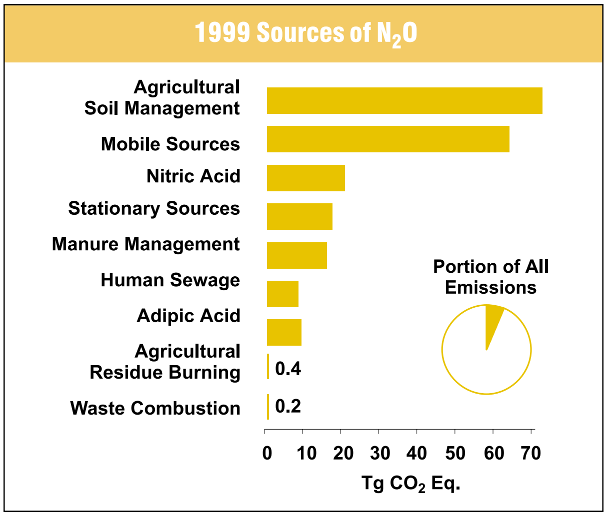
Other Sources

Methane is also produced from several other sources in the United States, including wastewater treatment, fuel combustion, and some industrial processes. Methane emissions from domestic wastewater treatment totaled 12.2 Tg CO_2 Eq. in 1999. Stationary and mobile combustion were responsible for methane emissions of 8.1 and 4.5 Tg CO_2 Eq., respectively. The majority of emissions from stationary combustion resulted from the burning of wood in the residential end-use sector. The combustion of gasoline in highway vehicles was responsible for the majority of the methane emitted from mobile combustion. Methane emissions from two industrial sources—petrochemical and silicon carbide production—were also estimated, totaling 1.7 Tg CO_2 Eq.

Nitrous Oxide Emissions

Nitrous oxide (N_2O) is a greenhouse gas that is produced both naturally—from a wide variety of biological sources in soil and water—and anthropogenically by a variety of agricultural, energy-related, industrial, and waste management activities. While total N_2O emissions are much smaller than CO_2 emissions, N_2O is approximately 310 times more powerful than CO_2 at trapping heat in the atmosphere (IPCC 1996). During the past two centuries, atmospheric concentrations of N_2O have risen by approximately 13 percent. The main anthropogenic activities producing N_2O in the United States were agricultural soil management, fuel combustion in motor vehicles, and adipic and nitric acid production processes (see Figure ES-17 and Table ES-10).

Figure ES-17


1999 Sources of N_2O

Agricultural Soil Management

Nitrous oxide (N_2O) is produced naturally in soils through microbial processes of nitrification and denitrification. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as N_2O by these microbial processes. These activities may add nitrogen to soils either directly or indirectly. Direct additions occur through the application of synthetic and organic fertilizers; production of nitrogen-fixing crops; the application of livestock manure, crop residues, and sewage sludge; cultivation of high-organic-content soils; and direct excretion by animals onto soil. Indirect additions result from volatilization and subsequent atmospheric deposition, and from leaching and surface run-off, of some of the nitrogen applied to soils as fertilizer, livestock manure, and sewage sludge.

In 1999, agricultural soil management accounted for 298.3 Tg CO_2 Eq., or 69 percent of U.S. N_2O emissions. From 1990 to 1999, emissions from this source increased by 11 percent as fertilizer consumption, manure production, and crop production rose.

Fuel Combustion

Nitrous oxide is a product of the reaction that occurs between nitrogen and oxygen during fuel combustion. Both mobile and stationary combustion emit N_2O, and the quantity emitted varies according to the type of

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

Source	1990	1995	1996	1997	1998	1999
Agricultural Soil Management	269.0	285.4	294.6	299.8	300.3	298.3
Mobile Combustion	54.3	66.8	65.3	65.2	64.2	63.4
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.2
Manure Management	16.0	16.4	16.8	17.1	17.2	17.2
Stationary Combustion	13.6	14.3	14.9	15.0	15.1	15.7
Adipic Acid	18.3	20.3	20.8	17.1	7.3	9.0
Human Sewage	7.1	8.2	7.8	7.9	8.1	8.2
Agricultural Residue Burning	0.4	0.4	0.4	0.4	0.5	0.4
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2
International Bunker Fuels*	1.0	0.9	0.9	1.0	1.0	1.0
Total*	**396.9**	**431.9**	**441.6**	**444.1**	**433.7**	**432.6**

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

fuel, technology, and pollution control device used, as well as maintenance and operating practices. For example, catalytic converters installed to reduce motor vehicle pollution can result in the formation of N_2O.

In 1999, N_2O emissions from mobile combustion totaled 63.4 Tg CO_2 Eq., or 15 percent of U.S. N_2O emissions. Emissions of N_2O from stationary combustion were 15.7 Tg CO_2 Eq., or 4 percent of U.S. N_2O emissions. From 1990 to 1999, combined N_2O emissions from stationary and mobile combustion increased by 16 percent, primarily due to increased rates of N_2O generation in motor vehicles.

Adipic Acid Production

The majority of the adipic acid produced in the United States is used to manufacture nylon 6,6. Adipic acid is also used to produce some low-temperature lubricants and to add a "tangy" flavor to foods. Nitrous oxide is emitted as a by-product of the chemical synthesis of adipic acid.

In 1999, U.S. adipic acid plants emitted 9.0 Tg CO_2 Eq. of N_2O, or 2 percent of U.S. N_2O emissions. Even though adipic acid production has increased, by 1998, all three major adipic acid plants in the United States had voluntarily implemented N_2O abatement technology. As a result, emissions have decreased by 51 percent since 1990.

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 1999, N_2O emissions from nitric acid production were 20.2 Tg CO_2 Eq., or 5 percent of U.S. N_2O emissions. From 1990 to 1999, emissions from this source category increased by 13 percent as nitric acid production grew.

Manure Management

Nitrous oxide is produced as part of microbial nitrification and denitrification processes in managed and unmanaged manure, the latter of which is addressed under agricultural soil management. Total N_2O emissions from managed manure systems in 1999 were 17.2 Tg CO_2 Eq., accounting for 4 percent of U.S. N_2O emissions. From 1990 to 1999, emissions from this source category increased by 7 percent, as poultry and swine populations have increased.

Other Sources

Other sources of N_2O included agricultural residue burning, waste combustion, and human sewage in wastewater treatment systems. In 1999, agricultural residue burning and municipal solid waste combustion each emitted less than 1 Tg CO_2 Eq. of N_2O. The human sewage component of domestic wastewater resulted in emissions of 8.2 Tg CO_2 Eq. in 1999.

HFC, PFC, and SF_6 Emissions

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

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

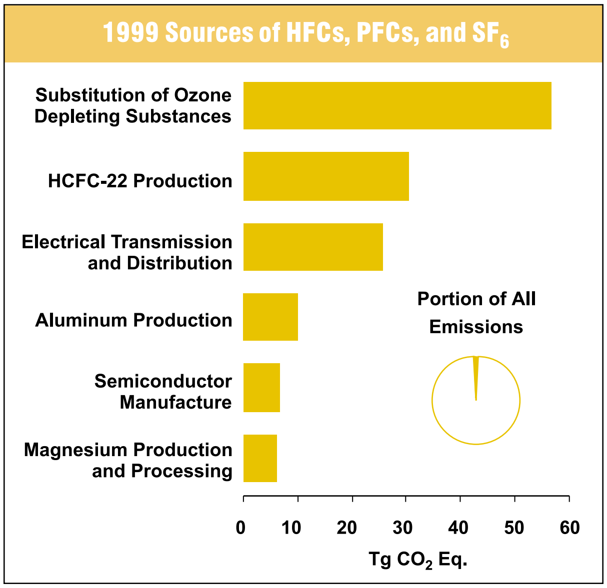
Other emissive sources of these gases include aluminum production, HCFC-22 production, semiconductor manufacturing, electrical transmission and distribution systems, and magnesium production and processing. Figure ES-18 and Table ES-11 present emission estimates for HFCs, PFCs, and SF_6, which totaled 135.7 Tg CO_2 Eq. in 1999.

Table ES-11: Emissions of HFCs, PFCs, and SF_6 (Tg CO_2 Eq.)

Source	1990	1995	1996	1997	1998	1999
Substitution of Ozone Depleting Substances	0.9	24.0	34.0	42.1	49.6	56.7
HCFC-22 Production	34.8	27.1	31.2	30.1	40.0	30.4
Electrical Transmission and Distribution	20.5	25.7	25.7	25.7	25.7	25.7
Aluminum Production	19.3	11.2	11.6	10.8	10.1	10.0
Semiconductor Manufacture	2.9	5.5	7.0	7.0	6.8	6.8
Magnesium Production and Processing	5.5	5.5	5.6	7.5	6.3	6.1
Total	**83.9**	**99.0**	**115.1**	**123.3**	**138.6**	**135.7**

Note: Totals may not sum due to independent rounding.

Figure ES-18



1999 Sources of HFCs, PFCs, and SF_6

Substitution of Ozone Depleting Substances

The use and subsequent emissions of HFCs and PFCs as substitutes for ozone depleting substances (ODS) increased from small amounts in 1990 to 56.7 Tg CO_2 Eq. in 1999. 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. In the short term, this trend is expected to continue, and will likely accelerate in the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol.* Improvements in the technologies associated with the use of these gases, however, may help to offset this anticipated increase in emissions.

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, which totaled 10.0 Tg CO_2 Eq. were estimated to have decreased by 48 percent between 1990 and 1999 due to voluntary emission reduction 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 30.4 Tg CO_2 Eq. in 1999, and have decreased by 13 percent since 1990. The intensity of HFC-23 emissions (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined significantly since 1990, although production has been increasing.

The semiconductor industry uses combinations of HFCs, PFCs, $SF_{6,}$ and other gases for plasma etching and to clean chemical vapor deposition tools. For 1999, it was estimated that the U.S. semiconductor industry emitted a total of 6.8 Tg CO_2 Eq. Emissions from this source category have increased with the growth in the semiconductor industry and the rising intricacy of chip designs.

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 since 1990, to 25.7 Tg CO_2 Eq. in 1999.

Box ES-6: 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). However, they are also potent greenhouse gases.

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

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

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

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

Compound	1990	1995	1996	1997	1998	1999
Class I						
CFC-11	52.4	19.1	11.7	10.7	9.8	9.2
CFC-12	226.9	71.1	72.2	63.6	54.9	64.4
CFC-113	39.0	7.6	+	+	+	+
CFC-114	0.7	0.8	0.8	0.8	0.6	+
CFC-115	2.2	1.6	1.6	1.4	1.1	1.1
Carbon Tetrachloride	25.1	5.5	+	+	+	+
Methyl Chloroform	27.9	8.7	1.6	+	+	+
Halon-1211	+	0.7	0.8	0.8	0.8	0.8
Halon-1301	1.0	1.8	1.9	1.9	1.9	1.9
Class II						
HCFC-22	33.9	46.2	48.8	50.6	52.3	83.0
HCFC-123	+	0.6	0.7	0.8	0.9	1.0
HCFC-124	+	5.6	5.9	6.2	6.4	6.5
HCFC-141b	+	20.6	25.4	25.1	26.7	28.7
HCFC-142b	+	7.3	8.3	8.7	9.0	9.5
HCFC-225ca/cb	+	+	+	+	+	+

Source: EPA
+ Does not exceed 0.05 Gg

Lastly, SF_6 is also used as a protective covergas for the casting of molten magnesium. Estimated emissions from primary magnesium production and magnesium casting were 6.1 Tg CO_2 Eq. in 1999, an increase of 11 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. Criteria pollutants do not have a direct global warming effect, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Carbon monoxide is produced when carbon-containing fuels are combusted incompletely. Nitrogen oxides (i.e., NO and NO_2) are created by lightning, fires, fossil fuel combustion, and in the stratosphere from nitrous oxide (N_2O). NMVOCs—which 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 coal by the electric power industry 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 and NO_x—criteria pollutants are regulated under the Clean Air Act. These gases also indirectly affect the global climate by reacting with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Unlike other criteria pollutants, SO_2 emitted into the atmosphere is believed to affect the Earth's radiative budget negatively; therefore, it is discussed separately.

One of the most important indirect climate change effects of criteria pollutants is their role as precursors for tropospheric ozone formation. They can also 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 2000).[14] Table ES-13 shows that fuel combustion accounts for the majority of emissions of these gases. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, $NO_{x,}$ and NMVOCs.

Box ES-7: 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 67 percent in 1999. Coal combustion contributes nearly all of those emissions (approximately 93 percent). Sulfur dioxide emissions have decreased in recent years, primarily as a result of electric utilities switching from high sulfur to low sulfur coal.

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[14] NO_x and CO emission estimates from agricultural residue burning were estimated separately, and therefore not taken from EPA (2000).

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

Gas/Activity	1990	1995	1996	1997	1998	1999
NO_x	**21,955**	**22,755**	**23,663**	**23,934**	**23,613**	**23,042**
Stationary Fossil Fuel Combustion	9,884	9,822	9,541	9,589	9,408	9,070
Mobile Fossil Fuel Combustion	10,900	11,870	12,893	13,095	13,021	12,794
Oil and Gas Activities	139	100	126	130	130	130
Industrial Processes	921	842	977	992	924	930
Solvent Use	1	3	3	3	3	3
Agricultural Burning	28	28	32	33	34	33
Waste	83	89	92	92	93	83
CO	**85,846**	**80,678**	**87,196**	**87,012**	**82,496**	**82,982**
Stationary Fossil Fuel Combustion	4,999	5,383	5,620	4,968	4,575	4,798
Mobile Fossil Fuel Combustion	69,523	68,072	72,390	71,225	70,288	68,179
Oil and Gas Activities	302	316	321	333	332	332
Industrial Processes	9,502	5,291	7,227	8,831	5,612	5,604
Solvent Use	4	5	1	1	1	1
Agricultural Burning	537	536	625	630	653	629
Waste	979	1,075	1,012	1,024	1,035	3,439
NMVOCs	**18,843**	**18,663**	**17,353**	**17,586**	**16,554**	**16,128**
Stationary Fossil Fuel Combustion	912	973	971	848	778	820
Mobile Fossil Fuel Combustion	8,154	7,725	8,251	8,023	7,928	7,736
Oil and Gas Activities	555	582	433	442	440	385
Industrial Processes	3,110	2,805	2,354	2,793	2,352	2,281
Solvent Use	5,217	5,609	4,963	5,098	4,668	4,376
Agricultural Burning	NA	NA	NA	NA	NA	NA
Waste	895	969	381	382	387	531
SO_2	**21,481**	**17,408**	**17,109**	**17,565**	**17,682**	**17,115**
Stationary Fossil Fuel Combustion	18,407	14,724	14,727	15,106	15,192	14,598
Mobile Fossil Fuel Combustion	1,339	1,189	1,081	1,116	1,145	1,178
Oil and Gas Activities	390	334	304	312	310	309
Industrial Processes	1,306	1,117	958	993	996	996
Solvent Use	0	1	1	1	1	1
Agricultural Burning	NA	NA	NA	NA	NA	NA
Waste	38	43	37	37	38	33

Source: (EPA 2000) except for estimates from agricultural residue burning.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

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 1999. A summary of these estimates is provided in Table 1-4 and Table 1-5 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.[1,2] This report also discusses the methods and data used to calculate these emission estimates.

In June of 1992, the United States signed, and later ratified in October, the United Nations Framework Convention on Climate Change (UNFCCC). The objective of the UNFCCC is "to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[3,4]

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…"[5] The United States views this report as an opportunity to fulfill this commitment under UNFCCC.

In 1988, preceding the creation of the UNFCCC, 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 collaborated 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 UNFCCC are consistent and comparable 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

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[1] See the section below entitled *Global Warming Potentials* for an explanation of GWP values.

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

[3] 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).

[4] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <http://www.unfccc.de>. (UNEP/WMO 2000)

[5] Article 4 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (also identified in Article 12). See <http://www.unfccc.de>. (UNEP/WMO 2000)

this inventory is presented in accordance with these guidelines. Additionally, in order to fully comply with the *Revised 1996 IPCC Guidelines*, the United States has provided estimates of carbon dioxide emissions from fossil fuel combustion using the IPCC Reference Approach in Annex R.

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 UNFCCC can estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change; and (3) as a prerequisite for accounting for reductions and evaluating possible mitigation strategies.

What is Climate Change?

Climate change refers to long-term fluctuations in temperature, precipitation, wind, and other elements of the Earth's climate system.[6] Natural processes such as solar-irradiance variations, variations in the Earth's orbital parameters,[7] and volcanic activity can produce variations in climate. The climate system can also be influenced by changes in the concentration of various gases in the atmosphere, which affect the Earth's absorption of radiation.

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).

Under the UNFCCC, 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."[8] 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

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse

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[6] The Earth's climate system comprises the atmosphere, oceans, biosphere, cryosphere, and geosphere.

[7] For example, eccentricity, precession, and inclination.

[8] Article 1 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. (UNEP/WMO 2000)

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).

> *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 halogenated 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).[9] Aerosols—extremely small particles or liquid droplets often produced by emissions of sulfur dioxide (SO_2) and other pollutants—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. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

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[9] Also referred to in the U.S. Clean Air Act as “criteria pollutants.”

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[10] times to 358 ppmv, a 28 percent increase (IPCC 1996).[11] 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 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 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 primarily 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 combustion; 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 upper stratosphere,[12] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[13] where it is the main compo-

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[10] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 1996).

[11] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750-1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 1996).

[12] 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.

[13] 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.

nent 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 is included in the category referred to as "criteria pollutants" in the United States under the Clean Air Act[14] and its subsequent amendments. The tropospheric concentrations of both ozone and these precursor gases are short-lived and, therefore, spatially variable.

Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride (SF_6). 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, methyl bromide, and hydrobromofluorocarbons (HBFCs)—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 because 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[15] 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 UNFCCC; however, they are reported in this inventory under Annex O.

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), 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, OH) 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.

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[14] [42 U.S.C § 7408, CAA § 108]

[15] 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 of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

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 ozone in the troposphere and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects.[16] Additionally, NO_x emissions from aircraft are also likely to decrease methane concentrations, thus having a negative radiative forcing effect (IPCC 1999). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning—both natural and anthropogenic fires—fuel combustion, and, in the stratosphere, from the photodegradation of 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)[17] emissions from fossil fuel and biomass burning. The net effect of aerosols is 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.[18] 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). Emission estimates for sulfur dioxide are provided in Annex P of this report.

Additionally, current research indicates that another constituent of aerosols, elemental carbon, may have a positive radiative forcing, second to only carbon dioxide, throughout the entire atmosphere (Jacobson 2001). Thus, it is possible that the net radiative forcing from aerosols may be slightly positive, but is in any event very uncertain. The large emission sources of elemental carbon include diesel exhaust, coal combustion, and biomass burning.

Global Warming Potentials

A Global Warming Potential (GWP) is intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas (see Table 1-1). 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 produce 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, and therefore GWP weighted emissions are measured in teragrams of CO_2 equivalents (Tg CO_2 Eq.)[19] The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

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[16] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

[17] Sulfur dioxide is a primary anthropogenic contributor to the formation of "acid rain" and other forms of atmospheric acid deposition.

[18] 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).

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

$$\text{Tg CO}_2\text{ Eq} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000\text{ Gg}}\right)$$

where,

Tg CO_2 Eq. = Teragrams of Carbon Dioxide Equivalents

Gg = Gigagrams (equivalent to a thousand metric tons)

GWP = Global Warming Potential

Tg = Teragrams

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 UNFCCC have also agreed to use GWPs based upon a 100 year time horizon although other time horizon values are available.

> *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*

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.

Box 1-1: Emission Reporting Nomenclature

The Global Warming Potential (GWP) weighted emissions of all direct greenhouse gases presented throughout this report are presented in terms of equivalent emissions of carbon dioxide (CO_2), using units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.) In previous year's inventories emissions were reported in terms of carbon—versus carbon dioxide—equivalent emissions, using units of million metric tons of carbon equivalents (MMTCE). This change of units for reporting was implemented so that the U.S. Inventory would be more consistent with international practices, which are to report emissions in carbon dioxide equivalent units.

In order to convert the emission estimates presented in this report to those provided previously, the following equation can be employed:

$\text{Tg CO}_2\text{ Eq.} = \text{MMTCE} \times ({}^{44}/_{12})$

There are two elements to the conversion. The first element is simply nomenclature, since one teragram is equal to one million metric tons:

$\text{Tg} = 10^9 \text{ kg} = 10^6 \text{ metric tons} = 1 \text{ megaton} = 1 \text{ million metric tons}$

The second element is the conversion, by weight, from carbon to carbon dioxide. The molecular weight of carbon is 12, and the molecular weight of oxygen is 16; therefore, the molecular weight of CO_2 is 44 (i.e., $12 + [16 \times 2]$), as compared to 12 for carbon alone. Thus, carbon comprises $12/44^{\text{ths}}$ of carbon dioxide by weight.

time horizon. In addition, Parties may also use other time horizons.[20]

Greenhouse gases with relatively 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 these 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).

Recent Trends in U.S. Greenhouse Gas Emissions

Total U.S. greenhouse gas emissions rose in 1999 to 6,746.1 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.)[21] (11.7 percent above 1990 baseline levels). The single year increase in emissions from 1998 to 1999 was 0.9 percent (59.2 Tg CO_2 Eq.), less than the 1.2 percent average annual rate of increase for the 1990s. The lower than average increase in emissions, especially given the robust economic growth in 1999, was primarily attributable to the following factors: 1) warmer than normal summer and winter conditions; 2) significantly increased output from existing nuclear power plants; and 3) reduced CH_4 emissions from coal mines and HFC-23 by-product emissions from the chemical manufacture of HCFC-22. Figure 1-1 through Figure 1-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute changes since 1990.

Figure 1-1

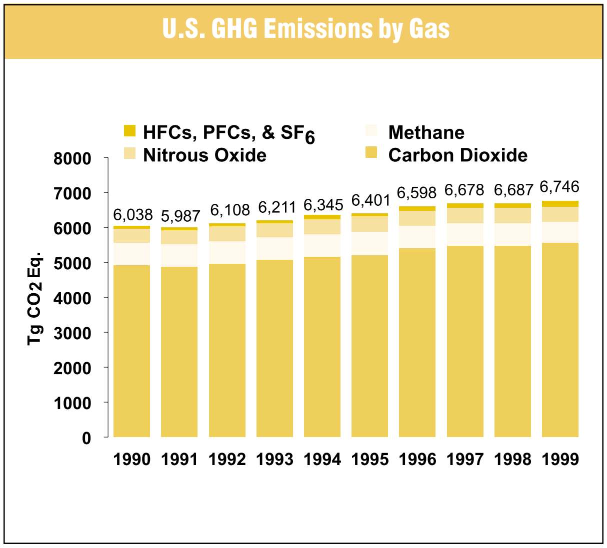
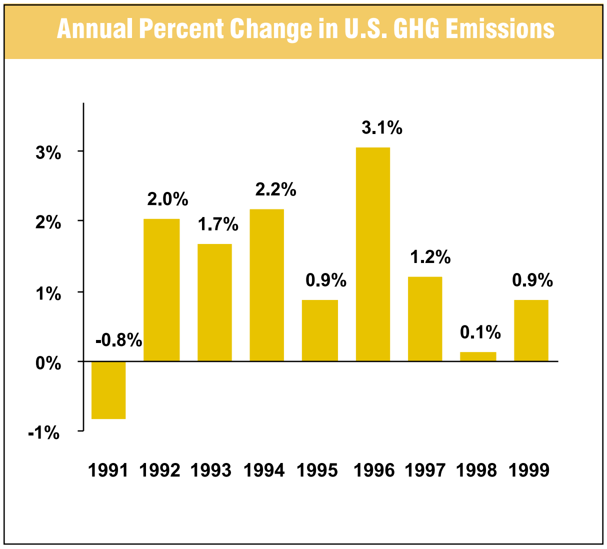


Figure 1-2



As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion accounted for a nearly constant 80 percent of global warming potential (GWP) weighted emissions in the 1990s.[22] Emissions from this source category grew by 13 percent (617.4 Tg CO_2

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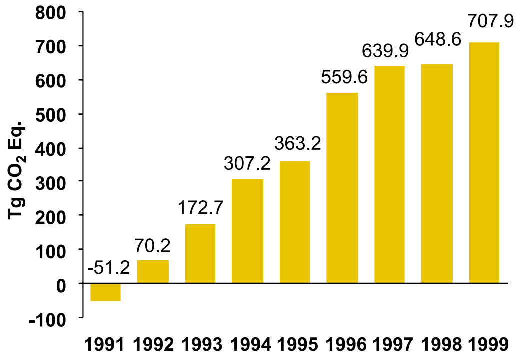
[20] Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties at its second session; held at Geneva from 8 to 19 July 1996; Addendum; Part Two: Action taken by the Conference of the Parties at its second session; Decision 9/CP.2; Communications 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. FCCC (1996).

[21] Estimates are presented in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.), which weights each gas by its Global Warming Potential, or GWP (see previous section) and is consistent with international practices.

Figure 1-3

Absolute Change in U.S. GHG Emissions Since 1990



Eq.) from 1990 to 1999 and were responsible for the majority of the increase in national emissions during this period. The annual increase in CO_2 emissions from fossil fuel combustion was 1.2 percent in 1999, a figure close to the source's average annual rate of 1.4 percent during the 1990s. Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. On an annual basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams would be expected to have proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

Longer-term changes in energy consumption patterns, however, tend to be more a function of changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs) and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Energy-related CO_2 emissions are also a function of the type fuel or energy consumed and its carbon intensity. Producing heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 emissions associated with energy consumption because of the lower carbon content of natural gas power unit of useful energy produced. Table 1-2 shows annual changes in emissions during the last few years of the 1990s for particular fuel types and sectors.

Carbon dioxide emissions from fossil fuel combustion grew rapidly in 1996, due primarily to two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as colder winter conditions and the associated rise in demand for natural gas from residential, commercial and industrial customers for heating caused gas prices to rise sharply; and 2) higher consumption of petroleum fuels for transportation. Milder weather conditions in summer and winter moderated the growth in emissions in 1997; however, the shut-down of several nuclear power plants lead electric utilities to increase their consumption of coal and other fuels to offset the lost capacity. In 1998, weather conditions were again a dominant factor in slowing the growth in emissions. Warm winter temperatures resulted in a significant drop in residential, commercial, and industrial natural gas consumption. This drop in emissions from natural gas used for heating was primarily offset by two factors: 1) electric utility emissions, which increased in part due to a hot summer and its associated air conditioning demand; and 2) increased motor gasoline consumption for transportation.

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[22] If a full accounting of emissions from fossil fuel combustion is made by including emissions from the combustion of international bunker fuels and CH_4 and N_2O emissions associated with fuel combustion, then this percentage increases to approximately 82 percent during the 1990s.

Table 1-2: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg CO_2 Eq. and Percent)

Sector	Fuel Type	1995 to 1996		1996 to 1997		1997 to 1998		1998 to 1999	
Electric Utility	Coal	89.9	5.7%	52.0	3.1%	14.3	0.8%	-32.1	-1.8%
Electric Utility	Natural Gas	-25.3	-14.7%	13.1	9.0%	16.2	10.1%	-7.8	-4.4%
Electric Utility	Petroleum	5.1	10.0%	8.1	14.4%	26.7	41.6%	-17.4	-19.1%
Transportation[a]	Petroleum	38.8	2.5%	7.6	0.5%	34.1	2.1%	57.6	3.6%
Residential	Natural Gas	21.4	8.1%	-14.0	-4.9%	-24.0	-8.9%	8.5	3.4%
Commercial	Natural Gas	7.0	4.3%	3.1	1.8%	-11.1	-6.4%	2.9	1.8%
Industrial	Coal	-7.3	-2.7%	2.0	0.8%	-1.1	-0.4%	29.2	11.2%
Industrial	Natural Gas	17.8	3.4%	-0.5	-0.1%	-14.5	-2.7%	1.6	0.3%
All Sectors[b]	**All Fuels[b]**	**181.7**	**3.5%**	**71.9**	**1.4%**	**11.9**	**0.2%**	**66.4**	**1.2%**

[a] Excludes emissions from International Bunker Fuels.

[b] Includes fuels and sectors not shown in table.

In 1999, the increase in emissions from fossil fuel combustion was driven largely by growth in petroleum consumption for transportation. In addition, heating fuel demand partially recovered in the residential, commercial and industrial sectors as winter temperatures dropped relative to 1998, although temperatures were still warmer than normal. These increases were offset, in part, by a decline in emissions from electric utilities due primarily to: 1) an increase in net generation of electricity by nuclear plants (8 percent) to record levels, which reduced demand from fossil fuel plants; and 2) moderated summer temperatures compared to the previous year—thereby reducing electricity demand for air conditioning. Utilization of existing nuclear power plants, measured as a plant's capacity factor,[23] has increased from just over 70 percent in 1990 to over 85 percent in 1999.

Another factor that does not affect total emissions, but does affect the interpretation of emission trends is the allocation of emissions from nonutility power producers. The Energy Information Administration (EIA) currently includes fuel consumption by nonutilities with the industrial end-use sector. In 1999, there was a large shift in generating capacity from utilities to nonutilities, as restructuring legislation spurred the sale of 7 percent of utility generating capability (EIA 2000b). This shift is illustrated by the increase in industrial end-use sector emissions from coal and the associated decrease in electric utility emissions. However, emissions from the industrial end-use sector did not increase as much as would be expected even though net generation by nonutilities increased from 11 to 15 percent of total U.S. electricity production (EIA 2000b).[24]

Other notable trends in emissions from additional source categories over the nine-year period from 1990 through 1999 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 55.8 Tg CO_2 Eq. This increase was partly offset, however, by reductions in PFC emissions from aluminum production (9.2 Tg CO_2 Eq. or 48 percent), and reductions in emissions of HFC-23 from the production of HCFC-22 (4.4 Tg CO_2 Eq. or 13 percent). Reductions in PFC emissions from aluminum production were the result of both voluntary industry emission reduction efforts and lower domestic aluminum production. HFC-23 emissions from the production of HCFC-22 decreased due to a reduction in the intensity of emissions from that

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[23] The capacity factor is defined as the ratio of the electrical energy produced by a generating unit for a given period of time to the electrical energy that could have been produced at continuous full-power operation during the same period (EIA 1999).

[24] It is unclear whether reporting problems for electric utilities and the industrial end-use sector have increased with the dramatic growth in nonutilities and the opening of the electric power industry to increased competition.

Box 1-2: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

There are several ways to assess a nation's greenhouse gas emitting intensity. The basis for measures of intensity can be 1) per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; 2) per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; 3) per unit of electricity consumption, because the electric power industry—utilities and nonutilities combined—were the largest sources of U.S. greenhouse gas emissions in 1999; 4) per unit of total gross domestic product as a measure of national economic activity; or 5) on a per capita basis. Depending upon the measure used, the United States could appear to have reduced or increased its national greenhouse gas intensity during the 1990s.

Table 1-3 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.2 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption—thereby indicating an improved or lower greenhouse gas emitting intensity—and much slower than that for either electricity consumption or overall gross domestic product. Emissions, however, are growing faster than national population, thereby indicating a worsening or higher greenhouse gas emitting intensity on a per capita basis (see Figure 1-4). Overall, atmospheric CO_2 concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

Table 1-3: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1991	1992	1993	1994	1995	1996	1997	1998	1999	Growth Rate[f]
GHG Emissions[a]	99	101	103	105	106	109	111	111	112	1.2%
Energy Consumption[b]	100	101	104	106	108	111	112	112	115	1.5%
Fossil Fuel Consumption[b]	99	101	103	106	107	110	112	112	113	1.4%
Electricity Consumption[b]	102	102	105	108	111	114	116	119	120	2.1%
GDP[c]	100	103	105	110	112	116	122	127	132	3.2%
Population[d]	101	102	103	104	105	106	107	108	109	1.0%
Atmospheric CO_2 Concentration[e]	100	101	101	101	102	102	103	104	104	0.4%

[a] GWP weighted values

[b] Energy content weighted values (EIA 2000a)

[c] Gross Domestic Product in chained 1996 dollars (BEA 2000)

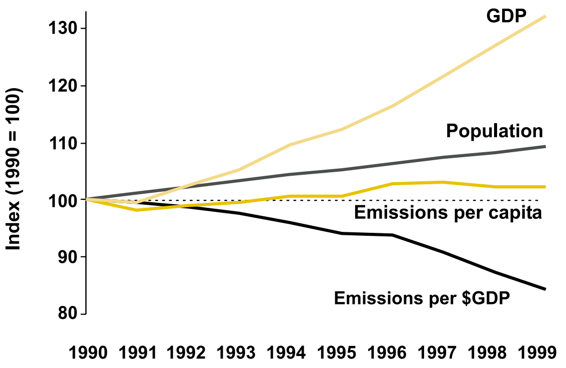
[d] (U.S. Census Bureau 2000)

[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 2000)

[f] Average annual growth rate

Figure 1-4

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



Source: BEA (2000), U.S. Census Bureau (2000) and Emission estimates in the report.

source, despite increased HCFC-22 production.

- Emissions of N_2O from mobile combustion rose by 9.1 Tg CO_2 Eq. (17 percent), primarily due to increased rates of N_2O generation in highway vehicles.
- Methane emissions from coal mining dropped by 26.0 Tg CO_2 Eq. (30 percent) as a result of the mining of less gassy coal from underground mines and the increased use of methane from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 29.3 Tg CO_2 Eq. (11 percent) as fertilizer consumption, livestock populations, and crop production rose.
- By 1998, all of the three major adipic acid producing plants had voluntarily implemented N_2O abatement technology, and as a result, emissions fell by 9.3 Tg CO_2 Eq. (51 percent). The majority of this decline occurred from 1997 to 1998, despite increased production.

Overall, from 1990 to 1999, total emissions of CO_2 and N_2O increased by 645.2 (13 percent) and 35.7 Tg CO_2 Eq. (9 percent), respectively, while CH_4 emissions decreased by 24.9 Tg CO_2 Eq. (4 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 51.8 Tg CO_2 Eq. (62 percent). Despite being emitted in smaller quantities relative to the other principle greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because many of them have extremely high global warming potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests and in landfilled carbon, which were estimated to be 15 percent of total emissions in 1999.

As an alternative, emissions can be aggregated across gases by the IPCC defined sectors, referred to here as chapters. Over the ten year period of 1990 to 1999, total emissions in the Energy, Industrial Processes, Agriculture, and Waste chapters climbed by 603.6 (12 percent), 58.2 (33 percent), 38.3 (8 percent), and 7.8 Tg CO_2 Eq. (3 percent), respectively. Estimates of net carbon sequestration in the Land-Use Change and Forestry chapter declined by 69.5 Tg CO_2 Eq. (7 percent).

Table 1-4 summarizes emissions and sinks from all U.S. anthropogenic sources in weighted units of Tg CO_2 Eq., while unweighted gas emissions and sinks in gigagrams (Gg) are provided in Table 1-5. Alternatively, emissions and sinks are aggregated by chapter in Table 1-6 and Figure 1-5.

Methodology and Data Sources

Emissions of greenhouse gases from various source and sink categories have been estimated using methodologies that are consistent with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). 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 most emission sources, 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 En-

Figure 1-5

U.S. GHG Emissions by Chapter/IPCC Sector

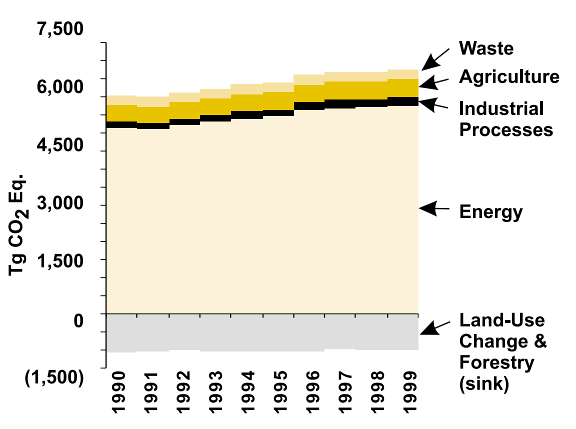


Table 1-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999
CO_2	**4,913.0**	**5,219.8**	**5,403.2**	**5,478.7**	**5,489.7**	**5,558.1**
Fossil Fuel Combustion	4,835.7	5,121.3	5,303.0	5,374.9	5,386.8	5,453.1
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	39.9
Waste Combustion	17.6	23.1	24.0	25.7	25.1	26.0
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.4
Natural Gas Flaring	5.1	13.6	13.0	12.0	10.8	11.7
Limestone and Dolomite Use	5.1	7.0	7.3	8.3	8.1	8.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.3	4.4	4.3	4.2
Carbon Dioxide Consumption	0.8	1.0	1.1	1.3	1.4	1.6
Land-Use Change and Forestry (Sink)[a]	(1,059.9)	(1,019.1)	(1,021.6)	(981.9)	(983.3)	(990.4)
International Bunker Fuels[b]	114.0	101.0	102.2	109.8	112.8	107.3
CH_4	**644.5**	**650.5**	**638.0**	**632.0**	**624.8**	**619.6**
Landfills	217.3	222.9	219.1	217.8	213.6	214.6
Enteric Fermentation	129.5	136.3	132.2	129.6	127.5	127.2
Natural Gas Systems	121.2	124.2	125.8	122.7	122.1	121.8
Coal Mining	87.9	74.6	69.3	68.8	66.5	61.8
Manure Management	26.4	31.0	30.7	32.6	35.2	34.4
Petroleum Systems	27.2	24.5	24.0	24.0	23.3	21.9
Wastewater Treatment	11.2	11.8	11.9	12.0	12.1	12.2
Rice Cultivation	8.7	9.5	8.8	9.6	10.1	10.7
Stationary Combustion	8.5	8.9	9.0	8.1	7.6	8.1
Mobile Combustion	5.0	4.9	4.8	4.7	4.6	4.5
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7
Agricultural Residue Burning	0.5	0.5	0.6	0.6	0.6	0.6
Silicon Carbide Production	+	+	+	+	+	+
International Bunker Fuels[b]	+	+	+	+	+	+
N_2O	**396.9**	**431.9**	**441.6**	**444.1**	**433.7**	**432.6**
Agricultural Soil Management	269.0	285.4	294.6	299.8	300.3	298.3
Mobile Combustion	54.3	66.8	65.3	65.2	64.2	63.4
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.2
Manure Management	16.0	16.4	16.8	17.1	17.2	17.2
Stationary Combustion	13.6	14.3	14.9	15.0	15.1	15.7
Adipic Acid	18.3	20.3	20.8	17.1	7.3	9.0
Human Sewage	7.1	8.2	7.8	7.9	8.1	8.2
Agricultural Residue Burning	0.4	0.4	0.4	0.4	0.5	0.4
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2
International Bunker Fuels[b]	1.0	0.9	0.9	1.0	1.0	1.0
HFCs, PFCs, and SF_6	**83.9**	**99.0**	**115.1**	**123.3**	**138.6**	**135.7**
Substitution of Ozone Depleting Substances	0.9	24.0	34.0	42.1	49.6	56.7
HCFC-22 Production	34.8	27.1	31.2	30.1	40.0	30.4
Electrical Transmission and Distribution	20.5	25.7	25.7	25.7	25.7	25.7
Aluminum Production	19.3	11.2	11.6	10.8	10.1	10.0
Semiconductor Manufacture	2.9	5.5	7.0	7.0	6.8	6.8
Magnesium Production and Processing	5.5	5.5	5.6	7.5	6.3	6.1
Total Emissions	**6,038.2**	**6,401.3**	**6,597.8**	**6,678.1**	**6,686.8**	**6,746.1**
Net Emissions (Sources and Sinks)	**4,978.3**	**5,382.3**	**5,576.2**	**5,696.2**	**5,703.5**	**5,755.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data.

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

Note: Totals may not sum due to independent rounding.

Note: Parentheses indicate negative values (or sequestration).

Table 1-5: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999
CO_2	**4,912,959**	**5,219,832**	**5,403,220**	**5,478,677**	**5,489,729**	**5,558,150**
Fossil Fuel Combustion	4,835,688	5,121,263	5,302,961	5,374,913	5,386,762	5,453,088
Cement Manufacture	33,278	36,847	37,079	38,323	39,218	39,896
Waste Combustion	17,572	23,065	23,968	25,674	25,145	25,960
Lime Manufacture	11,238	12,805	13,495	13,685	13,914	13,426
Natural Gas Flaring	5,121	13,587	12,998	12,026	10,839	11,701
Limestone and Dolomite Use	5,117	6,987	7,305	8,327	8,114	8,290
Soda Ash Manufacture and Consumption	4,144	4,309	4,273	4,434	4,325	4,217
Carbon Dioxide Consumption	800	968	1,140	1,294	1,413	1,572
Land-Use Change and Forestry (Sink)[a]	(1,059,900)	(1,019,000)	(1,021,400)	(981,900)	(983,400)	(990,400)
International Bunker Fuels[b]	114,001	101,014	102,197	109,788	112,771	107,345
CH_4	**30,689**	**30,978**	**30,379**	**30,096**	**29,754**	**29,504**
Landfills	10,346	10,614	10,435	10,371	10,171	10,221
Enteric Fermentation	6,166	6,492	6,295	6,172	6,072	6,057
Natural Gas Systems	5,772	5,912	5,993	5,841	5,814	5,799
Coal Mining	4,184	3,550	3,301	3,274	3,168	2,944
Manure Management	1,256	1,477	1,463	1,553	1,677	1,638
Petroleum Systems	1,294	1,168	1,143	1,142	1,108	1,044
Wastewater Treatment	533	561	567	572	577	583
Rice Cultivation	414	452	419	455	481	509
Stationary Combustion	403	422	430	386	361	386
Mobile Combustion	237	232	228	225	219	215
Petrochemical Production	56	72	75	77	77	79
Agricultural Residue Burning	25	24	28	29	30	28
Silicon Carbide Production	1	1	1	1	1	1
International Bunker Fuels[b]	2	2	2	2	2	2
N_2O	**1,280**	**1,393**	**1,424**	**1,433**	**1,399**	**1,395**
Agricultural Soil Management	868	921	950	967	969	962
Mobile Combustion	175	215	211	210	207	204
Nitric Acid	58	64	67	68	67	65
Manure Management	52	53	54	55	55	55
Stationary Combustion	44	46	48	49	49	51
Adipic Acid	59	66	67	55	23	29
Human Sewage	23	27	25	26	26	26
Agricultural Residue Burning	1	1	1	1	1	1
Waste Combustion	1	1	1	1	1	1
International Bunker Fuels[b]	3	3	3	3	3	3
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M
HCFC-22 Production[c]	3	2	3	3	3	3
Electrical Transmission and Distribution[d]	1	1	1	1	1	1
Aluminum Production	M	M	M	M	M	M
Semiconductor Manufacture	M	M	M	M	M	M
Magnesium Production and Processing[d]	0	0	0	0	0	0
NOx	**21,955**	**22,755**	**23,663**	**23,934**	**23,613**	**23,042**
CO	**85,978**	**80,784**	**87,306**	**87,131**	**82,619**	**83,093**
NMVOCs	**18,843**	**18,662**	**17,350**	**17,586**	**16,555**	**16,129**

M Mixture of multiple gases

[a] Sinks are not included in CO_2 emissions total, and are based partially on projected activity data.

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

[c] HFC-23 emitted

[d] SF_6 emitted

Note: Totals may not sum due to independent rounding.

Note: Parentheses indicate negative values (or sequestration).

Table 1-6: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg CO_2 Eq.)

Chapter/IPCC Sector	1990	1995	1996	1997	1998	1999
Energy	5,158.4	5,452.9	5,629.1	5,695.4	5,700.9	5,762.0
Industrial Processes	175.8	202.7	221.5	229.3	235.3	234.0
Agriculture	450.5	479.5	484.1	489.8	491.4	488.8
Land-Use Change and Forestry (Sink)*	(1,059.9)	(1,019.1)	(1,021.6)	(981.9)	(983.3)	(990.4)
Waste	253.4	266.2	263.1	263.6	259.2	261.3
Total Emissions	**6,038.2**	**6,401.3**	**6,597.8**	**6,678.1**	**6,686.8**	**6,746.1**
Net Emissions (Sources and Sinks)	**4,978.3**	**5,382.3**	**5,576.2**	**5,696.2**	**5,703.5**	**5,755.7**

* Sinks are only included in net emissions total, and are based partially on projected activity data.
Note: Totals may not sum due to independent rounding.
Note: Parentheses indicate negative values (or sequestration).

Box 1-3: 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 (FHWA). Likewise, the number of miles driven—up 13 percent from 1990 to 1999—and gallons of gasoline consumed each year in the United States have increased steadily since the 1980s, according to the FHWA and Energy Information Administration, respectively. These increases in motor vehicle usage are the result of a confluence of factors including population growth, economic growth, urban sprawl, low fuel prices, and increasing popularity of sport utility vehicles and other light-duty trucks that tend to have lower fuel efficiency.[25] A similar set of social and economic trends has led to a significant increase in air travel and freight transportation—by both air and road modes—during the 1990s.

One of the unintended consequences of these changes is a slowing of progress toward cleaner air in both urban and rural parts of the country. Passenger cars, trucks, motorcycles, and buses emit significant quantities of air pollutants with local, regional, and global effects. Motor vehicles are major sources of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nonmethane volatile organic compounds (NMVOCs), nitrogen oxides (NOx), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). Motor vehicles are also important contributors to many serious air pollution problems, including ground-level ozone (i.e., smog), acid rain, fine particulate matter, and global warming. Within the United States and abroad, government agencies have taken actions to reduce these emissions. Since the 1970s, the EPA has required the reduction of 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. New vehicles are now equipped with advanced emissions controls, which are designed to reduce emissions of NO_x, hydrocarbons, and CO.

Table 1-7 summarizes greenhouse gas emissions from all transportation-related activities. Overall, transportation activities—excluding international bunker fuels—accounted for an almost constant 26 percent of total U.S. greenhouse gas emissions from 1990 to 1999. These emissions were primarily CO_2 from fuel combustion, which increased by 16 percent from 1990 to 1999. However, because of larger increases in N_2O and HFC emissions during this period, overall emissions from transportation activities actually increased by 18 percent.

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[25] The average miles per gallon achieved by the U.S. highway vehicle fleet actually decreased by slightly less than one percent in both 1998 and 1999.

Table 1-7: Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Vehicle Type	1990	1995	1996	1997	1998	1999
CO_2	**1,474.4**	**1,581.8**	**1,621.2**	**1,631.4**	**1,659.0**	**1,716.4**
Passenger Cars	620.0	641.9	654.1	660.2	674.5	688.9
Light-Duty Trucks	283.1	325.3	333.5	337.3	356.9	364.8
Other Trucks	206.0	235.9	248.1	257.0	257.9	269.7
Buses	10.7	13.5	11.3	12.0	12.3	12.9
Aircraft[a]	176.7	171.5	180.2	179.0	183.0	184.6
Boats and Vessels	59.4	66.9	63.8	50.2	47.9	65.6
Locomotives	28.4	31.5	33.4	34.4	33.6	35.1
Other[b]	90.1	95.3	96.7	101.4	93.0	94.9
International Bunker Fuels[c]	114.0	101.0	102.2	109.8	112.8	107.3
CH_4	**5.0**	**4.9**	**4.8**	**4.7**	**4.6**	**4.5**
Passenger Cars	2.4	2.0	2.0	2.0	2.0	1.9
Light-Duty Trucks	1.6	1.9	1.6	1.6	1.5	1.4
Other Trucks and Buses	0.4	0.5	0.7	0.7	0.7	0.7
Aircraft	0.2	0.1	0.1	0.2	0.1	0.2
Boats and Vessels	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	+	+
Other[d]	0.2	0.2	0.2	0.2	0.2	0.2
International Bunker Fuels[c]	+	+	+	+	+	+
N_2O	**54.3**	**66.8**	**65.3**	**65.2**	**64.2**	**63.4**
Passenger Cars	31.0	33.0	32.7	32.4	32.1	31.5
Light-Duty Trucks	17.8	27.1	23.9	24.0	23.3	22.7
Other Trucks and Buses	2.6	3.6	5.6	5.8	5.9	6.1
Aircraft[a]	1.7	1.7	1.8	1.7	1.8	1.8
Boats and Vessels	0.4	0.5	0.4	0.3	0.3	0.4
Locomotives	0.3	0.3	0.3	0.2	0.2	0.2
Other[d]	0.6	0.6	0.6	0.6	0.6	0.6
International Bunker Fuels[c]	1.0	0.9	0.9	1.0	1.0	1.0
HFCs	**+**	**9.5**	**13.5**	**17.2**	**20.6**	**23.7**
Mobile Air Conditioners[e]	+	9.5	13.5	17.2	20.6	23.7
Total[c]	**1,533.7**	**1,663.0**	**1,704.8**	**1,718.5**	**1,748.4**	**1,808.0**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

[a] Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.

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

[c] Emissions from International Bunker Fuels include emissions from both civilian and military activities, but are not included in totals.

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

[e] Includes primarily HFC-134a.

Box 1-4: Greenhouse Gas Emissions from Electric Utilities

Like transportation, activities related to the generation, transmission, and distribution of electricity in the United States resulted in a significant fraction of total U.S. greenhouse gas emissions. The electric power industry in the United States is composed of traditional electric utilities as well as other entities, such as power marketers and nonutility power producers.

Table 1-8 presents emissions from electric utility-related activities. Aggregate emissions from electric utilities of all greenhouse gases increased by 11 percent from 1990 to 1999, and accounted for a relatively constant 29 percent of U.S. emissions during the same period. Emissions from nonutility generators are not included in these estimates. Nonutilities were estimated to have produced about 15 percent of the electricity generated in the United States in 1999, up from 11 percent in 1998 (EIA 2000c). Therefore a more complete accounting of greenhouse gas emissions from the electric power industry (i.e., utilities and nonutilities combined) would account for roughly 40 percent of U.S. CO_2 emissions (EIA 2000d).

The majority of electric utility-related emissions resulted from the combustion of coal in boilers to produce steam that is passed through a turbine to generate electricity. Overall, the generation of electricity—especially when nonutility generators are included—results in a larger portion of total U.S. greenhouse gas emissions than any other activity.

Table 1-8: Electric Utility-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Fuel Type or Source	1990	1995	1996	1997	1998	1999
CO_2	**1,757.3**	**1,810.6**	**1,880.3**	**1,953.5**	**2,010.7**	**1,953.4**
Coal	1,509.3	1,587.7	1,677.7	1,729.7	1,744.0	1,711.9
Natural Gas	151.1	171.8	146.5	159.6	175.8	168.0
Petroleum	96.8	51.0	56.0	64.1	90.8	73.4
Geothermal	0.2	0.1	0.1	0.1	0.1	+
CH_4	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Stationary Combustion (Utilities)	0.5	0.5	0.5	0.5	0.5	0.5
N_2O	**7.4**	**7.8**	**8.2**	**8.5**	**8.7**	**8.6**
Stationary Combustion (Utilities)	7.4	7.8	8.2	8.5	8.7	8.6
SF_6	**20.5**	**25.7**	**25.7**	**25.7**	**25.7**	**25.7**
Electrical Transmission and Distribution	20.5	25.7	25.7	25.7	25.7	25.7
Total	**1,785.7**	**1,844.5**	**1,914.7**	**1,988.2**	**2,045.6**	**1,988.2**

Note: Totals may not sum due to independent rounding.

Box 1-5: IPCC Good Practice Guidance

In response to a request by Parties to the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC) finalized a set of good practice guidance in May 2000 on uncertainty and good practices in inventory management. The report, entitled *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (Good Practice),* was developed with extensive participation of experts from the United States as well as many other countries.[26] It focuses on providing direction to countries to produce emission estimates that are as accurate, with the least uncertainty, as possible. In addition, G*ood Practice* was designed as a tool to compliment the methodologies suggested in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)*.

In order to obtain these goals, *Good Practice* establishes a set of guidelines for ensuring the following standards are met:

- The most appropriate estimation method is used, within the context of the *IPCC Guidelines*
- Quality control and quality assurance measures are adhered to
- Proper assessment and documentation of data and information is carried out
- Uncertainties are quantified and tracked for each source category as well as the inventory in its entirety

By providing such direction, the IPCC hopes to help countries provide inventories that are transparent, documented, and comparable, and that have been assessed for uncertainties, checked for quality control and quality assurance, and used resources efficiently.

ergy Information Administration (EIA) of the U.S. Department of Energy. 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 - 1999* (EPA 2000), which is an annual EPA publication that provides the latest estimates of regional and national emissions of 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 criteria pollutant estimates makes it difficult to reproduce the methodologies from EPA (2000) in this inventory document. In these instances, the references containing detailed documentation of the methods used are identified

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[26] See <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>

for the interested reader. For agricultural sources, the EPA criteria pollutant emission estimates were supplemented using 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.

Emissions from fossil fuels combusted in civilian and military ships and aircraft engaged in the international transport of passengers and 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 1999. 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 update it annually, in conjunction with its commitments under the UNFCCC. The methodologies used to estimate emissions will also be updated periodically as methods and information improve and as further guidance is received from the IPCC and UNFCCC.

Secondly, there are uncertainties associated with the emission 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 some other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated limits the scope or accuracy of the estimates presented. Despite these uncertainties, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) require that countries provide single point estimates for each gas and emission or removal source category. 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* 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 when applicable, 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 S for a discussion of the sources of greenhouse gas emissions and sinks 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 combustion is 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 SF_6 from electrical transmission and distribution is limited due to a lack of activity data regarding national SF_6 consumption or average equipment leak rates.

- *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. Overall, the main uncertainties in developing GWP values are the estimation of atmospheric lifetimes, assessing indirect effects, choosing the appropriate integration time horizon, and assessing instantaneous radiative forcing effects, which are dependent upon existing atmospheric concentrations. According to the IPCC, GWPs typically have an uncertainty of ±35 percent (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.

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 and sinks is segregated into six sector-specific chapters, listed below in Table 1-9.

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

Chapter/IPCC Sector: Overview of emission trends for each IPCC defined sector

Source: Description of source pathway and emission trends from 1990 through 1999

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

Table 1-9: IPCC Sector Descriptions

Chapter/IPCC Sector	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 Energy and Waste, 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)

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 and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electric utility sector, is treated individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-10.

Table 1-10: List of Annexes

ANNEX A	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
ANNEX B	Methodology for Estimating Carbon Stored in Products from Non-Energy Uses of Fossil Fuels
ANNEX C	Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Stationary Combustion
ANNEX D	Methodology for Estimating Emissions of CH_4, N_2O, and Criteria Pollutants from Mobile Combustion
ANNEX E	Methodology for Estimating CH_4 Emissions from Coal Mining
ANNEX F	Methodology for Estimating CH_4 Emissions from Natural Gas Systems
ANNEX G	Methodology for Estimating CH_4 Emissions from Petroleum Systems
ANNEX H	Methodology for Estimating Emissions from International Bunker Fuels Used by the U.S. Military
ANNEX I	Methodology for Estimating HFC, PFC, and SF_6 Emissions from Substitution of Ozone Depleting Substances
ANNEX J	Methodology for Estimating CH_4 Emissions from Enteric Fermentation
ANNEX K	Methodology for Estimating CH_4 Emissions from Manure Management
ANNEX L	Methodology for Estimating N_2O Emissions from Agricultural Soil Management
ANNEX M	Methodology for Estimating CH_4 Emissions from Landfills
ANNEX N	Global Warming Potential Values
ANNEX O	Ozone Depleting Substance Emissions
ANNEX P	Sulfur Dioxide Emissions
ANNEX Q	Complete List of Source Categories
ANNEX R	IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion
ANNEX S	Sources of Greenhouse Gas Emissions Excluded
ANNEX T	Constants, Units, and Conversions
ANNEX U	Abbreviations
ANNEX V	Chemical Symbols
ANNEX W	Glossary

2. Energy

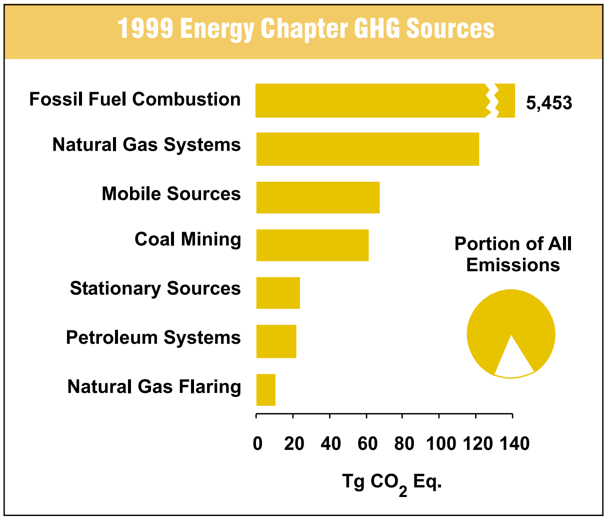
Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 85 percent of total emissions on a carbon equivalent basis in 1999. This included 98, 35, and 18 percent of the nation's carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 81 percent of national emissions from all sources on a carbon equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total national emissions (4 percent collectively).

Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 2-1). 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). Mobile fossil fuel combustion was the second largest source of N_2O emissions in the United States, and overall energy-related activities were collectively the largest source 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 in the Energy chapter 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 the atmosphere. The net impacts of land-use and forestry activities on the carbon cycle are accounted for in the Land-Use Change and Forestry chapter. Emissions of other greenhouse gases from the combustion of biomass and biomass based fuels are included in national totals under stationary and mobile combustion.

Figure 2-1



Overall, emissions from energy-related activities have increased from 1990 to 1999 due, in part, to the strong performance of the U.S. economy. Over this period, the U.S. Gross Domestic Product (GDP) grew approximately 32 percent, or at an average annual rate of 3.7 percent. This

Table 2-1: Emissions from Energy (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999
CO_2	**4,840.8**	**5,134.8**	**5,316.0**	**5,386.9**	**5,397.6**	**5,464.8**
Fossil Fuel Combustion	4,835.7	5,121.3	5,303.0	5,374.9	5,386.8	5,453.1
Natural Gas Flaring	5.1	13.6	13.0	12.0	10.8	11.7
Biomass-Wood*	174.9	193.2	197.0	187.6	187.4	226.3
International Bunker Fuels*	114.0	101.0	102.2	109.8	112.8	107.3
Biomass-Ethanol*	5.7	7.2	5.1	6.7	7.3	7.8
Carbon Stored in Products*	(276.2)	(317.9)	(323.1)	(338.6)	(343.4)	(361.7)
CH_4	**249.7**	**237.0**	**233.0**	**228.2**	**224.1**	**218.2**
Natural Gas Systems	121.2	124.2	125.8	122.7	122.1	121.8
Coal Mining	87.9	74.6	69.3	68.8	66.5	61.8
Petroleum Systems	27.2	24.5	24.0	24.0	23.3	21.9
Stationary Sources	8.5	8.9	9.0	8.1	7.6	8.1
Mobile Sources	5.0	4.9	4.8	4.7	4.6	4.5
International Bunker Fuels*	+	+	+	+	+	+
N_2O	**67.9**	**81.1**	**80.2**	**80.2**	**79.3**	**79.1**
Mobile Sources	54.3	66.8	65.3	65.2	64.2	63.4
Stationary Sources	13.6	14.3	14.9	15.0	15.1	15.7
International Bunker Fuels*	1.0	0.9	0.9	1.0	1.0	1.0
Total	**5,158.4**	**5,452.9**	**5,629.1**	**5,695.4**	**5,700.9**	**5,762.0**

+ Does not exceed 0.05 Tg CO_2 Eq.
* These values 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.

robust economic activity increased the demand for fossil fuels, with an associated increase in greenhouse gas emissions. Table 2-1 summarizes emissions for the Energy chapter in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.), while unweighted gas emissions in gigagrams (Gg) are provided in Table 2-2. Overall, emissions due to energy-related activities were 5,762.0 Tg CO_2 Eq. in 1999, an increase of 12 percent since 1990.

Carbon Dioxide Emissions from Fossil Fuel Combustion

Carbon dioxide (CO_2) emissions from fossil fuel combustion grew by 1.2 percent from 1998 to 1999. Mild winter conditions and increased output from nuclear plants in 1999 resulted in a demand for energy derived from fossil fuels that was less than what would have been expected given the strength of the economy and steady growth in population. In 1999, CO_2 emissions from fossil fuel combustion were 5,453.1 Tg CO_2 Eq., or 12.8 percent above emissions in 1990 (see Table 2-3).

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams would be expected to have proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

Longer-term changes in energy consumption patterns, however, tend to be more a function of changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Carbon dioxide emissions are also a function of the source of energy and its carbon intensity. The amount of carbon in fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per

Table 2-2: Emissions from Energy (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999
CO_2	**4,840,810**	**5,134,850**	**5,315,958**	**5,386,939**	**5,397,600**	**5,464,789**
Fossil Fuel Combustion	4,835,688	5,121,263	5,302,961	5,374,913	5,386,762	5,453,088
Natural Gas Flaring	5,121	13,587	12,998	12,026	10,839	11,701
Biomass-Wood*	174,862	193,245	196,973	187,585	187,433	226,287
International Bunker Fuels*	114,001	101,014	102,197	109,788	112,771	107,345
Biomass-Ethanol*	5,701	7,244	5,144	6,731	7,329	7,776
Carbon Stored in Products*	(276,233)	(317,931)	(323,052)	(338,611)	(343,383)	(361,712)
CH_4	**11,891**	**11,284**	**11,096**	**10,868**	**10,669**	**10,388**
Natural Gas Systems	5,772	5,912	5,993	5,841	5,814	5,799
Coal Mining	4,184	3,550	3,301	3,274	3,168	2,944
Petroleum Systems	1,294	1,168	1,143	1,142	1,108	1,044
Stationary Sources	403	422	430	386	361	386
Mobile Sources	237	232	228	225	219	215
International Bunker Fuels*	2	2	2	2	2	2
N_2O	**219**	**262**	**259**	**259**	**256**	**255**
Mobile Combustion	175	215	211	210	207	204
Stationary Combustion	44	46	48	49	49	51
International Bunker Fuels*	3	3	3	3	3	3

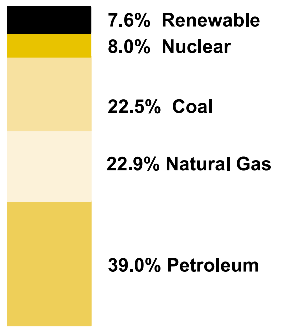
+ Does not exceed 0.05 Gg
* These values are presented for informational purposes only and are not included or are already accounted for in totals.
Note: Totals may not sum due to independent rounding.

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] Therefore, producing heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 emissions associated with energy consumption, and using nuclear or renewable energy sources (e.g., wind) can essentially eliminate emissions (see Box 2-2).

In the United States, 84 percent of the energy consumed was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure 2-2 and Figure 2-3). Of the remaining 16 percent, half was supplied by nuclear electric power and half by a variety of renewable energy sources, primarily hydroelectric power (EIA 2000a). Specifically, petroleum supplied the largest share of domestic energy demands, accounting

Figure 2-2

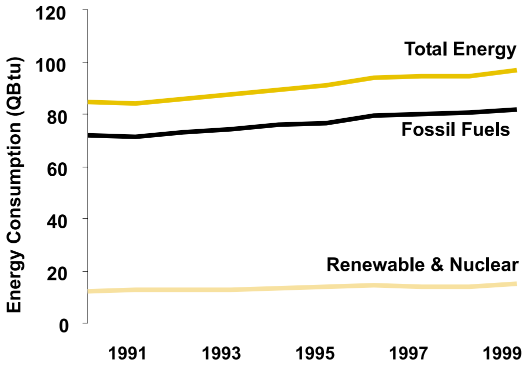
1999 U.S. Energy Consumption by Energy Source



Source: DOE/EIA-0384(99), Annual Energy Review 1998, Table 1.3, July 2000

Figure 2-3

U.S. Energy Consumption (Quadrillion Btu)



Note: Expressed as gross calorific values.
Source: DOE/EIA-0384(97), Annual Energy Review 1999, Table 1.3, July 2000

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[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 Sector (Tg CO_2 Eq.)

Fuel/Sector	1990	1995	1996	1997	1998	1999
Coal	**1,775.9**	**1,867.9**	**1,950.8**	**2,005.6**	**2,015.6**	**2,012.8**
Residential	5.8	5.0	5.1	5.5	4.2	4.2
Commercial	8.7	7.6	7.7	8.2	6.3	6.3
Industrial	251.4	266.6	259.3	261.3	260.2	289.4
Transportation	NE	NE	NE	NE	NE	NE
Electric Utilities	1,509.3	1,587.7	1,677.7	1,729.7	1,744.0	1,711.9
U.S. Territories	0.6	0.9	0.9	1.0	0.9	0.9
Natural Gas	**1,001.9**	**1,154.0**	**1,175.5**	**1,179.8**	**1,139.8**	**1,144.7**
Residential	238.5	263.1	284.6	270.5	246.5	255.0
Commercial	142.4	164.5	171.6	174.7	163.6	166.4
Industrial	433.8	516.2	534.0	533.5	519.0	520.5
Transportation	36.0	38.3	38.9	41.5	34.9	34.8
Electric Utilities	151.1	171.8	146.5	159.6	175.8	168.0
U.S. Territories	NE	NE	NE	NE	NE	NE
Petroleum	**2,057.8**	**2,099.2**	**2,176.5**	**2,189.4**	**2,231.3**	**2,295.6**
Residential	87.7	94.2	100.7	98.9	90.3	95.0
Commercial	66.1	51.8	53.5	50.8	47.6	50.3
Industrial	338.3	318.2	347.2	346.4	334.1	345.6
Transportation	1,435.8	1,541.1	1,579.8	1,587.4	1,621.6	1,679.2
Electric Utilities	96.8	51.0	56.0	64.1	90.8	73.4
U.S. Territories	33.1	43.1	39.1	41.8	47.0	52.1
Geothermal*	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	+
Total	**4,835.7**	**5,121.3**	**5,303.0**	**5,374.9**	**5,386.8**	**5,453.1**

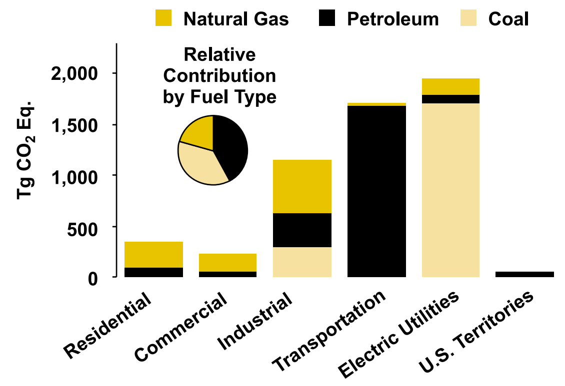
NE (Not estimated)
+ Does not exceed 0.05 Tg CO_2 Eq.
* Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes.
Note: Totals may not sum due to independent rounding.

for an average of 39 percent of total energy consumption from 1990 through 1999. Natural gas and coal followed in order of importance, each accounting for an average of 23 percent of total consumption. Most petroleum was consumed in the transportation end-use sector, while the vast majority of coal was used by electric utilities, with natural gas broadly consumed in all end-use sectors except transportation (see Figure 2-4) (EIA 2000a).

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process the carbon stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including methane (CH_4), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[2] These other carbon containing non-CO_2 gases are emitted as a by-product of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, except for the soot an

Figure 2-4

1999 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Note: Utilities also includes emissions of 0.04 Tg CO_2 Eq. from geothermal based electricity generation

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[2] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

Box 2-1: Weather and Non-Fossil Energy Adjustments to CO_2 from Fossil Fuel Combustion Trends

An analysis was performed using EIA's Short-Term Integrated Forecasting System (STIFS) model to examine the effects of variations in weather and output from nuclear and hydroelectric generating plants on U.S. energy-related CO_2 emissions.[3] Weather conditions affect energy demand because of the impact they have on residential, commercial, and industrial end-use sector heating and cooling demands. Warmer winters tend to reduce demand for heating fuels—especially natural gas—while cooler summers tend to reduce air conditioning-related electricity demand. Changes in electricity output from hydroelectric and nuclear power plants do not necessarily affect final energy demand, but increased output from these plants does offset electricity generation by fossil fuel power plants, and therefore leads to reduced CO_2 emissions.

The results of this analysis show that CO_2 emissions from fossil fuel combustion would have been roughly 1.9 percent higher (102 Tg CO_2 Eq.) if weather conditions and hydroelectric and nuclear power generation had achieved normal levels (see Figure 2-5). Similarly, emissions in 1997 and 1998 would have been roughly 0.5 and 1.2 percent (7 and 17 Tg CO_2 Eq.) greater under normal conditions, respectively.

In addition to the absolute level of emissions being greater, the growth rate in CO_2 emissions from fossil fuel combustion from 1998 to 1999 would have been 2.0 percent instead of the actual 1.2 percent if both weather conditions and nonfossil electricity generation had been normal (see Figure 2-6). Similarly, emissions in 1998 would have increased by 0.9 percent under normal conditions versus the actual rate of 0.2 percent.

Figure 2-5

Percent Difference in Adjusted and Actual Energy-Related CO_2 Emissions

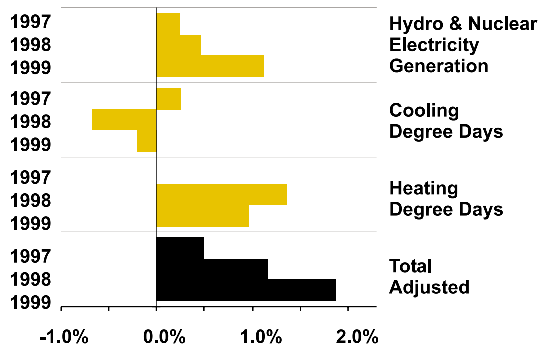
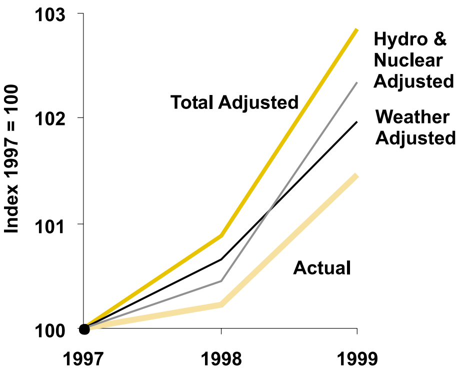


Figure 2-6

Recent Trends in Adjusted and Actual Energy-Related CO_2 Emissions



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[3] The STIFS model is employed in producing EIA's *Short-Term Energy Outlook* (DOE/EIA-0202). Complete model documentation can be found at < http://www.eia.doe.gov/emeu/steo/pub/contents.html>. A variety of other factors that influence energy-related CO_2 emissions were also examined such as: changes in output from energy intensive manufacturing industries, and changes in fossil fuel prices for 1997 through 1999. These additional factors, however, were found to have less of an impact on deviations in greenhouse gas emission trends than weather and non0fossil fuel generation fluxuations.

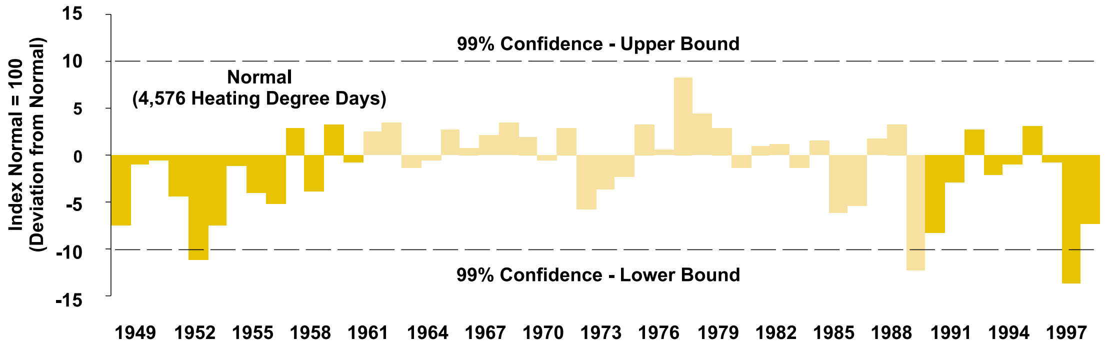
Box 2-1: Weather and Non-Fossil Energy Adjustments to CO_2 from Fossil Fuel Combustion Trends (continued)

Warmer winter conditions in both 1998 and 1999 had a significant effect on U.S. CO_2 emissions by reducing demand for heating fuels. Heating degree days in the United States in 1998 and 1999 were 14 and 7 percent below normal, respectively (see Figure 2-7).[4] These warm winters, however, were partially countered by increased electricity demand that resulted from hotter summers. Cooling degree days in 1998 and 1999 were 18 and 3 percent above normal, respectively (see Figure 2-8).

Although no new U.S. nuclear power plants have been constructed in many years, the utilization (i.e., capacity factors)[5] of existing plants reached record levels in 1998 and 1999, approaching 90 percent. This increase in utilization translated into an increase in electricity output by nuclear plants of slightly more than 7 percent in both years. This increase in nuclear plant output, however, was partially offset by reduced electricity output by hydroelectric power plants, which declined by 10 and 4 percent in 1998 and 1999, respectively. Electricity generated by nuclear plants provides approximately twice as much of the energy consumed in the United States as hydroelectric plants. Nuclear and hydroelectric power plant capacity factors since 1973 are shown in Figure 2-9.

Figure 2-7

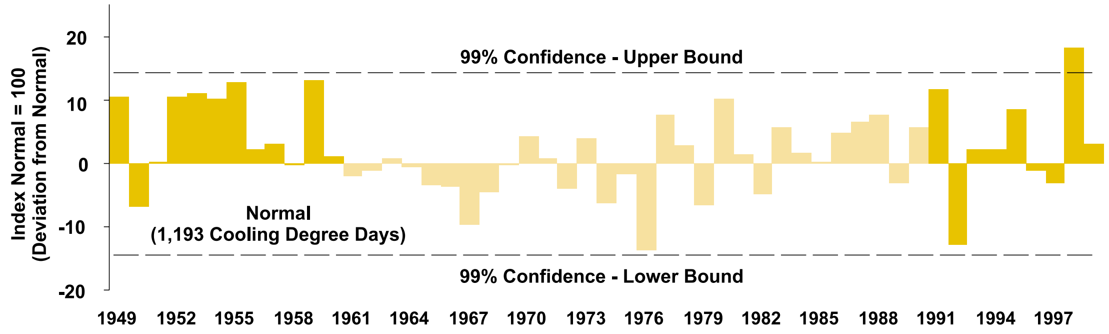
Annual Deviations from Normal Heating Degree Days for the United States (1949-1999)



Note: Climatological normal data is highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.
Source: NOAA (2000b)

Figure 2-8

Annual Deviations from Normal Cooling Degree Days for the United States (1949-1999)



Note: Climatological normal data is highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.
Source: NOAA (2000b)

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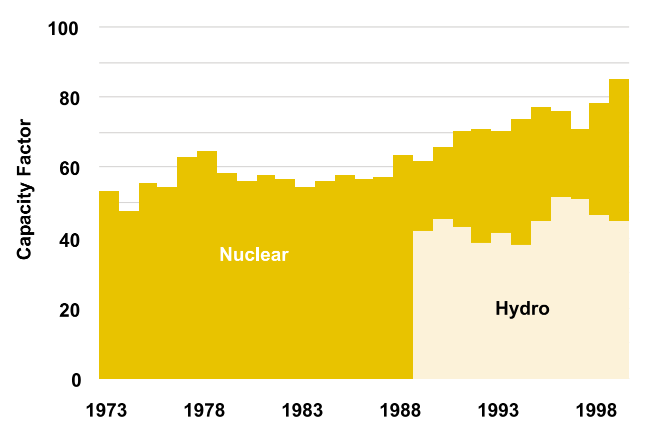
[4] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F, while cooling degree days are deviations of the mean daily temperature above 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990. The variation in these normals during this time period was ±10 percent and ±14 percent for heating and cooling degree days, respectively (99 percent confidence interval).

[5] The capacity factor is defined as the ratio of the electrical energy produced by a generating unit for a given period of time to the electrical energy that could have been produced at continuous full- power operation during the same period (DOE/EIA 2000).

Figure 2-9

Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1973-1999)



ash left behind during the combustion process, all the carbon in fossil fuels used to produce energy is generally converted to atmospheric CO_2.

For the purpose of international reporting, the IPCC (IPCC/UNEP/OECD/IEA 1997) requires that particular adjustments be made to national fuel consumption statistics. Certain fossil fuels can be manufactured into plastics, asphalt, lubricants, or other products. A portion of the carbon consumed for these non-energy products can be stored (i.e., sequestered) for long periods of time. To account for the fact that the carbon in these fuels ends up in products instead of being combusted (i.e., oxidized and released into the atmosphere), the fraction of fossil fuel-based carbon in manufactured products is subtracted from emission estimates. (See the Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter.) The fraction of this carbon stored in products that is eventually combusted in waste incinerators or combustion plants is accounted for in the Waste Chapter under Waste Combustion.

The IPCC (1997) also requires that CO_2 emissions from the consumption of fossil fuels for aviation and marine international transport activities (i.e., international bunker fuels) be reported separately, and not included in national emission totals. Estimates of carbon in products and international bunker fuel emissions for the United States are provided in Table 2-4 and Table 2-5.

End-Use Sector Consumption

When analyzing CO_2 emissions from fossil fuel combustion, four end-use sectors were defined: industrial, transportation, residential, and commercial.[6] Electric utilities also emit CO_2; however, these emissions occur as they combust fossil fuels to provide electricity to one of the four end-use sectors. For the discussion below, electric utility emissions have been distributed to each end-use sector based upon the sector's share of national electricity consumption. This method of distributing emissions assumes that each sector consumes electricity generated from an equally carbon-intensive mix of fuels and other energy sources. In reality, sources of electricity vary widely in carbon intensity (e.g., coal versus wind power). By giving equal carbon-intensity weight to each sector's electricity consumption, emissions attributed to one end-use sector may be somewhat overestimated, while emissions attributed to another end-use sector may be slightly underestimated. After the end-use sectors are discussed, emissions from electric utilities are

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[6] See Glossary (Annex W) for more detailed definitions of the industrial, residential, commercial, and transportation end-use sector, as well as electric utilities.

Table 2-4: Fossil Fuel Carbon in Products (Tg CO_2 Eq.)*

Sector	1990	1995	1996	1997	1998	1999
Industrial	274.4	315.8	320.5	335.9	340.6	358.8
Transportation	1.2	1.2	1.1	1.2	1.2	1.2
Territories	0.6	1.0	1.5	1.6	1.5	1.7
Total	**276.2**	**317.9**	**323.1**	**338.6**	**343.4**	**361.7**

* See Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section for additional detail.
Note: Totals may not sum due to independent rounding.

Table 2-5: CO_2 Emissions from International Bunker Fuels (Tg CO_2 Eq.)*

Vehicle Mode	1990	1995	1996	1997	1998	1999
Aviation	46.7	51.1	52.1	55.9	55.0	61.0
Marine	67.3	49.9	50.1	53.9	57.8	46.4
Total	**114.0**	**101.0**	**102.2**	**109.8**	**112.8**	**107.3**

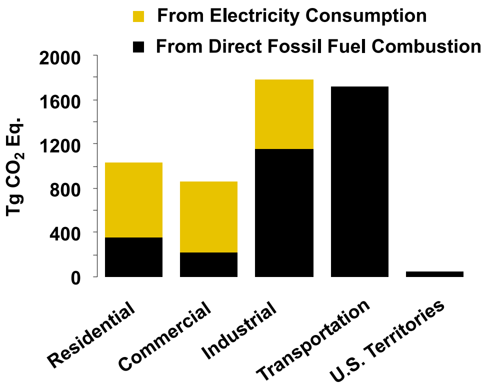
* See International Bunker Fuels section for additional detail.
Note: Totals may not sum due to independent rounding.

addressed separately. Emissions from U.S. territories are also calculated separately due to a lack of end-use-specific consumption data. Table 2-6 and Figure 2-10 summarize CO_2 emissions from direct fossil fuel combustion and pro-rated electric utility emissions from electricity consumption by end-use sector.

The electric power industry in the United States is currently undergoing significant changes. Both Federal and State government agencies are modifying regulations to create a competitive market for electricity generation from what was a market dominated by vertically integrated and regulated monopolies (i.e., electric utilities). These changes have led to the growth of nonutility power producers, including the sale of generating capacity by electric utilities to nonutilities.[7] As a result, the proportion of electricity in the United States generated by nonutilities has grown from about 8 percent in 1990 to 16 percent in 1999. Fuel consumption and emissions by nonutilities are currently allocated to the industrial end-use sector, separate from electric utilities, due to data limitations. Therefore, emissions associated with electricity generation in Table 2-6 are underestimated and emissions associated with direct fuel combustion by the industrial end-use sector are overestimated by an equal amount.

Figure 2-10

1999 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Note: All emissions related to the generation of electricity by nonutilities are currently allocated to the combustion category under the industrial sector due to data limitations.

Industrial End-Use Sector

The industrial end-use sector accounted for the largest share (33 percent) of CO_2 emissions from fossil fuel combustion. On average, 65 percent of these emissions resulted from the direct consumption of fossil fuels

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[7] In 1999, 50,884 megawatts of electrical generating capacity was sold by electric utilities to nonutilities, or 6.4 percent of total electric power industry capacity.

Table 2-6: Fossil Fuel Carbon in Products and CO_2 Emissions from International Bunker Fuel Combustion (Tg CO_2 Eq.)

End-Use Sector	1990	1995	1996	1997	1998	1999
Industrial	**1,636.0**	**1,709.5**	**1,766.0**	**1,783.6**	**1,758.8**	**1,783.9**
Combustion[a]	1,023.5	1,101.0	1,140.6	1,141.1	1,113.3	1,155.6
Electricity[b]	612.6	608.5	625.4	642.5	645.5	628.3
Transportation	**1,474.4**	**1,581.8**	**1,621.2**	**1,631.4**	**1,659.0**	**1,716.4**
Combustion	1,471.8	1,579.4	1,618.8	1,628.9	1,656.5	1,714.0
Electricity[b]	2.6	2.4	2.4	2.5	2.5	2.4
Residential	**930.7**	**988.7**	**1,047.5**	**1,044.2**	**1,040.9**	**1,035.8**
Combustion	332.1	362.3	390.4	374.9	341.0	354.1
Electricity[b]	598.6	626.4	657.0	669.3	699.9	681.6
Commercial	**760.8**	**797.2**	**828.2**	**872.9**	**880.2**	**864.0**
Combustion	217.3	223.9	232.8	233.7	217.4	223.0
Electricity[b]	543.6	573.3	595.4	639.2	662.8	641.0
U.S. Territories	**33.7**	**44.0**	**40.1**	**42.8**	**47.9**	**53.0**
Total	**4,835.7**	**5,121.3**	**5,303.0**	**5,374.9**	**5,386.8**	**5,453.1**

[a] Includes emissions related to the generation of electricity by nonutility power producers.

[b] Does not include emissions related to the consumption of electricity generated by nonutilities—versus regulated electric utilities. All emissions related to the generation of electricity by nonutilities are currently allocated to the combustion category under the industrial sector due to data limitations.

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

in order to meet industrial energy demands such as for steam and process heat. The remaining 35 percent was associated with their consumption of electricity for uses such as motors, electric furnaces, ovens, and lighting.[8]

The industrial end-use sector includes activities such as manufacturing, construction, mining, and agriculture.[9] The largest of these activities in terms of energy consumption is manufacturing, which was estimated in 1994 to have accounted for about 80 percent of industrial energy consumption (EIA 1997). Manufacturing energy consumption was dominated by several industries—petroleum products, chemical products, primary metals, paper and products, foods; and stone, clay, and glass products—which combined accounted for about 84 percent (i.e., roughly two-thirds of the entire industrial end-use sector in 1994).

In theory, emissions from the industrial end-use sector should be highly correlated with economic growth and industrial output; however, certain activities within the sector, such as heating of industrial buildings and agricultural energy consumption, are also affected by weather conditions.[10] In addition, structural changes within the U.S. economy that lead to shifts in industrial output away from energy intensive manufacturing products to less energy intensive products (e.g., from steel to computer equipment) also have a significant affect on industrial emissions.

From 1998 to 1999, total industrial production and manufacturing output were reported to have increased by 4.2 and 4.8 percent, respectively (FRB 2000). However, excluding the fast growing computer, communication equipment, and semiconductor industries from these indexes reduces their growth considerably—to 1.2 and 1.5 percent, respectively—and illustrates some of the structural changes occurring in the U.S. economy (see Figure 2-11).

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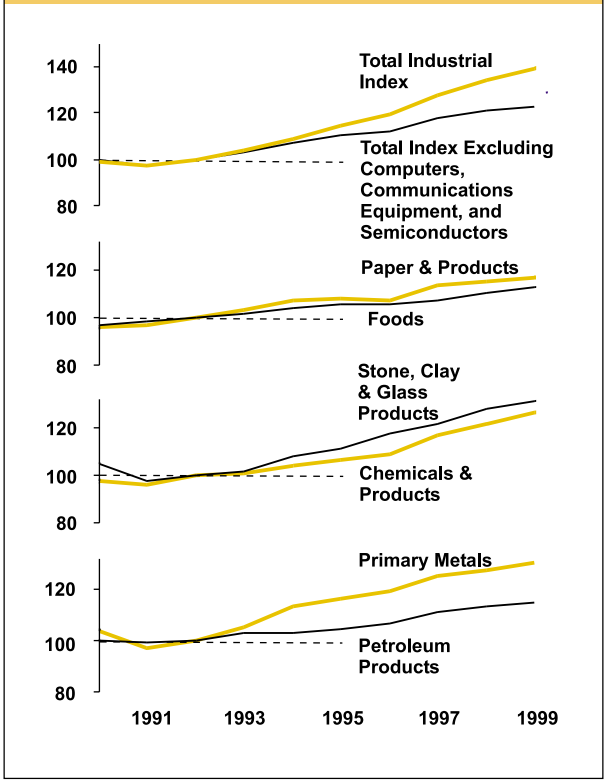
[8] This fraction only includes emissions from electric utilities, and therefore likely underestimates electricity associated emissions because it excludes CO_2 emissions associated with electricity generated by nonutility power producers. These nonutility power producers, however, are included in the direct fuel combustion category of the industrial end-use sector. Therefore, because of the inclusion of nonutilities and the fact that some industrial facilities generate their own electricity without obtaining it from electric utilities, the fraction of the industrial end-use sector's emissions associated with meeting actual steam and process heat demands is likely overestimated since a portion of that fuel is actually used to generate electricity (e.g., cogeneration).

[9] See Glossary (Annex W) for a more detailed definition of the industrial end-use sector.

[10] Some commercial customers are large enough to obtain an industrial price for natural gas and/or electricity and are consequently grouped with the industrial end-use sector in U.S. energy statistics. These misclassifications of large commercial customers likely cause the industrial end-use sector to appear to be more sensitive to weather conditions.

Figure 2-11

Industrial Production Indexes (Index 1992=100)



According to current EIA sectoral definitions, the industrial sector also includes emissions from nonutility generators (e.g., independent power producers) who produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market.[11] The number of nonutility generators and the quantity of electricity they produce has increased significantly as many States have begun opening their electricity markets to competition. In future inventories, these nonutility generators will be removed from the industrial sector and incorporated into a single electric power sector with electric utilities.

Despite the growth in industrial output (49 percent) and the overall U.S. economy (32 percent) from 1990 to 1999, emissions from the industrial end-use sector increased by only 9.0 percent, which is less that all other end-use sectors in percentage terms. For example, in 1998 emissions decreased by 1.4 percent and then in 1999 increased by the same percentage. The reasons for the disparity between rapid growth in industrial output and stagnant growth in industrial emissions are not entirely clear. It is likely, though, that several factors have influenced industrial emission trends, including: 1) a mild winter in 1998 and 1999, leading to lower than normal energy consumption in industries affected by the weather; 2) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries; 3) improvements in energy efficiency; and 4) a lowering of the carbon intensity of fossil fuel consumption as industry shifts from its historical reliance on coal and coke to heavier usage of natural gas. Assessments of industrial end-use sector trends, however, are complicated by the growth of nonutility generation and emissions.[12]

Industry was the largest user of fossil fuels for non-energy applications. Fossil fuels can be used for producing products such as fertilizers, plastics, asphalt, or lubricants that can sequester or store carbon 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 can also store carbon, if the material is not burned. The amount of carbon contained in industrial products made from fossil fuels rose 31 percent between 1990 and 1999, to 361.7 Tg CO_2 Eq.[13]

Transportation End-Use Sector

Transportation was second to the industrial end-use sector in terms of U.S. CO_2 emissions from fossil fuel combustion, accounting for slightly over 31 percent—excluding international bunker fuels. Almost all of the energy consumed in this end-use sector came from petroleum-based products, with nearly two-thirds due to gasoline consumption in automobiles and other highway

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[11] Nonutility generators also include cogenerators, who produce both useful process heat and electricity. See Glossary (Annex W) for a more detailed definition.

[12] The opening of the electric power industry to competition may have also led to some data collection problems as electric utility assets are transferred and government reporting requirements are revised. These reporting problems are expected to be corrected, however, in future inventories.

[13] See the Carbon Stored in Products in Non-Energy Uses of Fossil Fuels for a more detailed discussion. Also, see Waste Combustion in the Waste chapter for a discussion of emissions from the incineration or combustion of fossil fuel-based products.

vehicles. Other fuel uses, especially diesel fuel for the trucking industry and jet fuel for aircraft, accounted for the remainder.[14]

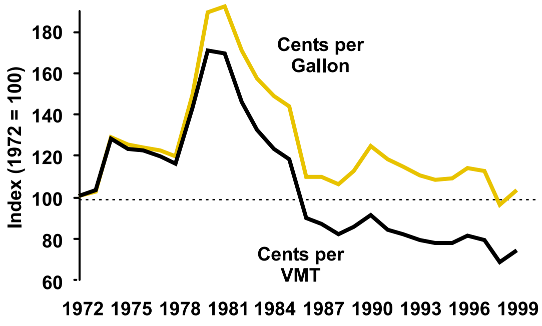
Carbon dioxide emissions from fossil fuel combustion for transportation increased by 16 percent from 1990 to 1999, to 1,716.4 Tg CO_2 Eq. The growth in transportation end-use sector emissions has been relatively steady, including a 3.5 percent single year increase in 1999. Demand for transportation fuels has been driven by several factors, including but not limited to: 1) increased activity in almost all modes of travel; 2) relatively low transportation fuel prices through 1999; and 3) stagnant vehicle fuel efficiency.

Since 1990, travel activity in the United States has grown more rapidly than population, with a 14 percent increase in vehicle miles traveled per capita and a 9 percent increase in per capita jet fuel consumption by U.S. commercial air carriers. Motor gasoline and other petroleum product prices during the 1990s generally declined, reaching historic lows in 1998 and only partially rebounding in 1999 (see Figure 2-12). Improvements in the average fuel efficiency for the U.S. vehicle fleet stagnated in the 1990s after increasing steadily since 1977 (EIA 2000a). The average miles per gallon achieved by the fleet actually decreased by slightly less than one percent in both 1998 and 1999. This trend was due, in part, to the increasing dominance of new motor vehicle sales by less fuel-efficient light-duty trucks and sport-utility vehicles (see Figure 2-13).

Table 2-7 below provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. Fifty-seven 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, accounting for 15 and 13 percent of CO_2 emissions from the transportation end-use sector, respectively.

Figure 2-12

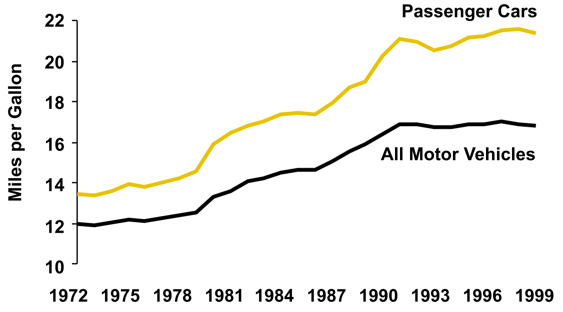
Motor Gasoline Retail Prices (Real)



Source for gasoline prices: DOE/EIA-0384(99), Annual Energy Review 1999, July, 2000, Table 5.22
Source for motor vehicle fuel efficiency: DOT/FHWA, Highway Statistics Summary to 1995, Highway Statistic 1996, 1997, 1998, 1999.

Figure 2-13

Motor Vehicle Fuel Efficiency



Source: DOT/FHWA, Highway Statistics Summary to 1995, Highway Statistics 1996, Highway Statistics 1997, 1998, 1999.

Residential and Commercial End-Use Sectors

The residential and commercial end-use sectors accounted for an average 19 and 16 percent, respectively, of CO_2 emissions from fossil fuel combustion. Both end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances contributing to about 74 and 66 percent of emissions from the commercial and residential end-use sectors, respectively.[15] The remaining emissions were largely due to the

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[14] See Glossary (Annex W) for a more detailed definition of the transportation end-use sector.

[15] These fractions only include emissions from electric utilities, and therefore likely underestimate electricity associated emissions because they exclude CO_2 emissions associated with electricity generated by nonutility power producers, which are currently allocated to the direct fuel combustion category under the industrial end-use sector.

Table 2-7: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (Tg CO_2 Eq.)

Fuel/Vehicle Type	1990	1995	1996	1997	1998	1999
Motor Gasoline	**955.5**	**1,023.0**	**1,041.4**	**1,050.6**	**1,074.0**	**1,096.6**
Passenger Cars	612.8	634.3	646.6	652.3	666.8	680.9
Light-Duty Trucks	274.1	314.2	320.4	323.1	342.4	349.6
Other Trucks	41.4	40.0	40.7	40.5	32.1	32.8
Motorcycles	1.6	1.7	1.7	1.7	1.7	1.8
Buses	2.0	3.0	2.1	2.2	0.8	0.9
Construction Equipment	2.2	2.4	2.4	2.5	2.0	2.0
Agricultural Machinery	4.4	7.9	7.8	8.2	7.6	7.8
Boats (Recreational)	16.9	19.5	19.7	20.1	20.5	21.0
Distillate Fuel Oil (Diesel)	**277.4**	**312.2**	**329.0**	**342.8**	**353.5**	**367.1**
Passenger Cars	7.1	7.6	7.6	7.9	7.6	8.0
Light-Duty Trucks	9.0	11.2	13.1	14.2	14.4	15.1
Other Trucks	164.1	195.4	207.0	216.1	225.5	236.5
Buses	7.9	9.9	8.6	9.2	10.7	11.2
Construction Equipment	10.5	10.5	10.9	11.2	10.8	11.3
Agricultural Machinery	23.1	23.0	23.8	24.5	23.7	24.9
Boats (Freight)	18.0	16.1	18.4	18.3	17.8	18.7
Locomotives	26.3	29.5	31.5	32.4	31.6	33.2
Marine Bunkers	11.4	9.1	8.2	9.0	11.4	8.2
Jet Fuel	**220.4**	**219.9**	**229.8**	**232.1**	**235.6**	**242.9**
General Aviation	6.3	5.3	5.8	6.1	7.7	8.4
Commercial Air Carriers	118.2	121.4	124.9	129.4	131.4	137.3
Military Vehicles	36.1	21.6	20.1	17.8	18.4	17.1
Aviation Bunkers	46.7	51.1	52.1	55.9	55.0	61.0
Other[a]	13.1	20.5	26.8	23.0	23.0	19.2
Aviation Gasoline	**3.1**	**2.7**	**2.6**	**2.7**	**2.4**	**2.7**
General Aviation	3.1	2.7	2.6	2.7	2.4	2.7
Residual Fuel Oil	**80.4**	**72.1**	**67.5**	**56.7**	**55.9**	**64.1**
Boats (Freight)[b]	24.5	31.3	25.7	11.8	9.5	25.9
Marine Bunkers[b]	55.8	40.8	41.8	44.9	46.4	38.2
Natural Gas	**36.0**	**38.3**	**38.9**	**41.5**	**34.9**	**34.8**
Passenger Cars	+	0.1	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Buses	+	0.1	0.1	0.2	0.2	0.2
Pipeline	36.0	38.2	38.8	41.3	34.7	34.6
LPG	**1.3**	**1.0**	**0.9**	**0.8**	**0.9**	**1.0**
Light-Duty Trucks	+	+	+	+	+	+
Other Trucks	0.5	0.5	0.4	0.4	0.3	0.4
Buses	0.8	0.5	0.5	0.4	0.5	0.6
Electricity	**2.6**	**2.4**	**2.4**	**2.5**	**2.5**	**2.4**
Buses	+	+	+	+	+	+
Locomotives	2.1	1.9	1.9	1.9	2.0	1.9
Pipeline	0.5	0.5	0.5	0.6	0.5	0.5
Lubricants	11.7	11.2	10.9	11.5	12.0	12.1
Total (Including Bunkers)[c]	**1,588.4**	**1,682.8**	**1,723.4**	**1,741.2**	**1,771.7**	**1,823.7**
Total (Excluding Bunkers)[c]	**1,474.4**	**1,581.8**	**1,621.2**	**1,631.4**	**1,659.0**	**1,716.4**

Note: Totals may not sum due to independent rounding.

[a] Including but not limited to fuel blended with heating oils and fuel used for chartered aircraft flights.

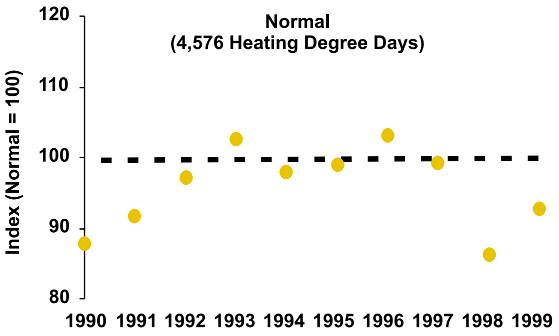
[b] Fluctuations in emission estimates from the combustion of residual fuel oil are currently unexplained, but may be related to data collection problems.

[c] Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates including international bunker fuel-related emissions are presented for informational purposes.

\+ Does not exceed 0.05 Tg of CO_2 Eq.

Figure 2-14

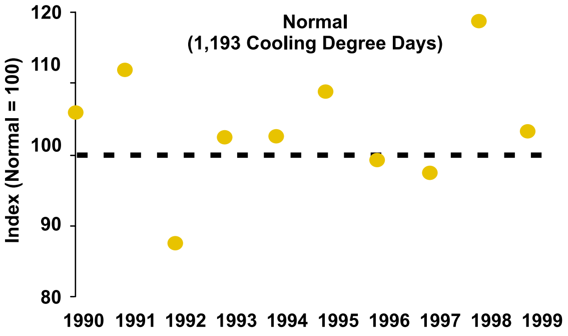
Heating Degree Days[16]



Note: Excludes Alaska and Hawaii
Source: DOE/EIA-0384(99), Annual Energy Review 1999, July, 2000, Table 1.7 and 1.8.

Figure 2-15

Cooling Degree Days[17]



Note: Excludes Alaska and Hawaii
Source: DOE/EIA-0384(99), Annual Energy Review 1999, July 2000, Table 1.7 and 1.8.

direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Coal consumption was a minor component of energy use in both these end-use sectors.

Emissions from residences and commercial buildings generally increased throughout the 1990s, and, unlike in other end-use sectors, emissions in these sectors did not decline during the economic downturn in 1991 (see Table 2-6). This difference exists because short-term fluctuations in energy consumption in these sectors are affected proportionately more by the weather than by prevailing economic conditions. In the long-term, both end-use sectors are also affected by population growth, regional migration trends, and changes in housing and building attributes (e.g., size and insulation).

In 1999, winter conditions in the United States were warmer than normal (i.e., heating degree days were 7 percent below normal), although not nearly as warm as in 1998 (see Figure 2-14). Due, in part, to this slight cooling relative to the previous year, emissions from natural gas consumption in residences and commercial establishments increased by 3 percent and 2 percent, respectively.

In 1999, electricity sales by electric utilities to the residential and commercial end-use sectors increased by 1.0 and 0.2 percent, respectively, as compared to the previous year. Cooler summer conditions in 1999 relative to 1998, although still warmer than normal, helped to moderate growth in air conditioning driven electricity consumption (see Figure 2-15). Historically, the change in energy demand associated with a change in heating degree days has been greater than an equivalent change in cooling degree days. These temperature trends—along with other trends such as overall population growth—led to a 0.5 and 1.8 percent decrease in residential and commercial end-use sector emissions from 1998 to 1999, respectively.

Electric Utilities

The United States relies on electricity to meet a significant portion of its energy requirements. Electricity was consumed primarily in the residential, commercial, and industrial end-use sectors for uses such as lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 2-16).

It is important to note that the electric utility sector includes only regulated utilities. According to current EIA sectoral definitions, nonutility generators of electricity (e.g., independent power producers, qualifying cogenerators, and other small power producers) are included in the industrial end-use sector. These nonutility

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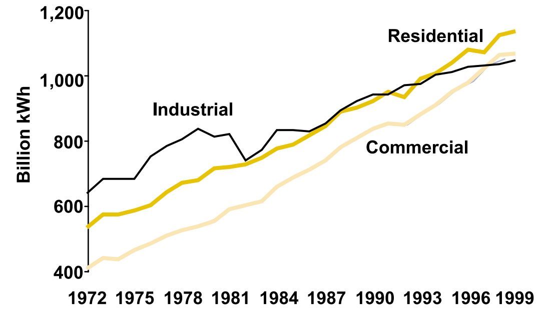
[16] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990.

[17] Degree days are relative measurements of outdoor air temperature. Cooling degree days are deviations of the mean daily temperature above 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990.

Figure 2-16

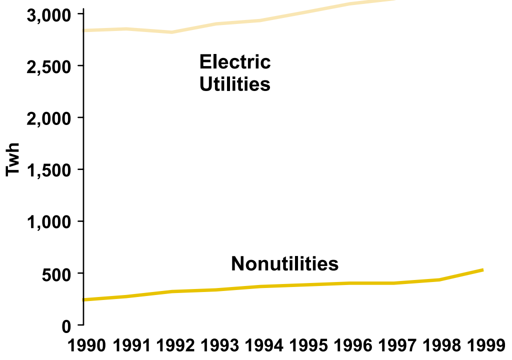
Electric Utility Retail Sales by End-Use Sector



Note: The transportation end-use sector consumes minor quantities of electricty.

Figure 2-17

Net Generation by Electric Utilities and Nonutilities



Source: EIA (2000c)

generators produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g., to utilities for distribution and resale to retail customers). The number of nonutility generators and quantity of electricity they produce has increased significantly as many States have begun opening their electricity markets for generation to competition (see Figure 2-17).

The Energy Information Agency has estimated emissions from the entire electric power industry, including regulated utilities and nonutilities was roughly 41 percent of U.S. CO_2 emissions from fossil fuel combustion versus 36 percent from utilities alone (EIA 2000c). As U.S. energy statistics are revised to account for the changes occurring in the electric power industry, these nonutility generators will be removed from the industrial end-use sector and incorporated into a single sector with electric utilities.[18]

In 1999, CO_2 emissions from electric utilities decreased by 2.9 percent relative to the previous year despite increased electricity consumption and the robust growth in the U.S. economy. A large part of this decrease can be attributed to the sale of approximately 7 percent of electric utility generating capacity to nonutility power producers in 1999.[19] In addition, the summer of 1999 for the United States, although slightly warmer than usual, was cooler than the pervious year's summer, with cooling degree days down by 13 percent (see Figure 2-15). A third factor leading to the decline in utility emissions was the increased output from nuclear plants, which offset the need for additional fossil fuel consumption. Net generation of electricity by nuclear plants increased by 8 percent from 1998 to 1999, reaching record levels along with plant capacity factors (i.e., utilization).[20]

To generate the majority of their electricity, utilities combusted fossil fuels, especially coal. The combustion of fossil fuels accounts for the majority (68 percent) of the electricity generated by utilities in the United States (EIA 2000a). Electric utilities rely on more carbon intensive coal for a majority of their primary energy; however, they also employ many low or near zero carbon emitting technologies such as nuclear, hydro, and wind.

Electric utilities were the dominant consumer of coal in the United States, accounting for 85 percent in 1999. Consequently, changes in electricity demand have a significant impact on coal consumption and associated U.S. CO_2 emissions. Coal consumption by utilities in 1999 decreased by 2 percent (343 Tbtu) in 1999, primarily due to the sale of generating capacity to nonutility power producers. This decrease, therefore, was offset by an 11 percent (314 Tbtu) increase in coal consumption by in industrial end-use sector (i.e., only the sector in which the emissions were accounted for actually changed).

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[18] It is important to note, though, that much of the electricity generated by nonutility power producers is sold to utilities for resale to retail customers, and therefore is included in electric utility sales statistics.

[19] Gross generation of electricity by nonutilities increased by about 35 percent from 1998 to 1999.

[20] Electricity output from hydroelectric dams was relatively constant, decreasing by 0.6 percent between 1998 and 1999.

Box 2-2: Sectoral Carbon Intensity Trends Related to Fossil Fuel and Overall Energy Consumption

Fossil fuels are the predominant source of energy in the United States, and carbon dioxide (CO_2) is emitted as a product from their complete combustion. Useful energy, however, can be generated from many other sources that do not emit CO_2 in the energy conversion process. In the United States, useful energy is also produced from renewable (i.e., hydropower, biofuels, geothermal, solar, and wind) and nuclear sources.[21]

Energy-related CO_2 emissions can be reduced by not only lowering total energy consumption (e.g., through conservation measures) but also by lowering the carbon intensity of the energy sources employed (e.g., fuel switching from coal to natural gas). The amount of carbon emitted—in the form of CO_2—from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that carbon that is oxidized.[22] Fossil fuels vary in their average carbon content, ranging from about 53 Tg CO_2 Eq./EJ for natural gas to upwards of 95 Tg CO_2 Eq./EJ for coal and petroleum coke.[23] In general, the carbon intensity per unit of energy of fossil fuels is the highest for coal products, followed by petroleum and then natural gas. Other sources of energy, however, may be directly or indirectly carbon neutral (i.e., 0 Tg CO_2 Eq./EJ). Energy generated from nuclear and many renewable sources do not result in direct emissions of CO_2. Biofuels such as wood and ethanol are also considered to be carbon neutral, as the CO_2 emitted during their combustion is assumed to be offset by the carbon sequestered in the growth of new biomass.[24] The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 2-8 provides a time series of the carbon intensity for each sector of the U.S. economy. The time series incorporates only the energy consumed from the direct combustion of fossil fuels in each sector. For example, the carbon intensity for the residential sector does not include the energy from or emissions related to the consumption of electricity for lighting or wood for heat. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest carbon intensity, which was related to the large percentage of energy derived from natural gas for heating. The carbon intensity of the commercial sector was greater than the residential sector for the period from 1990 to 1996, but then declined to a comparable level as commercial businesses shifted away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher carbon intensities over this period. The carbon intensity of the transportation sector was closely related to the carbon content of petroleum products (e.g., motor gasoline and jet fuel, both around 67 Tg CO_2 Eq./EJ), which were the primary sources of energy. Lastly, the electric utility sector had the highest carbon intensity due to its heavy reliance on coal for generating electricity.

Table 2-8: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (Tg CO_2 Eq./EJ)

Sector	1990	1995	1996	1997	1998	1999
Residential[a]	53.8	53.7	53.6	53.7	53.6	53.6
Commercial[a]	55.7	54.2	54.2	54.0	53.8	53.9
Industrial[a]	65.1	64.2	63.9	64.0	64.6	65.4
Transportation[a]	67.3	67.1	67.0	67.0	67.1	67.1
Electric Utilities[b]	82.0	82.1	83.1	82.9	82.3	82.5
All Sectors[c]	**69.4**	**68.9**	**69.0**	**69.1**	**69.5**	**69.5**

[a] Does not include electricity or renewable energy consumption.
[b] Does not include electricity produced using nuclear or renewable energy.
[c] Does not include nuclear or renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption. Exajoule (EJ) = 10^{18} joules = 0.9479 QBtu.

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[21] Small quantities of CO_2, however, are released from some geologic formations tapped for geothermal energy. These emissions are included with fossil fuel combustion emissions from the electric utilities. Carbon dioxide emissions may also be generated from upstream activities (e.g., manufacture of the equipment) associated with fossil fuel and renewable energy activities, but are not accounted for here.

[22] Generally, 97 to 99.5 percent of the carbon in fossil fuel is oxidized to CO_2 with most carbon combustion technologies used in the United States.

[23] One exajoule (EJ) is equal to 10^{18} joules or 0.9478 QBtu.

[24] This statement assumes that there is no net loss of biomass-based carbon associated with the land use practices used to produce these biomass fuels.

In contrast to Table 2-8, Table 2-9 presents carbon intensity values that incorporate energy consumed from all sources (i.e., fossil fuels, renewables, and nuclear). In addition, the emissions related to the generation of electricity have been attributed to both electric utilities and the end-use sector in which that electricity was eventually consumed.[25] This Table, therefore, provides a more complete picture of the actual carbon intensity of each end-use sector per unit of energy consumed. The transportation end-use sector in Table 2-9 emerges as the most carbon intensive when all sources of energy are included, due to its almost complete reliance on petroleum products and relatively minor amount of biomass based fuels such as ethanol. The "other end-use sectors" (i.e., residential, commercial, and industrial) use significant quantities of biofuels such as wood, thereby lowering the overall carbon intensity. The carbon intensity of electric utilities differs greatly from the scenario in Table 2-8, where only the energy consumed from the direct combustion of fossil fuels was included. This difference is due almost entirely to the inclusion of electricity generation from nuclear and hydropower sources, which do not emit carbon dioxide.

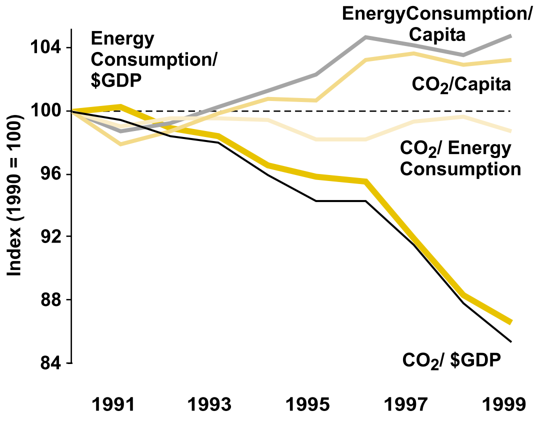
By comparing the values in Table 2-8 and Table 2-9, a couple of observations can be made. The usage of renewable and nuclear energy sources has resulted in a significantly lower carbon intensity of the U.S. economy. However, over the ten year period of 1990 through 1999, the carbon intensity of U.S. fossil fuel consumption has been fairly constant, as the proportion of renewable and nuclear energy technologies has not changed significantly.

Although the carbon intensity of total energy consumption has remained fairly constant, per capita energy consumption has increased leading to a greater energy-related CO_2 emissions per person in the United States since 1990 (see Figure 2-18). Because of the strong growth in the U.S. economy, though, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) declined in the 1990s.

Figure 2-19 and Table 2-10 present the detailed CO_2 emission trends underlying the carbon intensity differences and changes described in Table 2-8. In Figure 2-19, changes over time in both overall end-use sector-related emissions and electricity-related emissions for each year since 1990 are highlighted. In Table 2-10 changes in emissions since 1990 are presented by sector and fuel type to provide a more detailed accounting.

Figure 2-18

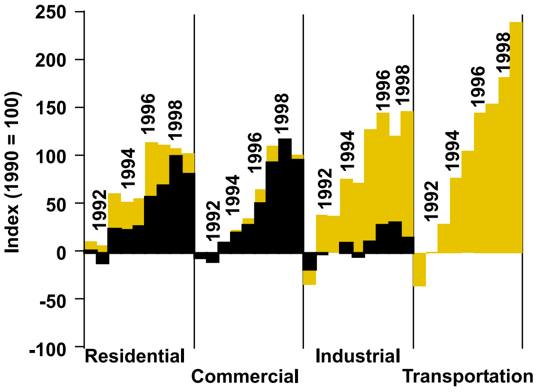
U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



Source: BEA (2000), Census (2000), Emission and energy consumption estimate, in this report.

Figure 2-19

Change in CO_2 Emissions from Fossil Fuel Combustion Since 1990 by End-Use Sector



Dark shaded columns relate to changes in emissions from electricity consumption. Lightly shaded columns relate to changes in emissions from both electricity and direct fossil fuel combustion.

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[25] In other words, the emissions from the generation of electricity are intentionally double counted by attributing them both to utilities and the end-use sector in which electricity consumption occurred.

Table 2-9: Carbon Intensity from Energy Consumption by Sector (Tg CO_2 Eq./EJ)

Sector	1990	1995	1996	1997	1998	1999
Transportation[a]	67.0	66.8	66.8	66.7	66.8	66.8
Other End-Use Sectors[a,b]	54.5	53.1	53.2	54.0	54.1	53.2
Electric Utilities[c]	56.0	54.4	54.8	56.3	56.3	55.2
All Sectors[d]	**58.6**	**57.5**	**57.6**	**58.2**	**58.4**	**57.9**

[a] Includes electricity (from fossil fuel, nuclear, and renewable sources) and direct renewable energy consumption.
[b] Other End-Use Sectors include the residential, commercial, and industrial sectors.
[c] Includes electricity generation from nuclear and renewable sources.
[d] Includes nuclear and renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption. Exajoule (EJ) = 10^{18} joules = 0.9479 QBtu.

Table 2-10: Change in CO_2 Emissions from Direct Fossil Fuel Combustion Since 1990 (Tg CO_2 Eq.)

Sector/Fuel Type	1991	1995	1996	1997	1998	1999
Residential	**9.9**	**30.2**	**58.3**	**42.8**	**8.9**	**22.0**
Coal	(0.5)	(0.8)	(0.7)	(0.4)	(1.6)	(1.6)
Natural Gas	8.8	24.6	46.0	32.0	8.0	16.4
Petroleum	1.7	6.4	13.0	11.2	2.6	7.3
Commercial	**1.5**	**6.6**	**15.5**	**16.4**	**0.1**	**5.7**
Coal	(0.8)	(1.2)	(1.0)	(0.5)	(2.5)	(2.5)
Natural Gas	5.8	22.1	29.2	32.3	21.1	24.0
Petroleum	(3.5)	(14.3)	(12.6)	(15.3)	(18.5)	(15.8)
Industrial	**(15.8)**	**77.6**	**117.1**	**117.7**	**89.8**	**132.1**
Coal	1.6	15.2	8.0	9.9	8.8	38.1
Natural Gas	6.8	82.4	100.2	99.7	85.2	86.8
Petroleum	(24.2)	(20.1)	8.9	8.1	(4.2)	7.3
Transportation	**(34.1)**	**107.6**	**147.0**	**157.1**	**184.7**	**242.2**
Coal	NE	NE	NE	NE	NE	NE
Natural Gas	(3.2)	2.3	2.9	5.5	(1.1)	(1.2)
Petroleum	(30.9)	105.3	144.1	151.7	185.8	243.4
Electric Utilities	**(20.4)**	**53.2**	**122.9**	**196.2**	**253.3**	**196.0**
Coal	(14.3)	78.5	168.4	220.4	234.7	202.7
Natural Gas	(0.4)	20.7	(4.6)	8.5	24.7	16.9
Petroleum	(5.7)	(45.9)	(40.8)	(32.7)	(6.0)	(23.4)
Geothermal	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)
U.S. Territories	**5.6**	**10.3**	**6.4**	**9.1**	**14.2**	**19.3**
Coal	0.1	0.3	0.3	0.3	0.3	0.3
Natural Gas	NE	NE	NE	NE	NE	NE
Petroleum	5.5	10.0	6.1	8.8	14.0	19.0
All Sectors	**(53.3)**	**285.6**	**467.3**	**539.2**	**551.1**	**617.4**

\+ Does not exceed 0.05 Tg CO_2 Eq.
NE (Not Estimated)
*Includes nonutility electricity generators.
Note: Totals may not sum due to independent rounding.

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 steps:

1. *Determine fuel consumption by fuel type and sector.* By aggregating consumption data by sector (e.g., commercial, industrial, etc.), primary fuel type (e.g., coal,

petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil, etc.), estimates of total U.S. fossil fuel consumption for a particular year were made. The United States does not include territories in its national energy statistics; therefore, fuel consumption data for territories was collected separately.[26]

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 in each fuel were converted to CO_2. The carbon content coefficients used by the United States are presented in Annex A.

3. *Subtract the amount of carbon stored in products.* Non-energy 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 fossil fuel products, such as lubricants or plastics, lose or emit some carbon when they are used and/or burned as waste. Aggregate U.S. energy statistics include consumption of fossil fuels for non-energy uses; therefore, the portion of carbon that remains in products after they are manufactured was subtracted from potential carbon emission estimates.[27] The amount of carbon remaining in products was based on the best available data on the end-uses and fossil fuel products. These non-energy uses occurred in the industrial and transportation sectors and U.S. territories. Emission of CO_2 associated with the disposal of these fossil fuel-based products are not accounted for here, but are instead accounted for under the Waste Combustion section in the Waste chapter.

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 and ash. The estimated amount of carbon not oxidized due to inefficiencies during the combustion process was assumed to be 1 percent for petroleum and coal and 0.5 percent for natural gas (see Annex A).

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—distillate fuel oil, residual fuel oil, and jet fuel—as part of consumption by the transportation end-use sector, emissions from international transport activities were calculated separately and subtracted from emission estimates for the transportation end-use sector. The calculations for emissions from bunker fuels follow 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).[28]

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,[29] a more detailed accounting of carbon dioxide emissions is provided. For fuel types other than jet fuel, 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 1999; therefore, the 1998 percentage allocations were applied to 1999 fuel consumption data in order to estimate emissions in 1999. Military vehicle jet fuel consumption was provided by the Defense Energy Support Center, under Department of Defense's (DoD) Defense Logistics Agency and the Office of the Undersecretary of Defense (Environmental Security). The difference between total U.S. jet fuel consumption (as reported by DOE/EIA) and civilian air carrier consumption for both domestic and international flights (as reported by DOT/BTS and BEA) plus

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[26] 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 emissions of 53 Tg of CO_2 Eq. in 1999.

[27] See Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter for a more detailed discussion.

[28] See International Bunker Fuels section in this chapter for a more detailed discussion.

[29] Electric utilities are not considered a final end-use sector, because they consume energy solely to provide electricity to the other sectors.

military jet fuel consumption is reported as "other" under the jet fuel category in Table 2-7, and includes such fuel uses as blending with heating oils and fuel used for chartered aircraft flights.

Data Sources

Data on fuel consumption for the United States and its territories, and carbon content of fuels 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 *Annual Energy Review* (EIA 2000a) and various EIA databases. Data on military jet fuel use was supplied by the Office of the Under Secretary of Defense (Environmental Security) and the Defense Energy Support Center (Defense Logistics Agency) of the U.S. Department of Defense (DoD). Estimates of international bunker fuel emissions are discussed in the section entitled International Bunker Fuels. Estimates of carbon stored in products are discussed in the section entitled Carbon Stored in Products from Nonfuel Uses of Fossil Fuels.

IPCC (IPCC/UNEP/OECD/IEA 1997) provided fraction oxidized values for petroleum and natural gas. Bechtel (1993) provided the fraction oxidation values for coal. Vehicle type fuel consumption data for the allocation of transportation end-use sector emissions were primarily taken from the *Transportation Energy Databook* prepared by the Center for Transportation Analysis at Oak Ridge National Laboratory (DOE 1993, 1994, 1995, 1996, 1997, 1998, 1999). Specific data on military fuel consumption were taken from DESC (2000). Densities for each military jet fuel type were obtained from the Air Force (1998).

Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2000a) and fossil fuel consumption data as discussed above and presented in Annex A.

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.[30]

It is also important to note that U.S. fossil fuel energy statistics are generally presented using gross calorific values (GCV) (i.e., higher heating values). Fuel consumption activity data presented here have not been adjusted to correspond to international standard, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[31]

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 production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

There are uncertainties, however, in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., petroleum), the amount of carbon contained in the fuel per unit of useful energy can vary.

Although statistics of total fossil fuel and other energy consumption are considered to be relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) are considerably more uncertain. For example, for some fuels the sectoral allocations are based

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[30] See IPCC Reference Approach for estimating CO_2 emissions from fossil fuel combustion in Annex R for a comparison of U.S. estimates using top-down and bottom-up approaches.

[31] A crude convention to convert between gross and net calorific values is to reduce the heat content of solid and liquid fossil fuels by 5 percent and gaseous fuels by 10 percent to account for the water content of the fuels. Biomass-based fuels in U.S. energy statistics are generally presented using net calorific values.

on price rates (i.e., tariffs). However, commercial establishment may be able to negotiate an industrial rate or a small industrial establishment may end up paying an industrial rate, leading to a misallocation of emissions. Also, the deregulation of the natural gas industry and the more recent deregulation of the electric power industry have likely led to problems in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

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 delayed rate. The proportions of fuels used in these non-energy 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. More detailed discussions on the uncertainties associated with Carbon Stored in Products from Non-Energy Uses of Fossil Fuels and with International Bunker Fuels are provided under those sections in this chapter.

Other sources of uncertainty are fuel consumption by U.S. territories. The United States does not collect energy statistics for its territories at the same level of detail as for the fifty States and the District of Columbia. Therefore estimating both emissions and bunker fuel consumption by these territories is difficult.

For Table 2-7, uncertainties also exist as to the data used to allocate CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom up estimates of fuel consumption by vehicle type do not match aggregate fuel-type estimates from EIA. Further research is planned to better allocate detailed transportation end-use sector emissions. In particular, fuel consumption data for marine vehicles are highly uncertain, as shown by the large fluctuations in emissions.

For the United States, however, these uncertainties impact on overall CO_2 emission estimates are believed to be relatively small. For the United States, CO_2 emission estimates from fossil fuel combustion are considered accurate within several percent. See, for example, Marland and Pippin (1990).

Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

Besides being combusted for energy, fossil fuels are also consumed for non-energy end uses. The types of fuels used for non-energy uses are listed in Table 2-11. The fuels are used in the industrial and transportation end-use sectors and are quite diverse, including natural gas, asphalt, a viscous liquid mixture of heavy crude oil distillates, and coking coal. The non-energy fuel uses are equally diverse, and include application as solvents, reduction agents in metals production, lubricants, and waxes, or as raw materials in the manufacture of plastics, rubber, synthetic fibers, and fertilizers.

Carbon dioxide emissions arise from non-energy uses via multiple pathways. Emissions may occur directly from the fuel's consumption, as is the case with coking coal used in iron blast furnaces. Emissions may also occur during the manufacture of a product, as is the case in producing plastics or rubber from feedstocks. Additionally, in the case of solvents or lubricants, for example, emissions may occur during the (fuel-derived) product's lifetime. Overall, more than 75 percent of the total carbon consumed for non-energy end uses is stored in products, and not released to the atmosphere. However, some of the products release CO_2 at the end of their commercial life when they are disposed. These emissions are covered in the Waste chapter under Waste Combustion.

In 1999, fossil fuel consumption for non-energy uses constituted 8 percent (6,886 TBtu) of overall fossil fuel consumption, an increase from 1990, when it accounted for 7 percent of total consumption. In 1999, the carbon in non-energy fuel consumption was approximately 478 Tg CO_2 Eq., an increase of 34 percent since 1990. Nearly 362 Tg CO_2 Eq. of this carbon was stored, while the remaining 117 Tg CO_2 Eq. was emitted. Since 1990, the proportion of carbon emitted has grown slightly from 23 percent to 24 percent of total non-energy consumption. Table 2-12 shows the fate of the non-energy fossil fuel carbon for 1990 and 1995 through 1999.

Table 2-11: 1999 Non-Energy Fossil Fuel Consumption, Storage, and Emissions (Tg CO_2 Eq. unless otherwise noted)

Sector/Fuel Type	Consumption (TBtu)	Carbon Content	Storage Factor (%)	Carbon Stored	Emissions
Industry	**6,476.86**	**448.04**	**-**	**358.8**	**89.2**
Industrial Coking Coal	24.48	2.29	0.75	1.7	0.6
Natural Gas to Chemical Plants	754.32	40.02	-	17.9	22.1
Nitrogenous Fertilizers	381.72	20.25	-	-	20.3
Other Uses	372.60	19.77	0.91	17.9	1.9
Asphalt & Road Oil	1,324.41	100.13	1.00	100.1	-
LPG	1,807.12	111.82	0.91	101.2	10.6
Lubricants	192.80	14.31	0.09	1.3	13.0
Pentanes Plus	331.68	22.18	0.91	20.1	2.1
Petrochemical Feedstocks	1,313.22	92.73	-	83.9	8.8
Naphtha (<401 deg. F)	502.08	33.39	0.91	30.2	3.2
Other Oil (>401 deg. F)	811.14	59.34	0.91	53.7	5.6
Still Gas	-	-	0.80	-	-
Petroleum Coke	376.80	38.48	0.50	19.2	19.2
Special Naphtha	145.40	10.59	-	-	10.6
Distillate Fuel Oil	6.99	0.51	0.50	0.3	0.3
Residual Fuel	50.30	3.96	0.50	2.0	2.0
Waxes	37.44	2.72	1.00	2.7	-
Miscellaneous Products	111.91	8.28	1.00	8.3	-
Transportation	**182.10**	**13.51**	**-**	**1.2**	**12.3**
Lubricants	182.10	13.51	0.09	1.2	12.3
U.S. Territories	**227.42**	**16.68**	**-**	**1.7**	**15.0**
Lubricants	1.39	0.10	0.09	+	0.1
Other Petroleum (Misc. Prod.)	226.03	16.58	0.10	1.7	14.9
Total	**6,886.38**	**478.23**	**-**	**361.7**	**116.5**

+ Less than 0.05 Tg CO_2 Eq.
- Not applicable.
Note: Totals may not sum due to independent rounding.

Table 2-12: Storage and Emissions from Non-Energy Fossil Fuel Consumption (Tg CO_2 Eq.)

Variable	1990	1995	1996	1997	1998	1999
Potential Emissions	357.6	406.8	417.4	434.5	450.5	478.2
Carbon Stored	276.2	317.9	323.1	338.6	343.4	361.7
Emissions	81.4	88.9	94.3	95.9	107.1	116.5

Methodology

The first step in estimating carbon stored in products was to determine the aggregate quantity of fossil fuels diverted to feedstock uses from energy-related combustion uses. The carbon content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific carbon content values (see Annex A).

Next, the amount of carbon stored was estimated by multiplying the potential emissions by a storage factor, which were calculated using U.S. data on carbon flows. For asphalt and road oil, petrochemical feedstocks, liquid petroleum gases (LPG), pentanes plus, and natural gas for other uses, carbon storage factors were calculated as the ratio of (a) the carbon stored by the fuel's non-energy products to (b) the total carbon content of the fuel consumed. A lifecycle approach was used in the development of these storage factors in order to account for losses in the production process—from raw material acquisition through manufacturing and processing—and during use. Details of these calculations are shown in Annex B. Because losses associated with waste management are handled separately in the Waste chapter, the storage factors do not account for losses at the disposal end of the life cycle. For the other fuel types, the storage factors were taken directly from Marland and Rotty (1984).

Lastly, emissions were estimated by subtracting the carbon stored from the potential emissions.

Data Sources

Non-energy fuel consumption and carbon content data were supplied by the EIA (2000). Where storage factors were calculated specifically for the United States, data was obtained on fuel products such as asphalt, plastics, synthetic rubber, synthetic fibers, pesticides, and solvents. Data was taken from a variety of industry sources, government reports, and expert communications. Sources include EPA compilations of air emission factors (EPA 1995, EPA 2000c), the National Asphalt Pavement Association (Connolly 2000), the Emissions Inventory Improvement Program (EIIP 1999), the U.S. Census Bureau (1999), the American Plastics Council (APC 2000), the International Institute of Synthetic Rubber Products (IISRP 2000), the Fiber Economics Bureau (FEB 2000), and the Chemical Manufacturer's Handbook (CMA 1999). For the other fuel types, storage factors were taken from Marland and Rotty (1984). Specific data sources are listed in full detail in Annex B.

Uncertainty

The fuel consumption data and the carbon content values employed here were taken from the same references as the data used for estimating overall CO_2 emissions from fossil fuel combustion. Given that the uncertainty in these data is expected to be small, the uncertainty of the estimate for the potential carbon emissions is also expected to be small. However, there is a large degree of uncertainty in the storage factors employed, depending upon the fuel type. For each of the calculated storage factors, the uncertainty is discussed in detail in Annex B. Generally, uncertainty arises from assumptions made to link fuel types with their derivative products and in determining the fuel products' carbon contents and emission or storage fates. The storage factors from Marland and Rotty (1984) are also highly uncertain.

Stationary Combustion (excluding CO_2)

Stationary combustion encompasses all fuel combustion activities except those related to 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).[32] Emissions of these gases from stationary combustion 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.

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 primarily a function of the CH_4 content of the fuel, combustion efficiency, and post-combustion controls.

Emissions of CH_4 increased slightly from 1990 to 1996, but fell to just below the 1990 level in 1999 to 8.1 Tg CO_2 Eq. (386 Gg). This decrease in emissions was primarily due to lower wood consumption in the residential sector. Nitrous oxide emissions rose 15 percent since 1990 to 15.7 Tg CO_2 Eq. (51 Gg) in 1999. The largest source of N_2O emissions was coal combustion by electric utilities, which alone accounted for 53 percent of total N_2O emis-

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[32] Sulfur dioxide (SO_2) emissions from stationary combustion are addressed in Annex M.

sions from stationary combustion in 1999. Overall, though, stationary combustion is a small source of CH_4 and N_2O in the United States.

In contrast, stationary combustion was a significant source of NO_x emissions, but a smaller source of CO and NMVOCs. In 1999, emissions of NO_x from stationary combustion represented 39 percent of national NO_x emissions, while CO and NMVOC emissions from stationary combustion contributed approximately 6 and 5 percent, respectively, to the national totals. From 1990 to 1999, emissions of NO_x, CO, and NMVOCs decreased by 8, 4, and 10 percent, respectively.

The decrease in NO_x emissions from 1990 to 1999 are mainly due to decreased emissions from electric utilities. Decreases in CO and NMVOC emissions over this time period can largely be attributed to decreased residential wood consumption, which is the most significant source of these pollutants from stationary combustion. Table 2-13 through and Table 2-16 provide CH_4 and N_2O emission estimates from stationary combustion by sector and fuel type. Estimates of NO_x, CO, and NMVOC emissions in 1998 are given in Table 2-17.[33]

Methodology

Methane and nitrous oxide emissions were estimated by multiplying emission factors (by sector and fuel type) by fossil fuel and wood consumption data. National coal, natural gas, fuel oil, and wood consumption data were grouped into four sectors—industrial, commercial/institutional, residential, and electric utilities.

For NO_x, CO, and NMVOCs, the major categories included in this section are those used in EPA (2000): coal, fuel oil, natural gas, wood, other fuels (including LPG, coke, coke oven gas, and others), and stationary internal combustion. The EPA 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., indus-

Table 2-13: CH_4 Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999
Electric Utilities	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Coal	0.3	0.4	0.4	0.4	0.4	0.4
Fuel Oil	0.1	+	+	0.1	0.1	0.1
Natural gas	0.1	0.1	0.1	0.1	0.1	0.1
Wood	+	+	+	+	+	+
Industrial	**2.7**	**3.0**	**3.0**	**3.1**	**3.0**	**3.3**
Coal	0.6	0.5	0.5	0.5	0.5	0.5
Fuel Oil	0.4	0.4	0.4	0.4	0.4	0.4
Natural gas	0.8	1.0	1.0	1.0	1.0	1.0
Wood	0.9	1.1	1.1	1.1	1.1	1.4
Commercial/Institutional	**0.7**	**0.7**	**0.8**	**0.8**	**0.7**	**0.8**
Coal	+	+	+	+	+	+
Fuel Oil	0.2	0.2	0.2	0.1	0.1	0.1
Natural gas	0.3	0.3	0.3	0.3	0.3	0.3
Wood	0.2	0.3	0.3	0.3	0.3	0.3
Residential	**4.6**	**4.7**	**4.7**	**3.8**	**3.3**	**3.5**
Coal	0.4	0.3	0.3	0.4	0.3	0.3
Fuel Oil	0.3	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.5	0.5	0.5	0.5	0.5	0.5
Wood	3.5	3.6	3.6	2.6	2.3	2.4
Total	**8.5**	**8.9**	**9.0**	**8.1**	**7.6**	**8.1**

\+ Does not exceed 0.05 Tg CO_2 Eq.
NA (Not Available)
Note: Totals may not sum due to independent rounding

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[33] See Annex C for a complete time series of criteria pollutant emission estimates for 1990 through 1999.

Table 2-14: N_2O Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999
Electric Utilities	**7.4**	**7.8**	**8.2**	**8.5**	**8.7**	**8.6**
Coal	7.1	7.6	8.0	8.2	8.4	8.4
Fuel Oil	0.2	0.1	0.1	0.2	0.2	0.2
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1
Wood	+	+	+	+	+	+
Industrial	**4.8**	**5.1**	**5.2**	**5.3**	**5.2**	**5.8**
Coal	1.2	1.1	1.0	1.0	1.0	1.0
Fuel Oil	1.6	1.6	1.7	1.7	1.7	1.8
Natural Gas	0.3	0.3	0.3	0.3	0.3	0.3
Wood	1.8	2.1	2.1	2.2	2.3	2.8
Commercial/Institutional	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1
Wood	+	0.1	0.1	0.1	0.1	0.1
Residential	**1.1**	**1.1**	**1.2**	**1.0**	**0.8**	**0.9**
Coal	+	+	+	+	+	+
Fuel Oil	0.2	0.3	0.3	0.3	0.2	0.3
Natural Gas	0.1	0.1	0.2	0.2	0.1	0.1
Wood	0.7	0.7	0.7	0.5	0.4	0.5
Total	**13.6**	**14.3**	**14.9**	**15.0**	**15.1**	**15.7**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 2-15: CH_4 Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999
Electric Utilities	**23**	**23**	**23**	**25**	**26**	**25**
Coal	16	17	18	19	19	19
Fuel Oil	4	2	2	2	4	3
Natural Gas	3	3	3	3	3	3
Wood	+	+	+	+	+	+
Industrial	**129**	**141**	**143**	**145**	**144**	**157**
Coal	27	25	24	24	23	22
Fuel Oil	17	17	18	19	18	19
Natural Gas	40	48	50	50	48	48
Wood	44	50	52	53	55	67
Commercial/Institutional	**33**	**36**	**38**	**37**	**35**	**39**
Coal	1	1	1	1	1	1
Fuel Oil	9	7	7	7	7	7
Natural Gas	13	15	15	16	15	15
Wood	11	13	14	13	13	16
Residential	**218**	**223**	**226**	**179**	**156**	**165**
Coal	19	16	16	17	13	13
Fuel Oil	13	14	15	14	13	14
Natural Gas	21	24	26	24	22	23
Wood	166	170	170	123	107	115
Total	**403**	**422**	**430**	**386**	**361**	**386**

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

Table 2-16: N_2O Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999
Electric Utilities	**24**	**25**	**27**	**27**	**28**	**28**
Coal	23	24	26	27	27	27
Fuel Oil	1	+	+	+	1	1
Natural Gas	+	+	+	+	+	+
Wood	+	+	+	+	+	+
Industrial	**16**	**16**	**17**	**17**	**17**	**19**
Coal	4	3	3	3	3	3
Fuel Oil	5	5	5	6	6	6
Natural Gas	1	1	1	1	1	1
Wood	6	7	7	7	7	9
Commercial/Institutional	**1**	**1**	**1**	**1**	**1**	**1**
Coal	+	+	+	+	+	+
Fuel Oil	1	+	+	+	+	+
Natural Gas	+	+	+	+	+	+
Wood	+	+	+	+	+	+
Residential	**3**	**4**	**4**	**3**	**3**	**3**
Coal	+	+	+	+	+	+
Fuel Oil	1	1	1	1	1	1
Natural Gas	+	+	1	+	+	+
Wood	2	2	2	2	1	2
Total	**44**	**46**	**48**	**49**	**49**	**51**

\+ Does not exceed 0.5 Gg

Note: Totals may not sum due to independent rounding

trial 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 combustion, as described above, is consistent with the methodology recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

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

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 - 1999* (EPA 2000). Fuel consumption data for CH_4 and N_2O estimates were provided by the U.S. Energy Information Administration's Annual Energy Review (EIA 2000). Estimates for wood biomass consumption for fuel combustion do not include wood wastes, liquors, municipal solid waste, tires, etc. that are reported as biomass by EIA. 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

Table 2-17: NO_x, CO, and NMVOC Emissions from Stationary Combustion in 1999 (Gg)

Sector/Fuel Type	NO_x	CO	NMVOC
Electric Utilities	**5,161**	**374**	**49**
Coal	4,477	217	26
Fuel Oil	183	16	5
Natural Gas	349	85	8
Wood	NA	NA	NA
Internal Combustion	152	55	10
Industrial	**2,844**	**1,069**	**162**
Coal	492	99	6
Fuel Oil	194	47	7
Natural Gas	1,090	310	54
Wood	NA	NA	NA
Other Fuels[a]	107	309	32
Internal Combustion	961	303	63
Commercial/Institutional	**373**	**136**	**26**
Coal	34	14	1
Fuel Oil	73	15	3
Natural Gas	241	63	14
Wood	NA	NA	NA
Other Fuels[a]	25	45	9
Residential	**692**	**3,220**	**582**
Coal[b]	NA	NA	NA
Fuel Oil[b]	NA	NA	NA
Natural Gas[b]	NA	NA	NA
Wood	36	2,994	552
Other Fuels[c]	656	226	31
Total	**9,070**	**4,798**	**820**

NA (Not Available)

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2000).

[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2000).

[c] "Other Fuels" include LPG, waste oil, coke oven gas, and coke (EPA 2000).

Note: Totals may not sum due to independent rounding. See Annex C for emissions in 1990 through 1999.

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 mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates 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 activity data projections.

Mobile Combustion (excluding CO_2)

Mobile combustion emits 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 stationary combustion, N_2O and NO_x emissions are closely related to fuel characteristics, air-fuel mixes, 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 CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile 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 combustion were estimated by transport mode (e.g., highway, 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 combustion emissions. Table 2-18 through Table 2-21 provide CH_4 and N_2O emission estimates from mobile combustion by vehicle type, fuel type, and transport mode. Estimates of NO_x, CO, and NMVOC emissions in 1999 are given in Table 2-22.[34]

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[34] See Annex C for a complete time series of criteria pollutant emission estimates for 1990 through 1998.

Table 2-18: CH_4 Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999
Gasoline Highway	**4.3**	**4.2**	**4.0**	**4.0**	**3.9**	**3.8**
Passenger Cars	2.4	2.0	2.0	2.0	1.9	1.9
Light-Duty Trucks	1.6	1.9	1.6	1.6	1.5	1.4
Heavy-Duty Vehicles	0.3	0.2	0.4	0.4	0.3	0.3
Motorcycles	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Diesel Highway	0.2	0.2	0.3	0.3	0.3	0.3
Passenger Cars	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Heavy-Duty Vehicles	0.2	0.2	0.3	0.3	0.3	0.3
Non-Highway	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Ships and Boats	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	+	+
Farm Equipment	0.1	0.1	0.1	0.1	0.1	0.1
Construction Equipment	+	+	+	+	+	+
Aircraft	0.2	0.1	0.1	0.2	0.1	0.2
Other*	+	+	+	+	+	+
Total	**5.0**	**4.9**	**4.8**	**4.7**	**4.6**	**4.5**

+ Does not exceed 0.05 Tg CO_2 Eq.
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 2-19: N_2O Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999
Gasoline Highway	**49.6**	**61.7**	**59.3**	**59.2**	**58.2**	**57.2**
Passenger Cars	30.9	33.0	32.7	32.4	32.1	31.5
Light-Duty Trucks	17.8	27.1	23.9	24.0	23.3	22.7
Heavy-Duty Vehicles	0.9	1.6	2.7	2.8	2.8	3.0
Motorcycles	+	+	+	+	+	+
Diesel Highway	**1.8**	**2.2**	**2.9**	**3.1**	**3.1**	**3.2**
Passenger Cars	0.1	0.1	+	+	+	+
Light-Duty Trucks	+	0.1	+	+	+	+
Heavy-Duty Vehicles	1.6	2.0	2.9	3.0	3.1	3.2
Non-Highway	**2.9**	**3.0**	**3.0**	**2.9**	**2.8**	**3.0**
Ships and Boats	0.4	0.5	0.4	0.3	0.3	0.4
Locomotives	0.3	0.3	0.3	0.2	0.2	0.2
Farm Equipment	0.3	0.3	0.3	0.3	0.3	0.3
Construction Equipment	0.1	0.1	0.1	0.2	0.2	0.1
Aircraft	1.7	1.7	1.8	1.7	1.8	1.8
Other*	0.1	0.1	0.1	0.1	0.1	0.1
Total	**54.3**	**66.8**	**65.3**	**65.2**	**64.2**	**63.4**

+ Does not exceed 0.05 Tg CO_2 Eq.
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 2-20: CH_4 Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999
Gasoline Highway	**207**	**199**	**192**	**189**	**184**	**179**
Passenger Cars	115	95	94	93	93	92
Light-Duty Trucks	76	89	76	75	72	68
Heavy-Duty Vehicles	12	11	17	17	16	16
Motorcycles	4	4	4	3	3	3
Diesel Highway	**10**	**11**	**16**	**16**	**16**	**16**
Passenger Cars	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Heavy-Duty Vehicles	9	11	15	16	16	16
Non-Highway	**21**	**21**	**21**	**20**	**19**	**20**
Ships and Boats	3	4	4	3	2	4
Locomotives	3	3	3	2	2	2
Farm Equipment	6	6	6	6	5	5
Construction Equipment	1	1	1	1	1	1
Aircraft	7	7	7	7	7	7
Other*	1	1	1	1	1	1
Total	**237**	**232**	**228**	**225**	**219**	**215**

\+ 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 2-21: N_2O Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	1996	1997	1998	1999
Gasoline Highway	**160**	**199**	**191**	**191**	**188**	**184**
Passenger Cars	100	106	105	104	103	102
Light-Duty Trucks	57	87	77	77	75	73
Heavy-Duty Vehicles	3	5	9	9	9	10
Motorcycles	+	+	+	+	+	+
Diesel Highway	**6**	**7**	**9**	**10**	**10**	**10**
Passenger Cars	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Heavy-Duty Vehicles	5	6	9	10	10	10
Non-Highway	**9**	**10**	**10**	**9**	**9**	**10**
Ships and Boats	1	1	1	1	1	1
Locomotives	1	1	1	1	1	1
Farm Equipment	1	1	1	1	1	1
Construction Equipment	+	+	+	+	+	+
Aircraft	6	5	6	6	6	6
Other*	+	+	+	+	+	+
Total	**175**	**215**	**211**	**210**	**207**	**204**

\+ 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 2-22: NO_x, CO, and NMVOC Emissions from Mobile Combustion in 1999 (Gg)

Fuel Type/Vehicle Type	NO_x	CO	NMVOCs
Gasoline Highway	**4,496**	**43,327**	**4,544**
Passenger Cars	2,582	24,664	2,604
Light-Duty Trucks	1,486	14,620	1,562
Heavy-Duty Vehicles	416	3,866	340
Motorcycles	12	177	38
Diesel Highway	**3,297**	**2,023**	**263**
Passenger Cars	7	7	3
Light-Duty Trucks	5	5	2
Heavy-Duty Vehicles	3,284	2,011	258
Non-Highway	**5,001**	**22,829**	**2,929**
Ships and Boats	975	2,170	874
Locomotives	1,092	108	44
Farm Equipment	826	458	99
Construction Equipment	1,137	1,333	214
Aircraft[a]	159	909	166
Other[b]	813	17,851	1,532
Total	**12,794**	**68,179**	**7,736**

\+ 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.

Mobile combustion was responsible for a small portion of national CH_4 emissions but was the second largest source of N_2O in the United States. From 1990 to 1999, CH_4 emissions declined by 10 percent, to 4.5 Tg CO_2 Eq. (215 Gg). Nitrous oxide emissions, however, rose 17 percent to 63.4 Tg CO_2 Eq. (204 Gg) (see Figure 2-20). 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 average 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.

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 1999, CO emissions from mobile combustion contributed 82 percent of national CO emissions and 56 and 48 percent of NO_x and NMVOC emissions, respectively. Since 1990, emissions of CO and NMVOCs from mobile combustion decreased by 2 and 5 percent, respectively, while emissions of NO_x increased by 17 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.[35] A complete discussion of the methodology used to estimate emissions from mobile combustion is provided in Annex D.

The EPA (2000b) provided emissions estimates of NO_x, CO, and NMVOCs for eight categories of highway vehicles,[36] aircraft, and seven categories of off-highway vehicles.[37]

Data Sources

Emission factors used in the calculations of CH_4 and N_2O emissions are presented in Annex D. 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 tempera-

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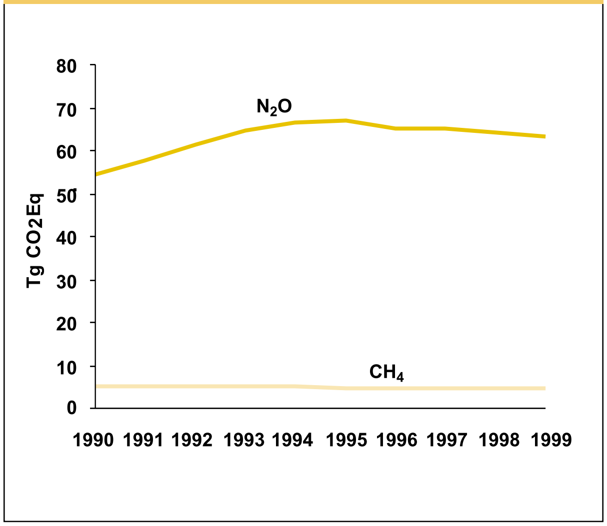
[35] The consumption of international bunker fuels is not included in these activity data, but are estimated separately under the International Bunker Fuels source category.

[36] 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.

[37] 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.

Figure 2-20

Mobile Source CH_4 and N_2O Emissions



ture, vehicle speeds, national vehicle registration distributions, gasoline volatility, and other variables in order to produce these factors (EPA 1997).

Emission factors for N_2O from gasoline highway vehicles came from EPA (1998). This report contains 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 default 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 additional testing data are available. For more details, see 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 (2000a), EIA (2000b), FHWA (1999), BEA (2000), DESC (2000), DOC (2000), FAA (2000), and DOT/BTS (2000). Control technology data for highway vehicles were obtained from the EPA's Office of Transportation and Air Quality. Annual VMT data for 1990 through 1999 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database, as noted in EPA (2000a).

Emissions estimates for NO_x, CO, NMVOCs were taken directly from the EPA's *National Air Pollutant Emissions Trends,* 1900 - 1999 (EPA 2000b).

Uncertainty

Mobile combustion 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 combustion were available, including VMT by vehicle type for highway vehicles. The allocation of this VMT to individual model years was done using temporally variable profiles of both vehicle usage by vehicle age and vehicle usage by model year in the United States. Data for these profiles were provided by EPA (2000a).

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 combustion—CO, NO_x, and hydrocarbons—have been extensively researched, and thus 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 combustion—a component of which is methane—are regulated.

In calculating CH_4 and N_2O emissions from highway vehicles, only data for Low Emission Vehicles (LEVs) in California has been obtained. Data on the number of LEVs in the rest of the United States will be researched and may be included in future inventories.

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.

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.

U.S. jet fuel and aviation gasoline consumption is currently all attributed to the transportation sector by EIA, and it is assumed here that it is all used to fuel aircraft. However, it is likely that some fuel purchased by airlines is not necessarily used in aircraft, but instead used to power auxiliary power units, in ground equipment, and to test engines. Some jet fuel may also be used for other purposes such as blending with diesel fuel or heating oil.

In calculating CH_4 emissions from aircraft, an average emission factor is applied to total jet fuel consumption. This average emission factor takes into account the fact that CH_4 emissions occur only during the landing and take-off (LTO) cycles, with no CH_4 being emitted during the cruise cycle. While there is some evidence that fuel emissions in cruise conditions may actually destroy methane, the average emission factor used does not take this into account.

Lastly, in EPA (2000b), U.S. aircraft emission estimates for CO, NOx, and NMVOCs are based upon landing and take-off (LTO) cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates presented here overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including LTO cycles by aircraft on international flights but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes.

Coal Mining

All underground and surface coal mining liberates methane as part of normal operations. The amount of methane liberated depends upon the amount that remains in the coal ("*in situ*") and surrounding strata when mining occurs. This methane content depends upon the amount of methane created during the coal formation (or coalification) process, and the geologic characteristics of the coal seams. Deeper coal deposits tend to generate more methane during coalification and retain more of the gas afterwards. Accordingly, deep underground coal seams generally have higher methane contents than shallow coal seams or surface deposits.

Three types of coal mining activities release methane to the atmosphere: underground mining, surface mining, and post-mining activities. Underground 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 can exhaust significant amounts of methane to the atmosphere in low concentrations. Additionally, twenty gassy U.S. coal mines supplement ventilation systems with degasification systems. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large volumes of methane before, during or after mining. In 1999, 11 coal mines collected methane from degasification systems and sold 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; however, the level of emissions is much lower than from underground mines. Finally, some of the methane retained in the coal after mining is released during processing, storage, and transport of the coal.

Total methane emissions in 1999 were estimated to be 61.8 Tg CO_2 Eq. (2,944 Gg), declining 30 percent since 1990 (see Table 2-23 and Table 2-24). Of this amount, underground mines accounted for 64 percent, surface mines accounted for 14 percent, and post-mining emissions accounted for 21 percent. With the exception of 1994 and 1995, total methane emissions declined in each successive year during this period. In 1993, methane generated from underground mining dropped, primarily due to labor strikes at many large underground mines. In 1995, there was an increase in methane emissions from underground mining due to particularly increased emissions at the highest-emitting coal mine in the country. The decline in methane emissions from underground mines in 1999 is the result of a decrease in coal production, and the mining of less gassy coal. Surface mine emissions and post-mining emissions remained relatively constant from 1990 to 1999.

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. Emissions reductions attributed to CMOP are estimated at 0.8, 5.1, 5.5, 6.6, 6.2, and 7.0 Tg CO_2 Eq. in 1994 through 1999, respectively.

Methodology

The methodology for estimating methane emissions from coal mining consists of two steps. The first step involves 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 involves estimating emissions from surface mines and post-mining activities by multiplying basin-specific coal production by basin-specific emissions factors.

Table 2-23: CH_4 Emissions from Coal Mining (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999
Underground Mining	62.8	52.2	46.3	45.0	43.0	39.8
Liberated	68.8	64.8	60.4	61.7	60.6	57.2
Recovered & Used	(6.0)	(12.6)	(14.1)	(16.7)	(17.5)	(17.4)
Surface Mining	10.2	8.9	9.2	9.5	9.4	8.8
Post- Mining (Underground)	13.1	11.9	12.4	12.8	12.6	11.7
Post-Mining (Surface)	1.7	1.5	1.5	1.5	1.5	1.4
Total	**87.9**	**74.6**	**69.3**	**68.8**	**66.5**	**61.8**

Note: Totals may not sum due to independent rounding.

Table 2-24: CH_4 Emissions from Coal Mining (Gg)

Activity	1990	1995	1996	1997	1998	1999
Underground Mining	2,991	2,487	2,204	2,141	2,049	1,896
Liberated	3,278	3,086	2,875	2,938	2,884	2,726
Recovered & Used	(288)	(599)	(671)	(797)	(835)	(829)
Surface Mining	488	425	436	451	446	421
Post- Mining (Underground)	626	569	590	609	600	558
Post-Mining (Surface)	79	69	71	73	72	68
Total	**4,184**	**3,550**	**3,301**	**3,274**	**3,168**	**2,944**

Note: Totals may not sum due to independent rounding.

Underground mines. Total methane emitted from underground mines was estimated as the sum of methane liberated from ventilation systems, plus methane liberated from degasification systems, minus methane recovered and used. The Mine Safety and Heath Administration (MSHA) samples methane emissions from ventilation systems for all mines with detectable[38] methane concentrations. These mine-by-mine measurements are used to estimate methane emissions from ventilation systems.

Some of the higher-emitting underground mines also use degasification systems (e.g., wells or boreholes) that remove methane before, during, 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 report to EPA the amounts of methane liberated from their degasification systems. For mines that sell recovered methane to a pipeline, pipeline sales data were used to estimate degasification emissions. Finally, for those mines for which no other data are 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 1999, 11 active coal mines sold recovered methane to pipelines. 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 occurs. Additionally, some of the State agencies provide 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. Surface mining emissions factors were developed by assuming that surface mines emit 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 this analysis, it was assumed that twice the average in-situ methane content was emitted. 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. For this analysis, it was assumed that 32.5 percent of the average in-situ methane content was emitted.

Data Sources

The Mine Safety and Health Administration provided mine-specific information on methane liberated from ventilation systems at underground mines. The 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, information supplied by mine operators regarding the number of years in advance of mining that gas recovery occurred, and reports of gas used on-site. Annual coal production data were taken from the Energy Information Administration's *Coal Industry Annual* (see Table 2-25) (EIA 1999). Data on in situ methane content and emissions factors are taken from EPA (1993).

Uncertainty

The emission estimates from underground ventilation systems were based upon actual measurement data, which were estimated to have relatively high accuracy. A degree of imprecision was introduced because the measurements were not continuous but rather an average of quarterly instantaneous readings. Additionally, the measurement equipment used possibly resulted in an average of 10 percent overestimation of annual methane emissions (Mutmansky and Wang 2000). Estimates of methane liberated from degasification systems are less certain because the EPA assigns default recovery efficiencies for a subset of U.S. mines. Compared to underground mines, there is considerably more uncertainty associated

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[38] 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 2-25: Coal Production (Thousand Metric Tons)

Year	Underground	Surface	Total
1990	384,250	546,818	931,068
1991	368,635	532,656	901,291
1992	368,627	534,290	902,917
1993	318,478	539,214	857,692
1994	362,065	575,529	937,594
1995	359,477	577,638	937,115
1996	371,816	593,315	965,131
1997	381,620	607,163	988,783
1998	378,964	634,864	1,013,828
1999[39]	352,753	639,701	992,454

with surface mining and post-mining emissions because of the difficulty in developing accurate emissions factors from field measurements. The EPA plans to update the basin specific surface mining emission factors. Because underground emissions comprise the majority of total coal mining emissions, the overall uncertainty is estimated to be only ±15 percent. Currently, the estimate does not include emissions from abandoned coal mines because of limited data. The EPA is conducting research on the feasibility of including an estimate in future years.

Natural Gas Systems

The U.S. natural gas system is vast, encompassing hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. Overall, natural gas systems emitted 121.8 Tg CO_2 Eq. (5,799 Gg) of methane in 1999, a slight increase over emissions in 1990 (see Table 2-26 and Table 2-27). Improvements in management practices and technology, along with the normal replacement of older equipment, have helped to stabilize emissions. In addition, EPA's Natural Gas STAR Program, initiated in 1993, is successfully working with the gas industry to promote profiTable practices and technologies that reduce methane emissions.[40]

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. Below is a characterization of the four major stages of the natural gas system. Each of the stages is described and the different factors affecting methane emissions are discussed.

Field Production. In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, gathering pipelines, and well-site gas treatment facilities such as dehydrators and separators. Fugitive emissions and emissions from pneumatic devices account for the majority of emissions. Emissions from field production accounted for approximately 25 percent of methane emissions from natural gas systems between 1990 and 1999. Emissions rose between 1990 and 1993 but by 1999 had returned to slightly above 1990 levels because of emission reductions by firms participating in the Natural Gas STAR Program.

Processing. In this stage, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Fugitive emissions from compressors, including compressor seals, are the primary emission source from this stage. Processing plants account for about 12 percent of methane emissions from natural gas systems.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities, which contain large reciprocating and turbine compressors, are used to move the gas throughout the United States transmission system. Fugitive emissions from these compressor stations and from metering and regulating stations account for the majority

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[39] The EIA Coal Industry Annual was not yet available, however, total production was available in the U.S. Coal Supply and Demand: 1999 Review. The split between underground and surface mining production is a preliminary estimate based on data from previous years.

[40] Natural Gas STAR Program reductions are included in emission estimates.

Table 2-26: CH_4 Emissions from Natural Gas Systems (Tg CO_2 Eq.)

Stage	1990	1995	1996	1997	1998	1999
Field Production	29.6	31.0	30.9	29.6	31.7	30.8
Processing	14.7	15.0	14.9	14.9	14.7	14.6
Transmission and Storage	46.7	46.7	47.1	46.0	44.8	44.8
Distribution	30.3	31.5	32.9	32.2	30.9	31.6
Total	**121.2**	**124.2**	**125.8**	**122.7**	**122.1**	**121.8**

Note: Totals may not sum due to independent rounding.

Table 2-27: CH_4 Emissions from Natural Gas Systems (Gg)

Stage	1990	1995	1996	1997	1998	1999
Field Production	1,407	1,477	1,474	1,407	1,510	1,468
Processing	702	712	708	710	698	694
Transmission and Storage	2,223	2,225	2,243	2,192	2,135	2,134
Distribution	1,441	1,498	1,567	1,532	1,471	1,503
Total	**5,772**	**5,912**	**5,993**	**5,841**	**5,814**	**5,799**

Note: Totals may not sum due to independent rounding.

of the emissions from this stage. Pneumatic devices and engine exhaust are also sources of emissions from transmission facilities. Methane emissions from transmission account for approximately 37 percent of the emissions from natural gas systems.

Natural gas is also injected and stored in underground formations during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Compressors and dehydrators are the primary contributors to emissions from these storage facilities. Approximately one percent of total emissions from natural gas systems can be attributed to storage facilities.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through mains and service lines to individual end users. There were over 980,000 miles of distribution mains in 1998,[41] an increase from just over 837,000 miles in 1990 (AGA 1998). Distribution system emissions, which account for approximately 26 percent of emissions from natural gas systems, resulted mainly from fugitive emissions from gate stations and non-plastic piping (cast iron, steel).[42] An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced the growth in emissions from this stage. Distribution system emissions in 1999 were only slightly higher than 1990 levels.

Methodology

The basis for estimates of methane emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute and EPA (EPA/GRI 1996). The EPA/GRI study developed over 100 emission and activity factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The study was based on a combination of process engineering studies and measurements at representative gas facilities. From this analysis, the EPA developed a 1992 base year emissions estimate using the emission and activity factors. For other years, the EPA has developed a set of industry activity factor drivers that can be used to update activity factors. These drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations.

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[41] 1998 is the latest year for which distribution pipeline mileage data was available.

[42] The percentages of total emissions from each stage may not add to 100 because of independent rounding.

The methodology also adjusts the emission factors to reflect underlying technological improvement through both innovation and normal replacement of equipment. For the period 1990 through 1995, the emission factors were held constant. Thereafter, emission factors are reduced at a rate of 0.2 percent per year such that by 2020, emission factors will have declined by 5 percent from 1995. See Annex F for more detailed information on the methodology and data used to calculate methane emissions from natural gas systems.

Data Sources

Activity factor data were obtained from the following sources: American Gas Association (AGA 1991 through 1999); Natural Gas Annual (EIA 1998); Natural Gas Monthly (EIA 1999); Oil and Gas Journal (PennWell Corporation 1999, 2000); Independent Petroleum Association of America (IPAA 1998, 1999), and the Department of Transportation's Office of Pipeline Safety (OPS 2000). The Minerals Management Service (DOI 1997 through 2000) supplied offshore platform data. All emission factors were taken from EPA/GRI (1996).

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

Methane emissions from petroleum systems are primarily associated with crude oil production, transportation, and refining operations. During each of these activities, methane is released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. The EPA estimates that total methane emissions from petroleum systems in 1999 were 21.9 Tg CO_2 Eq. (1,044 Gg). Since 1990, emissions declined gradually primarily due to a decline in domestic oil production. (See Table 2-28 and Table 2-29.) The various sources of emissions are detailed below.

Production Field Operations. Production field operations account for approximately 97 percent of total methane emissions from petroleum systems. Vented methane from oil wells, storage tanks, and related production field processing equipment account for the vast majority of the emissions from production, with storage tanks and natural-gas-powered pneumatic devices being the dominant sources. (The emissions from storage tanks occur when the methane, entrained in crude oil under high pressure, volatilizes once the crude oil is dumped into storage tanks at atmospheric pressure.) The next most dominant sources of venting emissions are oil wells and offshore platforms. The remaining emissions from production can be attributed to fugitives and combustion. The EPA expects future emissions from production fields to decline as the number of oil wells declines and crude production in the United States slows.

Crude Oil Transportation. Crude transportation activities account for approximately one half percent of total methane emissions from the oil industry. Venting from tanks and marine vessel loading operations accounts for the majority of methane emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for the remainder.

Crude Oil Refining. Crude oil refining processes and systems account for only two percent of total methane emissions from the oil industry because most of the methane in crude oil is removed or escapes before the crude oil is delivered to the refineries. Within refineries, vented emissions account for about 87 percent of the emissions from refining, while fugitive and combustion emissions account for approximately seven and six percent, respectively. Refinery system blowdowns for maintenance and the process of asphalt blowing—with air to harden it—are the primary venting contributors. Most of the fugitive emissions from refineries are from leaks in the fuel gas system. Refinery combustion emissions accumulate from small amounts of unburned methane in process heater stack emissions and from unburned methane

Table 2-28: CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999
Production Field Operations	**26.5**	**23.9**	**23.3**	**23.3**	**22.6**	**21.2**
Tank venting	11.8	10.4	10.2	10.2	9.8	9.1
Pneumatic device venting	11.7	10.6	10.3	10.3	10.0	9.4
Wellhead fugitives	0.5	0.5	0.5	0.5	0.5	0.5
Combustion & process upsets	1.0	0.9	1.0	1.0	0.9	0.9
Misc. venting & fugitives	1.5	1.4	1.4	1.4	1.3	1.3
Crude Oil Transportation	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Refining	**0.5**	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**
Total	**27.2**	**24.5**	**24.0**	**24.0**	**23.3**	**21.9**

Note: Totals may not sum due to independent rounding.

Table 2-29: CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990	1995	1996	1997	1998	1999
Production Field Operations	**1,263**	**1,136**	**1,111**	**1,109**	**1,075**	**1,011**
Tank venting	564	493	485	484	466	433
Pneumatic device venting	559	507	491	490	475	447
Wellhead fugitives	24	25	25	24	24	24
Combustion & process upsets	46	45	45	46	45	44
Misc. venting & fugitives	70	66	65	65	64	63
Crude Oil Transportation	**7**	**6**	**6**	**6**	**6**	**6**
Refining	**25**	**25**	**26**	**27**	**27**	**27**
Total	**1,294**	**1,168**	**1,143**	**1,142**	**1,108**	**1,044**

Note: Totals may not sum due to independent rounding.

in engine exhausts and flares. The very slight increase in emissions from refining, relative to the decline in emissions from field production operations, is due to increasing imports of crude oil.

Methodology

The EPA's methodology for estimating methane emissions from petroleum systems is based on a comprehensive study of methane emissions from U.S. petroleum systems, *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report)* (EPA 1999). The study estimates emissions from 70 activities occurring in petroleum systems from the oil wellhead through crude oil refining, including 39 activities for crude oil production field operations, 11 for crude oil transportation activities, and 20 for refining operations. Annex G explains the emission estimates for these 70 activities in greater detail. The estimates of methane emissions from petroleum systems do not include emissions downstream from oil refineries because these emissions are very small compared to methane emissions upstream from oil refineries.

The methodology for estimating methane emissions from the 70 oil industry activities employs emission and activity factors initially developed in EPA (1999). The EPA estimates emissions for each activity by multiplying emission factors (e.g., emission rate per equipment item or per activity) by their corresponding activity factor (e.g., equipment count or frequency of activity). The report provides emission factors and activity factors for all activities except those related to offshore oil production. For offshore oil production, the EPA calculates an emission factor by dividing an emission estimate from the Minerals Management Service (MMS) by the number of platforms (the activity factor). Emission factors are held constant for the period 1990 through 1999.

The EPA collects activity factors for 1990 through 1999 from a wide variety of statistical resources. For some years, complete activity factor data are not available. In this case, the EPA employs one of three options. Where appropriate, the activity factor is assumed to be directly proportional to annual oil production. Proportionality constants are calculated by dividing the activity factor for 1995 by the annual oil production for 1995. The resulting proportionality constants are then multiplied by the annual oil production in years for which activity factors must be estimated. In other cases, the activity factor is kept constant from 1990 through 1999. Lastly, previous year data are used when current year data are not yet available. These data are subsequently updated in the next inventory cycle.

Data Sources

Nearly all emission factors were taken from earlier work performed by Radian International LLC (Radian 1996e). Other emission factors were taken from an American Petroleum Institute publication (API 1996), EPA default values, MMS reports (MMS 1995 and 1999), the Exploration and Production (E&P) Tank model (API and GRI), reports by the Canadian Association of Petroleum Producers (CAPP 1992 and 1993), and consensus of industry peer review panels.

The EPA uses many references to obtain activity factors. Among the more important references are the Energy Information Administration annual and monthly reports (EIA 1995, 1996, 1997, 1998), the API Basic Petroleum Data Book (API 1997 and 1999), *Methane Emissions from the Natural Gas Industry* prepared for the Gas Research Institute (GRI) and EPA (Radian 1996a-d), consensus of industry peer review panels, MMS reports (MMS 1995 and 1999), and the *Oil & Gas Journal* (OGJ 1998a,b). Annex G provides a complete list of references.

Uncertainty

The detailed, bottom-up analysis used to evaluate U.S. petroleum systems for the current Inventory reduces the uncertainty related to the methane emission estimates compared to previous estimates. However, a number of uncertainties remain. Published activity factors were not available every year for all 70 activities analyzed for petroleum systems. For example, there is uncertainty associated with the estimate of annual venting emissions in production field operations because a recent census of tanks and other tank battery equipment, such as separators and pneumatic devices, was not available. These uncertainties are important because storage tanks account for 41 percent of total 1999 methane emissions from petroleum systems. Uncertainties are also associated with emission factors because emission rates can vary highly from reservoir to reservoir and well to well. A single summary emission factor cannot reflect this variation. Since the majority of methane emissions occur during production field operations, where methane can first escape crude oil, a better understanding of tanks and tank equipment would reduce the uncertainty. Because of the dominance of crude storage tank venting and pneumatics, Table 2-30 provides emission estimate ranges for these sources. For tank venting, these ranges include numbers that are 25 percent higher than or lower than the given point estimates. For pneumatics, the range is between 33 percent lower than and 25 percent higher than the point estimates.

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

The flaring of natural gas from oil 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 volatile organic compounds (NMVOCs). This source accounts for only a small proportion of overall emissions of each of these gases. Emissions of CO_2, NO_x, and CO from petroleum and natural gas production activities were all less than 1 percent of national totals, while NMVOC emissions were roughly 2 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 may be vented, with the remaining 80 percent flared; however, it is now believed that flaring accounts for an even greater proportion, although some venting still occurs. Methane emissions from venting are accounted for under Petroleum Systems. For 1999, CO_2 emissions from flaring were estimated to be approximately 11.7 Tg CO_2 Eq. (11,701 Gg), an increase of 128 percent since 1990 (see Table 2-31).

Criteria pollutant emissions from oil and gas production, transportation, and storage, constituted a rela-

Table 2-30: Uncertainty in CH_4 Emissions from Production Field Operations (Gg)

Activity	1990	1995	1996	1997	1998	1999
Tank venting (point estimate)	**564**	**493**	**485**	**484**	**466**	**433**
Low	423	370	364	363	349	325
High	705	617	606	605	582	541
Pneumatic devices (point estimate)	**559**	**507**	**491**	**490**	**475**	**447**
Low	372	338	328	327	317	300
High	698	634	614	613	594	559

tively small and stable portion of the total emissions of these gases from the 1990 to 1999 (see Table 2-32).

Methodology

The estimates for CO_2 emissions were prepared using an emission factor of 54.71 Tg CO_2 Eq./QBtu of flared gas, and an assumed flaring efficiency of 100 percent. The quantity of flared gas was estimated as the total reported vented and flared gas minus the amount assumed to be vented annually, which varied from 65,772 million cubic feet in 1990 to 52,670 million cubic feet in 1999.[43]

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 in terms of total natural gas vented and flared for estimating CO_2 emissions from natural gas flaring were taken from EIA's *Natural Gas Annual* (EIA 2000). The emission and thermal conversion factors were also provided by EIA (see Table 2-33).

EPA (2000) 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.

Uncertainty

Uncertainties in CO_2 emission estimates primarily arise from assumptions concerning what proportion of natural gas is flared and the flaring efficiency. Uncertainties in criteria pollutant emission estimates are partly due to the accuracy of the emission factors used and projections of growth.

Table 2-31: CO_2 Emissions from Natural Gas Flaring

Year	Tg CO_2 Eq.	Gg
1990	5.1	5,121
1995	13.6	13,587
1996	13.0	12,998
1997	12.0	12,026
1998	10.8	10,839
1999	11.7	11,701

Table 2-32: NO_x, NMVOCs, and CO Emissions from Oil and Gas Activities (Gg)

Year	NO_x	CO	NMVOCs
1990	139	302	555
1995	100	316	582
1996	126	321	433
1997	130	333	442
1998	130	332	440
1999	130	332	385

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[43] See the methodological discussion under Petroleum Systems for the basis of the portion of natural gas assumed vented.

Table 2-33: Total Natural Gas Reported Vented and Flared (Million Ft^3) and Thermal Conversion Factor (Btu/Ft^3)

Year	Vented and Flared	Thermal Conversion Factor
1990	150,415	1,106
1991	169,909	1,108
1992	167,519	1,110
1993	226,743	1,106
1994	228,336	1,105
1995	283,739	1,106
1996	272,117	1,109
1997	256,351	1,107
1998	234,472	1,110
1999	245,180	1,111

International Bunker Fuels

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the United Nations Framework Convention on Climate Change (UNFCCC), are currently not included in national emission totals, but are reported separately based upon location of fuel sales. The decision to report emissions from international bunker fuels separately, instead of allocating them to a particular country, was made by the Intergovernmental Negotiating Committee in establishing the Framework Convention on Climate Change.[44] These decisions are reflected in the *Revised 1996 IPCC Guidelines*, in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC/UNEP/OECD/IEA 1997). The Parties to the UNFCCC have yet to decide on a methodology for allocating these emissions.[45]

Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), oxides of nitrogen (NO_x), nonmethane volatile organic compounds (NMVOCs), particulate matter, and sulfur dioxide (SO_2).[46] Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine. Emissions from ground transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

The IPCC Guidelines distinguish between different modes of air traffic. Civil aviation comprises aircraft used for the commercial transport of passengers and freight, military aviation comprises aircraft under the control of national armed forces, and general aviation applies to recreational and small corporate aircraft. The IPCC Guidelines further define international bunker fuel use from civil aviation as the fuel combusted for civil (e.g., commercial) aviation purposes by aircraft arriving or departing on international flight segments. However, as mentioned above, and in keeping with the IPCC Guidelines, only the fuel purchased in the United States and used by aircraft taking-off (i.e., departing) from the United States are reported here. The standard fuel used for civil aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[47]

Emissions of CO_2 from aircraft are essentially a function of fuel use. Methane, N_2O, CO, NO_x, and NMVOC emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Methane, CO, and NMVOCs are the product of incomplete combustion and occur mainly during the landing and take-off phases. In jet engines, N_2O and NO_x are primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase. The impact of NO_x on atmospheric

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[44] See report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the work of its ninth session, held at Geneva from 7 to 18 February 1994 (A/AC.237/55, annex I, para. 1c) (contact secretariat@unfccc.de).

[45] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International civil Aviation Organization.

[46] Sulfur dioxide emissions from jet aircraft and marine vessels, although not estimated here, are mainly determined by the sulfur content of the fuel. In the U.S., jet fuel, distillate diesel fuel, and residual fuel oil average sulfur contents of 0.05, 0.3, and 2.3 percent, respectively. These percentages are generally lower than global averages.

[47] Naphtha-type jet fuel is used primarily by the military in turbojet and turboprop aircraft engines.

chemistry depends on the altitude of the actual emission. The cruising altitude of supersonic aircraft, near or in the ozone layer, is higher than that of subsonic aircraft. At this higher altitude, NO_x emissions contribute to ozone depletion.[48] At the cruising altitudes of subsonic aircraft, however, NO_x emissions contribute to the formation of ozone. At these lower altitudes, the positive radiative forcing effect of ozone is most potent.[49] The vast majority of aircraft NO_x emissions occur at these lower cruising altitudes of commercial subsonic aircraft (NASA 1996).[50]

International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger carrying, military (i.e., Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going vessels: distillate diesel fuel and residual fuel oil. Carbon dioxide is the primary greenhouse gas emitted from marine shipping. In comparison to aviation, the atmospheric impacts of NO_x from shipping are relatively minor, as the emissions occur at ground level.

Overall, aggregate greenhouse gas emissions in 1999 from the combustion of international bunker fuels from both aviation and marine activities were 108.3 Tg CO_2 Eq., or 6 percent below emissions in 1990 (see Table 2-34). Although emissions from international flights departing from the United States have increased significantly (30 percent), emissions from international shipping voyages departing the United States appear to have decreased by 31 percent since 1990. Increased military activity during the Persian Gulf War resulted in an increased level of military marine emissions in 1990 and 1991; civilian marine emissions during this period exhibited a similar trend.[51] The majority of these emissions were in the form of carbon dioxide; however, small amounts of CH_4 and N_2O were also emitted. Of the criteria pollutants, emissions of NO_x by aircraft at cruising altitudes are of primary concern because of their effects on ozone formation (see Table 2-35).

Emissions from both aviation and marine international transport activities are expected to grow in the future as both air traffic and trade increase, although emission rates should decrease over time due to technological changes.[52]

Methodology

Emissions of CO_2 were estimated through the application of carbon content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under CO_2 from Fossil Fuel Combustion. A complete description of the methodology and a listing of the various factors employed can be found in Annex A. See Annex H for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4, N_2O, CO, NO_x, and NMVOCs were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Data Sources

Carbon content and fraction oxidized factors for kerosene-type and naphtha-type jet fuel, distillate fuel oil, and residual fuel oil were taken directly from the Energy Information Administration (EIA) of the U.S. Department of Energy and are presented in Annex A. Heat content and density conversions were taken from EIA (2000) and USAF (1998). Emission factors used in the

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[48] In 1996, there were only around a dozen civilian supersonic aircraft in service around the world which flew at these altitudes, however.

[49] However, at this lower altitude, ozone does little to shield the earth from ultraviolet radiation.

[50] Cruise altitudes for civilian subsonic aircraft generally range from 8.2 to 12.5 km (27,000 to 41,000 feet).

[51] See Uncertainty section for a discussion of data quality issues.

[52] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

Table 2-34: Emissions from International Bunker Fuels (Tg CO_2 Eq.)

Gas/Mode	1990	1995	1996	1997	1998	1999
CO_2	**114.0**	**101.0**	**102.2**	**109.8**	**112.8**	**107.3**
Aviation	46.7	51.1	52.1	55.9	55.0	61.0
Marine	67.3	49.9	50.1	53.9	57.8	46.4
CH_4	+	+	+	+	+	+
Aviation	+	+	+	+	+	+
Marine	+	+	+	+	+	+
N_2O	**1.0**	**0.9**	**0.9**	**1.0**	**1.0**	**1.0**
Aviation	0.5	0.5	0.5	0.5	0.5	0.6
Marine	0.5	0.4	0.4	0.4	0.4	0.4
Total	**115.0**	**101.9**	**103.1**	**110.8**	**113.8**	**108.3**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 2-35: Emissions from International Bunker Fuels (Gg)

Gas/Mode	1990	1995	1996	1997	1998	1999
CO_2	**114,001**	**101,014**	**102,197**	**109,788**	**112,771**	**107,345**
Aviation	46,728	51,093	52,135	55,899	54,988	60,970
Marine	67,272	49,921	50,062	53,889	57,783	46,376
CH_4	**2**	**2**	**2**	**2**	**2**	**2**
Aviation	1	1	1	2	2	2
Marine	1	0	0	0	1	0
N_2O	**3**	**3**	**3**	**3**	**3**	**3**
Aviation	1	2	2	2	2	2
Marine	2	1	1	1	1	1
CO	**116**	**113**	**115**	**124**	**124**	**128**
Aviation	77	84	86	92	91	100
Marine	39	29	29	32	34	27
NO_x	**1,987**	**1,541**	**1,548**	**1,665**	**1,768**	**1,485**
Aviation	184	202	207	221	218	242
Marine	1,803	1,339	1,341	1,444	1,550	1,243
NMVOC	**59**	**48**	**49**	**52**	**55**	**48**
Aviation	12	13	13	14	14	15
Marine	48	36	36	38	41	33

Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

calculations of CH_4, N_2O, CO, NO_x, and NMVOC emissions were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). For aircraft emissions, the following values, in units of grams of pollutant per kilogram of fuel consumed (g/kg), were employed: 0.09 for CH_4, 0.1 for N_2O, 5.2 for CO, 12.5 for NO_x, and 0.78 for NMVOCs. For marine vessels consuming either distillate diesel or residual fuel oil the following values, in the same units, except where noted, were employed: 0.03 for CH_4, 0.08 for N_2O, 1.9 for CO, 87 for NO_x, and 0.052 g/MJ for NMVOCs.

Activity data on aircraft fuel consumption were collected from three government agencies. Jet fuel consumed by U.S. flag air carriers for international flight segments was supplied by the Bureau of Transportation Statistics (DOT/BTS 2000). It was assumed that 50 percent of the fuel used by U.S. flagged carriers for international flights—both departing and arriving in the United States—was purchased domestically for flights departing from the United States. In other words, only one-half of the total annual fuel consumption estimate was used in the calculations. Data on jet fuel expenditures by foreign flagged carriers departing U.S. airports was taken from unpublished data collected by the Bureau of Economic Analysis (BEA) under the U.S. Department of Commerce (BEA 2000). Approximate average fuel prices paid by air carriers for aircraft on international flights was taken from DOT/BTS (2000) and used to convert the BEA expenditure data to gallons of fuel consumed. Data on jet fuel expenditures by the U.S. military was supplied by the Office of the Under Secretary of Defense (Environmental Security), U.S. Department of Defense (DoD). Estimates of the percentage of each services' total operations that were international operations were developed by DoD. Military aviation bunkers included international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Data on fuel delivered to the military within the United States was provided from unpublished data by the Defense Energy Support Center, under DoD's Defense Logistics Agency (DESC 2000). Together, the data allow the quantity of fuel used in military international operations to be estimated. Jet fuel densities for each fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 2-36. See Annex H for additional discussion of military data.

Activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were taken from unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 2000). Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by the Defense Energy Support Center (DESC). The total amount of fuel provided to naval vessels was reduced by 13 percent to account for fuel used while the vessels were not-underway (i.e., in port). Data on the percentage of steaming hours underway versus not-underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 2-37.

Uncertainty

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[53] For example, smaller aircraft on shorter routes often carry sufficient fuel to complete several flight segments without refueling in order to minimize time spent at the airport gate or take advantage of lower fuel prices at particular airports. This practice, called tankering, when done on international flights, complicates the use of fuel sales data for estimating bunker fuel emissions. Tankering is less common with the type of large, long-range aircraft that make many international flights from the United States, however. Similar practices occur in the marine shipping industry where fuel costs represent a significant portion of overall operating costs and fuel prices vary from port to port, leading to some tankering from ports with low fuel costs.

Particularly for aviation, the DOT/BTS (2000) international flight segment fuel data used for U.S. flagged carriers does not include smaller air carriers and unfortunately defines flights departing to Canada and some flights to Mexico as domestic instead of international. As

Table 2-36: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990	1995	1996	1997	1998	1999
U.S. Carriers	1,982	2,256	2,329	2,482	2,363	2,638
Foreign Carriers	2,062	2,549	2,629	2,918	2,935	3,305
U.S. Military	862	581	540	496	502	488
Total	**4,905**	**5,385**	**5,497**	**5,895**	**5,799**	**6,431**

Note: Totals may not sum due to independent rounding.

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[53] See uncertainty discussions under CO_2 from Fossil Fuel Combustion and Mobile Combustion.

Table 2-37: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	1995	1996	1997	1998	1999
Residual Fuel Oil	4,781	3,495	3,583	3,843	3,974	3,272
Distillate Diesel Fuel & Other	617	573	456	421	627	308
U.S. Military Naval Fuels	522	334	362	477	506	506
Total	**5,920**	**4,402**	**4,402**	**4,740**	**5,107**	**4,085**

Note: Totals may not sum due to independent rounding.

for the BEA (2000) data on foreign flagged carriers, there is some uncertainty as to the average fuel price, and to the completeness of the data. It was also not possible to determine what portion of fuel purchased by foreign carriers at U.S. airports was actually used on domestic flight segments; this error, however, is believed to be small.[54]

Uncertainties exist with regard to the total fuel used by military aircraft and ships, and in the activity data on military operations and training that were used to estimate percentages of total fuel use reported as bunker fuel emissions. There are also uncertainties in fuel end-use consumption by fuel-type, emissions factors, fuel densities, diesel fuel sulfur content, and aircraft and vessel engine characteristics and fuel efficiencies.

Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the Navy and Air Force from the Defense Logistics Agency. This data may slightly over or under estimate actual total fuel use in aircraft and ships because each service may have procured fuel from, and/or may have sold to, traded with, and/or given fuel to other ships, aircraft, governments, or other entities. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type.

There are uncertainties in aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities reported as bunker fuel emissions had to be estimated based on a combination of available data and expert judgements.

Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data which reports fuel used while underway and fuel used while not underway; however, this approach does not capture some voyages which could be classified as domestic.

There is also uncertainty in the methodology used to estimate emissions for 1990 through 1994. These emissions were estimated based on the 1995 values of the original data set and extrapolated back in time based on a closely correlating, but not matching, data set of fuel usage.

The magnitude of the potential errors related to the various uncertainties has not been calculated, but is believed to be small. The uncertainties associated with future military bunker fuel emissions estimates could be reduced through additional data collection.

Although aggregate fuel consumption data has been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO_2 in the *Revised 1996 IPCC Guidelines* is to use data by specific aircraft type (IPCC/UNEP/OECD/IEA 1997). The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[55] The EPA is developing revised esti-

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[54] Although foreign flagged air carriers are prevented from providing domestic flight services in the United States, passengers may be collected from multiple airports before an aircraft actually departs on its international flight segment. Emissions from these earlier domestic flight segments should be classified as domestic, not international, according to the IPCC.

[55] It should be noted that in the EPA's *National Air Pollutant Emissions Trends*, 1900-1999 (EPA 2000), U.S. aviation emission estimates for CO, NOx, and NMVOCs are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates given under Mobile Source Fossil Fuel Combustion overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes. EPA (1998) is also likely to include emissions from ocean-going vessels departing from U.S. ports on international voyages.

mates based on this more detailed activity data, and these estimates are to be presented in future inventories.

There is also concern as to the reliability of the existing DOC (2000) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

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 uptake of CO_2 resulting from 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 U.S. totals. Net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands are accounted for in the Land-Use Change and Forestry chapter.

In 1999, CO_2 emissions due to burning of woody biomass within the industrial and residential/commercial sectors and by electric utilities were about 226.3 Tg CO_2 Eq. (226 Gg) (see Table 2-38 and Table 2-39). As the largest consumer of woody biomass, the industrial sector in 1999 was responsible for 83 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, making up 14 percent of total emissions from woody biomass. The commercial end-use sector and electric utilities accounted for the remainder.

Biomass-derived fuel consumption in the United States consisted mainly of ethanol use in the transportation sector. Ethanol is primarily produced from corn grown in the Midwest, and was used mostly 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.

Table 2-38: CO_2 Emissions from Wood Consumption by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990		1995	1996	1997	1998	1999
Industrial	124.8		141.5	144.9	148.6	153.0	188.9
Residential	46.4		47.6	47.5	34.6	30.1	32.3
Commercial	3.0		3.6	3.9	3.8	3.7	4.5
Electric Utility	0.7		0.5	0.7	0.6	0.6	0.6
Total	**174.9**		**193.2**	**197.0**	**187.6**	**187.4**	**226.3**

Note: Totals may not sum due to independent rounding.

Table 2-39: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	1990		1995	1996	1997	1998	1999
Industrial	124,808		141,505	144,881	148,624	152,966	188,915
Residential	46,424		47,622	47,542	34,598	30,123	32,281
Commercial	2,956		3,596	3,899	3,752	3,749	4,526
Electric Utility	673		522	651	612	595	566
Total	**174,862**		**193,245**	**196,973**	**187,585**	**187,433**	**226,287**

Note: Totals may not sum due to independent rounding.

In 1999, the United States consumed an estimated 112 trillion Btus of ethanol. Emissions of CO_2 in 1999 due to ethanol fuel burning were estimated to be approximately 7.8 Tg CO_2 Eq. (7,776 Gg) (see Table 2-40).

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 1997). Production in 1998 and 1999 returned to normal historic levels.

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.

Table 2-40: CO_2 Emissions from Ethanol Consumption

Year	Tg CO_2 Eq.	Gg
1990	5.7	5,701
1995	7.2	7,244
1996	5.1	5,144
1997	6.7	6,731
1998	7.3	7,329
1999	7.8	7,776

Table 2-41: Woody Biomass Consumption by Sector (Trillion Btu)

Year	Industrial	Residential	Commercial	Electric Utility
1990	1,562	581	37	8
1991	1,528	613	39	8
1992	1,593	645	42	8
1993	1,625	548	44	9
1994	1,724	537	45	8
1995	1,771	596	45	7
1996	1,813	595	49	8
1997	1,860	433	47	8
1998	1,914	377	47	7
1999	2,364	404	57	7

Data Sources

Woody biomass consumption data were provided by EIA (2000) (see Table 2-41). Estimates of wood biomass consumption for fuel combustion do not include wood wastes, liquors, municipal solid waste, tires, etc. that are reported as biomass by EIA. 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).

Emissions from ethanol were estimated using consumption data from EIA (2000) (see Table 2-42). The carbon coefficient used was provided by OTA (1991).

Uncertainty

The fraction oxidized (i.e., 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.

Table 2-42: Ethanol Consumption

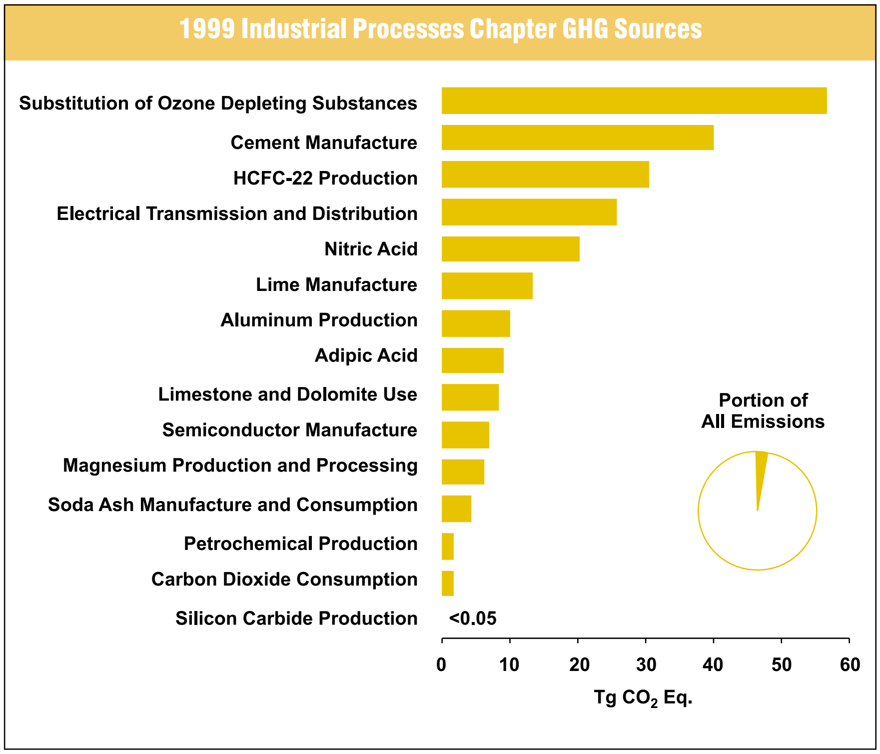
Year	Trillion Btu
1990	82
1991	65
1992	78
1993	88
1994	97
1995	104
1996	74
1997	97
1998	105
1999	112

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 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 can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), or 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 consumption, iron and steel production, ammonia manufacture, ferroalloy production, aluminum production, petrochemical production, 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 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

Figure 3-1



1999 Industrial Processes Chapter GHG Sources

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[1] Carbon dioxide emissions from iron and steel production, ammonia manufacture, ferroalloy production, and aluminum production are accounted for in the Energy chapter under Fossil Fuel Combustion of industrial coking coal, natural gas, and petroleum coke.

primary substitutes for ozone depleting substances (ODSs), 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.

In 1999, industrial processes generated emissions of 234.0 Tg CO_2 Eq., or 3.5 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 67.4 Tg CO_2 Eq. (67,401 Gg) in the same year. This amount accounted for only 1.2 percent of national CO_2 emissions. Methane emissions from petrochemical and silicon carbide production resulted in emissions of approximately 1.7 Tg CO_2 Eq. (80 Gg) in 1999, which was less than 1 percent of U.S. CH_4 emissions. Nitrous oxide emissions from adipic acid and nitric acid production were 29.2 Tg CO_2 Eq. (94 Gg) in 1999, or 6.8 percent of total U.S. N_2O emissions. In the same year, combined emissions of HFCs, PFCs and SF_6 totaled 135.7 Tg CO_2 Eq. Overall, emissions from industrial processes increased by 33 percent from 1990 to 1999, which was the result of increases in emissions from several industrial processes—the largest being substitutes for ozone depleting substances—which was offset by decreases in emissions from adipic acid production, aluminum production, and production of HCFC-22.

Emission estimates are presented in this chapter for several industrial processes that are actually accounted for within the Energy chapter. Although process-related 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 chapter, then emissions from energy would decrease by approximately 105.0 Tg CO_2 Eq. in 1999, 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 chapter. 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), involves 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 for the Industrial Processes chapter in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.), while unweighted gas emissions in gigagrams (Gg) are provided in Table 3-2.

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

Table 3-1: Emissions from Industrial Processes (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999
CO_2	**54.6**	**61.9**	**63.3**	**66.1**	**67.0**	**67.4**
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	39.9
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.4
Limestone and Dolomite Use	5.1	7.0	7.3	8.3	8.1	8.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.3	4.4	4.3	4.2
Carbon Dioxide Consumption	0.8	1.0	1.1	1.3	1.4	1.6
Iron and Steel Production*	87.6	81.4	79.0	79.4	77.1	71.8
Ammonia Manufacture*	23.1	23.7	24.4	24.3	25.1	25.8
Ferroalloy Production*	1.8	1.6	1.7	1.8	1.8	1.8
Aluminum Production*	6.0	5.0	5.3	5.3	5.5	5.6
CH_4	**1.2**	**1.5**	**1.6**	**1.6**	**1.6**	**1.7**
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7
Silicon Carbide Production	+	+	+	+	+	+
N_2O	**36.1**	**40.2**	**41.5**	**38.3**	**28.1**	**29.2**
Nitric Acid Production	17.8	19.9	20.7	21.2	20.9	20.2
Adipic Acid Production	18.3	20.3	20.8	17.1	7.3	9.0
HFCs, PFCs, and SF_6	**83.9**	**99.0**	**115.1**	**123.3**	**138.6**	**135.7**
Substitution of Ozone Depleting Substances	0.9	24.0	34.0	42.1	49.6	56.7
HCFC-22 Production	34.8	27.1	31.2	30.1	40.0	30.4
Electrical Transmission and Distribution	20.5	25.7	25.7	25.7	25.7	25.7
Aluminum Production	19.3	11.2	11.6	10.8	10.1	10.0
Semiconductor Manufacture	2.9	5.5	7.0	7.0	6.8	6.8
Magnesium Production and Processing	5.5	5.5	5.6	7.5	6.3	6.1
Total	**175.8**	**202.7**	**221.5**	**229.3**	**235.3**	**234.0**

+ Does not exceed 0.05 Tg CO_2 Eq.
* Emissions from these sources are accounted for in the Energy chapter and are not included in the Industrial Processes totals.
Note: Totals may not sum due to independent rounding.

Cement Manufacture

Cement manufacture is an energy and raw material intensive process resulting in the generation of carbon dioxide (CO_2) from both the energy consumed in making the cement and the chemical process itself.[3] Cement production has accounted for about 2.4 percent of total global industrial and energy-related CO_2 emissions (IPCC 1996), and the United States is the world's third largest cement producer. Cement is manufactured 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 largest sources of industrial CO_2 emissions in the United States.

During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature of about 1,300°C (2,400°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 earlier 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 cement. The production of masonry cement from Portland cement requires additional lime and, thus, results in additional CO_2 emissions. However, this additional lime is already accounted for in the Lime Manufacture source category in this chapter; therefore, the additional emissions from making masonry cement from clinker are not counted in this source category's total. They are presented here for informational purposes only.

In 1999, U.S. clinker production—including Puerto Rico—totaled 77,152 thousand metric tons, and U.S. masonry cement production was estimated to be 4,127 thousand metric tons (USGS 2000). The resulting emissions of

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[3] The CO_2 emissions related to the consumption of energy for cement manufacture are accounted for under CO_2 from Fossil Fuel Combustion in the Energy chapter.

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

Gas/Source	1990	1995	1996	1997	1998	1999
CO_2	**54,577**	**61,917**	**63,293**	**66,063**	**66,984**	**67,401**
Cement Manufacture	33,278	36,847	37,079	38,323	39,218	39,896
Lime Manufacture	11,238	12,805	13,495	13,685	13,914	13,426
Limestone and Dolomite Use	5,117	6,987	7,305	8,327	8,114	8,290
Soda Ash Manufacture and Consumption	4,144	4,309	4,273	4,434	4,325	4,217
Carbon Dioxide Consumption	800	968	1,140	1,294	1,413	1,572
Iron and Steel Production[a]	87,600	81,440	79,040	79,360	77,120	71,840
Ammonia Manufacture[a]	23,138	23,682	24,390	24,346	25,141	25,799
Ferroalloy Production[a]	1,809	1,625	1,695	1,789	1,793	1,771
Aluminum Production[a]	5,951	4,961	5,258	5,296	5,458	5,555
CH_4	**57**	**72**	**76**	**77**	**78**	**80**
Petrochemical Production	56	72	75	77	77	79
Silicon Carbide Production	1	1	1	1	1	1
N_2O	**117**	**130**	**134**	**124**	**91**	**94**
Nitric Acid Production	58	64	67	68	67	65
Adipic Acid Production	59	66	67	55	23	29
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**
HCFC-22 Production[b]	3	2	3	3	3	3
Electrical Transmission and Distribution[c]	1	1	1	1	1	1
Substitution of Ozone Depleting Substances	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M
Semiconductor Manufacture	M	M	M	M	M	M
Magnesium Production and Processing[c]	+	+	+	+	+	+

+ Does not exceed 0.5 Gg

M (Mixture of gases)

[a] Emissions from these sources are accounted for in the Energy chapter 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.

CO_2 from clinker production were estimated to be 39.9 Tg CO_2 Eq. (39,896 Gg) (see Table 3-3). Emissions from masonry production from clinker raw material were estimated to be 0.09 Tg CO_2 Eq. (93 Gg) in 1999, but again 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 1999, emissions increased by 20 percent. In 1999, output by cement plants increased 2 percent over 1998, to 77,152 thousand metric tons. Cement is a critical component of the construction industry; therefore, the availability of public construction funding, as well as overall economic growth, have had considerable influence on cement production.

Table 3-3: CO_2 Emissions from Cement Production*

Year	Tg CO_2 Eq.	Gg
1990	33.3	33,278
1995	36.8	36,847
1996	37.1	37,079
1997	38.3	38,323
1998	39.2	39,218
1999	39.9	39,896

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

Methodology

Carbon dioxide emissions from cement manufacture 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 2000) and a constant reflecting the mass of CO_2 released per unit of lime. This calculation yields an emission factor of 0.507 tons of CO_2 per ton of clinker produced, which was determined as follows:

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

During clinker production, some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker emission factor. The IPCC recommends that these additional CKD CO_2 emissions should be estimated as 2 percent of the CO_2 emissions calculated from clinker production. Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2000).

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 are 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 clinker and masonry cement production (see Table 3-4) were obtained from U.S. Geological Survey (USGS 1992, 1995a, 1995b, 1996, 1997, 1998, 1999, 2000). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants. The 1999 value for masonry cement production was calculated by applying the average annual growth rate for 1995 through 1998 to the reported 1998 masonry cement production value.

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker, in the amount of lime added to masonry cement, and in the percentage of CKD recycled inside the clinker kiln. The lime content of clinker varies from 64 to 66 percent. CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some amount of CO_2 is

Table 3-4: Cement Production (Gg)

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	71,706	3,469
1997	74,112	3,634
1998	75,842	3,989
1999	77,152	4,127

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. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated.

Lime Manufacture

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Its major uses are in steel making, flue gas desulfurization (FGD) at coal-fired electric power plants, construction, pulp and paper manufacturing, and water purification. Lime has historically ranked fifth in total production of all chemicals in the United States. For U.S. operations, the term "lime" actually refers to a variety of chemical compounds. These include calcium oxide (CaO), or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

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. The CO_2 is driven off as a gas and is normally emitted to the atmosphere. Some of the CO_2 generated during the production process, however, is recovered at some facilities for use in sugar refining and precipitated calcium carbonate (PCC)[4] production. It is also important to note that, for certain applications, lime reabsorbs CO_2 during use (see Uncertainty, below).

Lime production in the United States—including Puerto Rico—was reported to be 19,618 thousand metric tons in 1999 (USGS 2000). This resulted in estimated CO_2 emissions of 13.4 Tg CO_2 Eq. (13,426 Gg) (see Table 3-5 and Table 3-6).

At the turn of the century, over 80 percent of lime consumed in the United States went for construction uses. The contemporary quicklime market is distributed across its four end-use categories as follows: metallurgical uses, 39 percent; chemical and industrial uses, 26 percent; environmental uses, 24 percent; and construction uses, 11 percent. Construction end-uses are still important to the hydrated lime market, accounting for 54 percent of consumption. However, hydrated lime constitutes only 10 percent of the total lime market.

Lime production in 1999 declined 2 percent from 1998, the first drop in annual production since 1991. Overall, from 1990 to 1999, lime production increased by 24 percent. The increase in production is attributed in part to growth in demand for environmental applications, especially flue gas desulfurization technologies. In 1993,

Table 3-5: Net CO_2 Emissions from Lime Manufacture

Year	Tg CO_2 Eq.
1990	11.2
1995	12.8
1996	13.5
1997	13.7
1998	13.9
1999	13.4

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

Year	Potential	Recovered*	Net Emissions
1990	11,731	(493)	11,238
1995	13,702	(896)	12,805
1996	14,348	(852)	13,495
1997	14,649	(964)	13,685
1998	14,975	(1,061)	13,914
1999	14,609	(1,183)	13,426

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

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[4] Precipitated calcium carbonate is a specialty filler used in premium-quality coated and uncoated papers.

the U.S. Environmental Protection Agency (EPA) completed regulations under the Clean Air Act capping sulfur dioxide (SO_2) emissions from electric utilities. Lime scrubbers' high efficiencies and increasing affordability have allowed the FGD end-use to expand from 10 percent of total lime consumption in 1990 to 14 percent in 1999 (USGS 1992, 2000).

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. To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors. The emission factor is the product of a constant reflecting the mass of CO_2 released per unit of lime and the average calcium plus magnesium oxide (CaO + MgO) content for lime (95 percent for both types of lime). The emission factors were calculated as follows:

For high-calcium lime: $[(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.75 \text{ g } CO_2\text{/g lime}$

For dolomitic lime: $[(88.02 \text{ g/mole } CO_2) \div (97.01 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.86 \text{ g } CO_2\text{/g lime}$

Production is adjusted to remove the mass of water found in hydrated lime, using the midpoint of default ranges provided by the *IPCC Good Practice Guidance* (IPCC 2000). These factors set the water content to 27 percent for high-calcium hydrated lime, and 24 percent for dolomitic hydrated lime.

Lime production in the United States was 19,618 thousand metric tons in 1999 (USGS 2000), resulting in potential CO_2 emissions of 14,609 Gg. 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 1,983 thousand metric tons in 1999, generating 1.5 Tg of CO_2. It was assumed that approximately 80 percent of the CO_2 involved in sugar refining and PCC was recovered.

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 obtained from USGS (1992, 1994, 1995, 1996, 1997, 1998, 1999, 2000). The CaO and CaO•MgO contents of lime were obtained from the *IPCC Good Practice Guidance* (IPCC 2000). Since data for the individual lime types was not provided prior to 1997, total lime production for 1990 through 1996 was allocated according to the 1997 distribution. For lime consumption, it was assumed that 100 percent was high-calcium based on communication with the National Lime Association (Males 2001).

Uncertainty

Uncertainties in the emission estimate can be attributed to slight differences in the chemical composition of these products. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide,

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

Year	High-Calcium Production[a]	Dolomite Production[a,b]	Use
1990	12,941	2,901	826
1991	12,833	2,845	964
1992	13,300	2,932	1,023
1993	13,734	3,031	1,279
1994	14,268	3,122	1,374
1995	15,185	3,313	1,503
1996	15,849	3,441	1,429
1997	16,120	3,552	1,616
1998	16,750	3,423	1,779
1999	16,010	3,608	1,983

[a] Includes hydrated limes.
[b] Includes dead-burned dolomite

Table 3-8: Hydrated Lime Production (Thousand Metric Tons)

Year	High-Calcium Hydrate	Dolomitic Hydrate
1990	1,777	323
1991	1,836	334
1992	1,887	343
1993	1,904	346
1994	1,938	352
1995	2,023	367
1996	1,853	337
1997	1,820	352
1998	1,950	383
1999	1,910	298

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. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate (PCC) reacts with CO_2; whereas most of the lime used in steelmaking reacts with impurities such as silica, sulfur, and aluminum compounds. 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.[5] 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.[6] The lime generated by these processes is not included in the USGS data for commercial lime consumption. In the paper industry, mills that 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 ($CaCO_3MgCO_3$)[7] 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 industrial applications. For some of these applications, limestone is sufficiently heated during the process to generate CO_2 as a by-product. Examples of such applications include limestone 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.

In 1999, approximately 16,568 thousand metric tons of limestone and 2,068 thousand metric tons of dolomite were used for these applications. Overall, both limestone and dolomite usage resulted in aggregate CO_2 emissions of 8.3 Tg CO_2 Eq. (8,290 Gg) (see Table 3-9 and Table 3-10).

Emissions in 1999 increased 2 percent from the previous year and 62 percent since 1990. In the future, increases in demand for crushed stone are anticipated. Demand for crushed stone from the transportation sector continues to drive growth in limestone and dolomite use. The Transportation Equity Act for the 21st Century, which commits over $200 billion dollars to highway work through 2003, is expected to maintain the upward trend in consumption.

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[5] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime offsets as much as a third of the CO_2 emissions from calcination.

[6] Some carbide producers may also regenerate lime from their calcium hydroxide by-products, which does not result in emissions 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 [$Ca(OH)_2$ + heat $\rightarrow CaO + H_2O$] and no CO_2 is released to the atmosphere.

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

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

Activity	1990	1995	1996	1997	1998	1999
Flux Stone	3.0	3.9	4.2	5.0	5.1	5.3
Glass Making	0.2	0.5	0.4	0.4	0.2	0.2
FGD	1.9	2.6	2.7	2.9	2.8	2.8
Total	**5.1**	**7.0**	**7.3**	**8.3**	**8.1**	**8.3**

Note: Totals may not sum due to independent rounding.

Table 3-10: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Activity	1990	1995	1996	1997	1998	1999
Flux Stone	**3,005**	**3,903**	**4,249**	**5,042**	**5,142**	**5,312**
Limestone	2,554	2,523	3,330	3,970	4,298	4,441
Dolomite	452	1,380	919	1,072	844	871
Glass Making	**189**	**526**	**362**	**383**	**191**	**197**
Limestone	189	421	251	266	65	67
Dolomite	NA	105	110	117	125	129
FGD	**1,922**	**2,558**	**2,695**	**2,902**	**2,781**	**2,781**
Total	**5,117**	**6,987**	**7,305**	**8,327**	**8,114**	**8,290**

NA (Not Available)

Note: Totals may not sum due to independent rounding.

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 oxidized and released to 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 1999 of limestone and dolomite used as flux stone and in glass manufacturing (see Table 3-11) were obtained from the USGS (1993, 1995a, 1995b, 1996, 1997, 1998, 1999, 2000). Consumption data for limestone used in FGD were taken from unpublished survey data in the Energy Information Administration's Form EIA-767, "Steam Electric Plant Operation and Design Report" (EIA 1997, 1998, 1999). For 1990 and 1994, the USGS did not provide a breakdown of limestone and dolomite production by end-use and for

Table 3-11: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Flux Stone	**6,737**	**6,052**	**5,185**	**4,263**	**5,487**	**8,586**	**9,468**	**11,239**	**11,512**	**11,893**
Limestone	5,804	5,213	4,447	3,631	3,149	5,734	7,569	9,024	9,769	10,093
Dolomite	933	838	738	632	2,339	2,852	1,899	2,215	1,743	1,801
Glass Making	**430**	**386**	**495**	**622**	**949**	**1,174**	**799**	**847**	**407**	**421**
Limestone	430	386	495	622	949	958	571	605	148	153
Dolomite	NA	NA	NA	NA	NA	216	228	242	259	267
FGD	**4,369**	**4,606**	**4,479**	**4,274**	**5,080**	**5,815**	**6,125**	**6,595**	**6,322**	**6,322**

NA (Not Available)

1999 the end-use breakdowns had not yet been finalized at the time of publication. Consumption figures for these years were estimated by assuming that limestone and dolomite accounted for the same percentage of total crushed stone consumption for a given year as the average of the percentages for the years before and after.[8] Furthermore, following 1996, limestone used in glass manufacture has only been reported for 1998. For 1996 and 1997, limestone used in glass manufacture was estimated based on the percent of total crushed stone for 1995 and 1998.

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-use's fraction of total consumption in that year.[9]

Uncertainty

Uncertainties in this estimate are due in part 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. Also, some of the limestone reported as "limestone" is believed to actually be dolomite, which has a higher carbon content than limestone. Lastly, the uncertainty of the estimates for limestone used in glass making are especially high. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey respondees. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. However, since glass making accounts for no more than 10 percent of limestone consumption, its contribution to the overall emissions estimate is low.

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.[10] 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 may also be released when soda ash is consumed.

In 1999, CO_2 emissions from the manufacture of soda ash from trona were approximately 1.5 Tg CO_2 Eq.

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[8] Exception: 1990 and 1999 consumption were estimated using the percentages for only 1991 and 1998, respectively.

[9] This approach was recommended by USGS.

[10] 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 then precipitates from the brine solution. 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 not emitted.

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

Year	Tg CO_2 Eq.
1990	4.1
1996	4.3
1997	4.4
1998	4.3
1999	4.2

Table 3-13: CO_2 Emissions from Soda Ash Manufacture and Consumption (Gg)

Year	Manufacture	Consumption	Total
1990	1,435	2,709	4,144
1995	1,607	2,702	4,309
1996	1,587	2,685	4,273
1997	1,666	2,768	4,434
1998	1,607	2,718	4,325
1999	1,549	2,668	4,217

Note: Totals may not sum due to independent rounding.

(1,549 Gg). Soda ash consumption in the United States also generated 2.7 Tg CO_2 Eq. (2,668 Gg) in 1999. Total emissions from this source in 1999 were then 4.2 Tg CO_2 Eq. (4,217 Gg) (see Table 3-12 and Table 3-13). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 1999 decreased by 3 percent from the previous year, but have increased 2 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 1999 was glass making, 51 percent; chemical production, 26 percent; soap and detergent manufacturing, 11 percent; distributors, 5 percent; flue gas desulfurization, pulp and paper production, and water treatment, 2 percent each; and miscellaneous constituted for the remaining 1 percent (USGS 2000).

Soda ash production and consumption decreased by 4 and 2 percent from 1998 values, respectively. Exports were a driving force behind U.S. soda ash production and the Asian economic crisis beginning in late 1997 has been cited as a major cause for the drop in world soda ash demand. However, growing demand in Asia and South America is expected to lead to moderate growth (between 0.5 and 1 percent) in U.S. soda ash production.

Construction is currently underway on a major soda ash plant that will use a new feedstock—nahcolite, a natural sodium bicarbonate found in deposits in Colorado's Piceance Creek Basin. The new facility will have an annual capacity of 900,000 tons of soda ash and is slated to open in January 2001 (USGS 2000). Part of this production process involves the stripping of CO_2. At this point, however, it is unknown whether any CO_2 will be released to the atmosphere or captured and used for conversion back to sodium bicarbonate.

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 by-products of the calcination process. Carbon dioxide emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$\underset{\text{[trona]}}{2(\mathrm{Na_3H(CO_3)_2} \times 2\mathrm{H_2O})} \rightarrow \underset{\text{[soda ash]}}{3\mathrm{Na_2CO_3}} + 5\mathrm{H_2O} + \mathrm{CO_2}$$

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2. Thus, the 15.9 million metric tons of trona mined in 1999 for soda ash production (USGS 2000) resulted in CO_2 emissions of approximately 1.5 Tg CO_2 Eq. (1,549 Gg).

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 consumed 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.

Data Sources

The activity data for trona production and soda ash consumption (see Table 3-14) were taken from USGS (1994, 1995, 1996, 1997, 1998, 1999, 2000). Soda ash manufacture and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. All six of the soda ash manufacturing operations in the United States completed surveys to provide data to the USGS.

Uncertainty

Emissions from soda ash manufacture are considered to be relatively certain. Both the emissions factor and activity data are reliable. However, emissions from soda ash consumption are dependent upon the type of processing employed by each end-use. Specific information characterizing the emissions from each end-use is limited. Therefore, uncertainty exists as to the accuracy of the emission factors.

Carbon Dioxide Consumption

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.[11] For the most part, however, CO_2 used in non-EOR applications will eventually be released to 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 primarily manufactured using natural gas as a feedstock. Carbon dioxide emissions from this process are accounted for in the Energy chapter under Fossil Fuel Combustion and, therefore, are not included here.

In 1999, CO_2 emissions from this source not accounted for elsewhere were 1.6 Tg CO_2 Eq. (1,572 Gg) (see Table 3-15). This amount represents an increase of 11 percent from the previous year and is 97 percent higher than emissions in 1990.

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 re-

Table 3-14: Soda Ash Manufacture and Consumption (Thousand Metric Tons)

Year	Manufacture*	Consumption
1990	14,734	6,527
1991	14,674	6,278
1992	14,900	6,360
1993	14,500	6,350
1994	14,600	6,240
1995	16,500	6,510
1996	16,300	6,470
1997	17,100	6,670
1998	16,500	6,550
1999	15,900	6,430

* Soda ash manufactured from trona ore only.

Table 3-15: CO_2 Emissions from Carbon Dioxide Consumption

Year	Tg CO_2 Eq.	Gg
1990	0.8	800
1995	1.0	968
1996	1.1	1,140
1997	1.3	1,294
1998	1.4	1,413
1999	1.6	1,572

* Soda ash manufactured from trona ore only.

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[11] It is unclear to what extent the CO_2 used for EOR will be re-released. For example, the CO_2 used for EOR may 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 from EOR operations. For the purposes of this analysis, it is assumed that all of the CO_2 remains sequestered.

covery was about 7,861 thousand metric tons in 1999. The Freedonia Group estimates that, in the United States, there is an 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).

Data Sources

Carbon dioxide consumption data (see Table 3-16) were obtained from *Industrial Gases* to 2003, published by the Freedonia Group Inc. (1994, 1996, 1999a, 1999b). The 1999 report contains actual data for 1998 only. Data for 1996 were obtained by personal communication with Paul Ita of the Freedonia Group Inc. (Ita 1997). Data for 1997 and 1999 production were calculated from annualized growth rates for 1994 through 1996 and 1996 through 1998 respectively. The 1997 and 1999 values for enhanced oil recovery were set equal to the 1998 value. The percent of carbon dioxide produced from natural wells was obtained from Freedonia Group Inc. (1991).

Uncertainty

Uncertainty exists in the assumed allocation of carbon dioxide produced 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.

Table 3-16: 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
1997	6,468
1998	7,067
1999	7,861

Iron and Steel Production

In addition to being an energy intensive process, the production of iron and steel also generates process-related emissions of 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 this 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.

Emissions of CO_2 from iron and steel production in 1999 were 71.8 Tg CO_2 Eq. (71,840 Gg). Emissions fluctuated significantly from 1990 to 1999 due to changes in domestic economic conditions and changes in imports and exports. For the past several years, pig iron production has experienced a downward trend. Production in 1999 was 7 percent lower than 1998, and 12 percent below 1995 levels. Asian economic problems and the availability of low-priced imports continue to keep growth in check (USGS 2000).

CO_2 emissions from iron and steel production are not included in totals for the Industrial Processes chapter because they are accounted for with Fossil Fuel Combustion emissions from industrial coking coal in the Energy chapter.[12] Emissions estimates are presented here for informational purposes only (see Table 3-17). Additional CO_2 emissions also occur from the use of limestone or dolomite flux during production; however, these emissions are accounted for under Limestone and Dolomite Use.

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

Table 3-17: CO_2 Emissions from Iron and Steel Production

Year	Tg CO_2 Eq.	Gg
1990	87.6	87,600
1995	81.4	81,440
1996	79.0	79,040
1997	79.4	79,360
1998	77.1	77,120
1999	71.8	71,840

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/metric 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 1997 (see Table 3-18) were obtained from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Volume I-Metals and Minerals* (USGS 1995, 1996, 1997, 1998, 1999); data for 1999 were obtained from USGS's *Mineral Commodity Summaries* (2000).

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 could 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.

Table 3-18: 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
1997	49,600
1998	48,200
1999	44,900

Ammonia Manufacture

Emissions of carbon dioxide (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; however, the latter reaction does not lead to CO_2 emissions. Carbon monoxide (CO) in the first two processes is transformed into CO_2 in the presence of a catalyst (usually a metallic oxide). 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 1999 were 25.8 Tg CO_2 Eq. (25,799 Gg). Carbon dioxide emissions from this source are not included in totals for the Industrial Processes chapter because these emissions are accounted for with non-energy use of natural gas under Fossil Fuel Combustion in the Energy chapter.[13] Emissions estimates are presented here for informational purposes only (see Table 3-19).

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

Methodology

Emissions of CO_2 were calculated by multiplying annual estimates of ammonia production by an emission factor (1.5 metric ton CO_2/metric 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). Ammonia production data (see Table 3-20) were obtained from the Census Bureau of the U.S. Department of Commerce (Census Bureau 1998, 2000) as reported in *Chemical and Engineering News*, "Facts & Figures for the Chemical Industry."

Uncertainty

It is uncertain how accurately the emission factor used represents an average across all ammonia plants. By using natural gas consumption data for 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.

Table 3-19: CO_2 Emissions from Ammonia Manufacture

Year	Tg CO_2 Eq.	Gg
1990	23.1	23,138
1995	23.7	23,682
1996	24.4	24,390
1997	24.3	24,346
1998	25.1	25,141
1999	25.8	25,799

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 metallurgical 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:

Emissions of CO_2 from ferroalloy production in 1999 were 1.8 Tg CO_2 Eq. (1,771 Gg). Carbon dioxide emissions from this source are not included in the totals for the Industrial Processes chapter because these emissions are accounted for in the calculations for industrial coking coal under Fossil Fuel Combustion in the Energy chapter.[14] Emission estimates are presented here for informational purposes only (see Table 3-21).

Table 3-20: Ammonia Manufacture

Year	Thousand Metric Tons
1990	15,425
1991	15,576
1992	16,261
1993	15,599
1994	16,211
1995	15,788
1996	16,260
1997	16,231
1998	16,761
1999	17,200

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

Methodology

Emissions of CO_2 were calculated by multiplying annual 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, other biomass, or graphite carbon inputs.

Data Sources

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Ferroalloy production data for 1990 through 1998 (see Table 3-22) were obtained from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Volume I—Metals and Minerals* (USGS, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000); data for 1999 for ferrosilicon 75 percent and silicon metal were obtained from USGS (2000) *Mineral Industry Surveys: Silicon in December 1999*. Data for ferrosilicon 50 percent are no longer provided separately in USGS Mineral Industry Surveys, so the 1999 value was forecasted using the average annual growth in ferrosilicon 50 percent production for 1995 through 1998.

Uncertainty

Although some ferroalloys may be produced using wood or other 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.[15] 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 agent used in the process, rather than on the amount of ferroalloys produced. These data were not available, however.

Table 3-21: CO_2 Emissions from Ferroalloy Production

Year	Tg CO_2 Eq.	Gg
1990	1.8	1,809
1995	1.6	1,625
1996	1.7	1,695
1997	1.8	1,789
1998	1.8	1,793
1999	1.8	1,771

Petrochemical Production

Small amounts of methane (CH_4) are released during the production of some petrochemicals. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. Emissions are presented here from the production of five chemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol.

Carbon black is an intensely black powder made by the incomplete combustion of an aromatic petroleum feedstock. Almost all output is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. Ethylene is consumed in the production processes of the plastics industry including

Table 3-22: Production of Ferroalloys (Metric Tons)

Year	Ferrosilicon 50%	Ferrosilicon 75%	Silicon 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
1997	175,000	147,000	187,000
1998	162,000	147,000	195,000
1999	156,121	145,000	195,000

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[15] Emissions and sinks of biogenic carbon are accounted for in the Land-Use Change and Forestry chapter.

polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE), polyvinyl chloride (PVC), ethylene dichloride, ethylene oxide, and ethylbenzene. Ethylene dichloride is one of the first manufactured chlorinated hydrocarbons with reported production as early as 1795. In addition to being an important intermediate in the synthesis of chlorinated hydrocarbons, ethylene dichloride is used as an industrial solvent and as a fuel additive. Styrene is a common precursor for many plastics, rubber, and resins. It can be found in many construction products, such as foam insulation, vinyl flooring, and epoxy adhesives. Methanol is an alternative transportation fuel as well as a principle ingredient in windshield wiper fluid, paints, solvents, refrigerants, and disinfectants. In addition, methanol-based acetic acid is used in making PET plastics and polyester fibers. The United States produces close to one quarter of the world's supply of methanol.

Aggregate emissions of CH_4 from petrochemical production in 1999 were 1.7 Tg CO_2 Eq. (79 Gg CH_4) (see Table 3-23). Production levels of all five chemicals have shown steady growth over the past 5 years, with increases ranging from 2 to 4 percent. However, petrochemicals are currently in oversupply and production for 2000 is expected to decrease slightly.

Table 3-23: CH_4 Emissions from Petrochemical Production

Year	Tg CO_2 Eq.	Gg
1990	1.2	56
1995	1.5	72
1996	1.6	75
1997	1.6	77
1998	1.6	77
1999	1.7	79

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,[16] 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 for 1990 through 1998 (see Table 3-24) were obtained from the *Chemical Manufacturer's Association Statistical Handbook* (CMA 1999). Production for 1999 was projected using each chemical's average annual growth rate for 1993 through 1998.

Table 3-24: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Carbon Black	1,306	1,225	1,365	1,452	1,492	1,524	1,560	1,588	1,610	1,644
Ethylene	16,542	18,124	18,563	18,709	20,201	21,199	22,197	23,088	23,474	24,563
Ethylene Dichloride	6,282	6,221	6,872	8,141	8,482	7,829	8,596	9,152	8,868	9,021
Styrene	3,637	3,681	4,082	4,565	5,112	5,167	5,387	5,171	5,183	5,316
Methanol	3,785	3,948	3,666	4,782	4,904	4,888	5,330	5,806	5,693	5,895

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[16] The emission factor obtained from IPCC/UNEP/OECD/IEA (1997), page 2.23 is assumed to have a misprint; the chemical identified should be dichloroethylene ($C_2H_2Cl_2$) instead of ethylene dichloride ($C_2H_4Cl_2$).

Uncertainty

The emission factors used here were based on a limited number of studies. Using plant-specific factors instead of average factors could increase the accuracy of the emissions estimates, however, such data were not available. There may also be other significant sources of methane arising from petrochemical production activities that 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 chapter. Emissions of CH_4 from silicon carbide production in 1999 (see Table 3-25) were 1 Gg CH_4 (less than 0.05 Tg CO_2 Eq.).

Methodology

Emissions of CH_4 were calculated by multiplying annual silicon carbide production by an emission factor (11.6 kg CH_4/metric ton silicon carbide). This emission factor was derived empirically from measurements 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 1998 (see Table 3-26) were obtained from the *Minerals Yearbook: Volume I-Metals and Minerals, Manufactured Abrasives* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000).

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. A better 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. These data were not available, however.

Adipic Acid Production

Adipic acid production has been identified as an anthropogenic source of nitrous oxide (N_2O) emissions. Worldwide, there are few adipic acid plants. The United States is the major producer with three companies in four locations accounting for approximately forty percent of world production. 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

Table 3-25: CH_4 Emissions from Silicon Carbide Production

Year	Tg CO_2 Eq.	Gg
1990	+	1
1995	+	1
1996	+	1
1997	+	1
1998	+	1
1999	+	1

+ Does not exceed 0.05 Tg CO_2 Eq.

Table 3-26: 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
1997	68,200
1998	69,800
1999	69,800

polyesters. Approximately 80 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. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce adipic acid. Nitrous oxide is generated as a by-product of the nitric acid oxidation stage and is emitted in the waste gas stream. Process emissions from the production of adipic acid will vary with the types of technologies and level of emissions controls employed by a facility. In 1990, two of the three major adipic acid producing plants implemented N_2O abatement technologies and as of 1998, all of the major adipic acid production facilities had control systems in place.[17] Only one small plant does not control for N_2O, representing approximately 2 percent of production.

Adipic acid production for 1999 was 1,100 thousand metric tons. Nitrous oxide emissions from this source were estimated to be 9.0 Tg CO_2 Eq. (29 Gg) in 1999 (see Table 3-27).

In 1999, adipic acid production reached its highest level in fifteen years. This increase is chiefly due to a 120,000 metric ton expansion in production capacity and to rising demand for engineering plastics. Though production continues to increase, emissions have been significantly reduced due to the widespread installation of pollution control measures. The N_2O abatement technology voluntarily implemented at the three major producing plants accounts for an overall reduction of emissions by approximately 51 percent between 1990 and 1999.

Table 3-27: N_2O Emissions from Adipic Acid Production

Year	Tg CO_2 Eq.	Gg
1990	18.3	59
1995	20.3	66
1996	20.8	67
1997	17.1	55
1998	7.3	23
1999	9.0	29

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. Emissions are determined using the following equation:

$$\begin{aligned} N_2O \text{ emissions} = {} & [\text{production of adipic acid}] \times \\ & [0.3 \text{ kg } N_2O / \text{kg adipic acid}] \times \\ & [\,1 - (N_2O \text{ destruction factor} \times \\ & \text{abatement system utility factor})\,] \end{aligned}$$

The “N_2O destruction factor” represents the amount of N_2O expressed as a percentage of N_2O emissions that are destroyed by the currently installed abatement technology. The “abatement system utility factor” represents the percent of time that the abatement equipment operates. Overall, in the United States, 63 percent of production employs catalytic destruction, 34 percent uses thermal destruction, and 3 percent of production has no N_2O abatement measures. The N_2O abatement system destruction factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer et al. 1999, Reimer 1999). The abatement system utility factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer et al. 1999, Reimer 1999).

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[17] During 1997, the N_2O emission controls installed by the third plant operated for approximately a quarter of the year.

Data Sources

Adipic acid production data for 1990 through 1995 (see Table 3-28) were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992, 1993, 1994, 1995, 1996). For 1996 and 1997 data were projected from the 1995 manufactured total based upon suggestions from industry contacts. For 1998, production data were obtained from *Chemical Week*, Product focus: adipic acid/adiponitrile (CW 1999). Production data for 1999 are based on an estimate provided by the adipic acid industry (Reimer 2000). The emission factor was taken from Thiemens and Trogler (1991). Adipic acid plant capacities for 1998 and 1999 were updated using *Chemical Week*, Product focus: adipic acid/adiponitrile (CW 1999). Plant capacities for previous years were obtained from Chemical Market Reporter (1998).

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.

Table 3-28: Adipic Acid Production

Year	Thousand Metric Tons
1990	735
1991	771
1992	708
1993	765
1994	815
1995	816
1996	835
1997	860
1998	866
1999	1,100

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 fertilizers. 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.

Currently, the nitric acid industry controls for NO and NO_2, (i.e., NO_x). As such the industry uses a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very affective at destroying N_2O. However, NSCR units are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. NSCRs were widely installed in nitric plants built between 1971 and 1977. Currently, it is estimated that approximately 20 percent of nitric acid plants use NSCR (Choe, et al. 1993). The remaining 80 percent use SCR or extended absorption, neither of which is known to reduce N_2O.

Nitric acid production was 8,165 thousand metric tons in 1999 (C&EN 2000). Nitrous oxide emissions from this source were estimated at 20.2 Tg CO_2 Eq. (65 Gg) (see Table 3-29). Emissions from nitric acid production decreased slightly in 1999, but have increased 13 percent since 1990.

Methodology

Nitrous oxide emissions were calculated by multiplying nitric acid production by the amount of N_2O emitted per unit of nitric acid produced. The emissions factor was determined as a weighted average of 2 kg for plants using non-selective catalytic reduction (NSCR) systems and 9.5

Table 3-29: N_2O Emissions from Nitric Acid Production

Year	Tg CO_2 Eq.	Gg
1990	17.8	58
1995	19.9	64
1996	20.7	67
1997	21.2	68
1998	20.9	67
1999	20.2	65

kg for plants not equipped with NSCR (Reimer et al. 1992). An estimated 20 percent of HNO_3 plants in the U.S. were equipped with NSCR (Choe, et al. 1993). In the process of destroying NO_x, NSCR systems also destroy 80 to 90 percent of the N_2O. Hence, the emission factor is equal to $(9.5 \times 0.80) + (2 \times 0.20) = 8$ kg N_2O / metric ton HNO_3.

Data Sources

Nitric acid production data for 1990 through 1999 (see Table 3-30) were obtained from *Chemical and Engineering News*, “Facts and Figures” (C&EN 2000). The emission factor range was taken from Reimer et al. (1992).

Uncertainty

In general, the nitric acid industry is not well categorized. A significant degree of uncertainty exists in nitric acid production figures because nitric acid plants are often part of larger production facilities, such as fertilizer or explosive manufacturing. As a result, only a small volume of nitric acid is sold on the market making production quantities difficult to track. Emission factors are also difficult to determine because of the large number of plants using many different technologies. Based on expert judgment, it is estimated that the N_2O destruction factor for NSCR nitric acid facilities is associated with an uncertainty of approximately ± 10 percent.

Table 3-30: Nitric Acid Production

Year	Thousand Metric Tons
1990	7,196
1991	7,191
1992	7,381
1993	7,488
1994	7,905
1995	8,020
1996	8,351
1997	8,557
1998	8,423
1999	8,165

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.[18] 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 potent greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 3-31 and Table 3-32.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs 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.[19] In 1993, use of HFCs in foams and aerosols began, and in

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[18] [42 U.S.C § 7671, CAA § 601]

[19] R-404 contains HFC-125, HFC-143a, and HFC-134a.

Table 3-31: Emissions of HFCs and PFCs from ODS Substitution (Tg CO_2 Eq.)

Gas	1990	1995	1996	1997	1998	1999
HFC-23	+	+	0.1	0.1	0.2	0.3
HFC-32	+	+	+	+	+	+
HFC-125	+	1.3	1.9	2.5	3.1	3.6
HFC-134a	0.7	18.6	24.7	30.5	34.9	39.4
HFC-143a	+	0.4	0.8	1.3	1.9	2.6
HFC-236fa	+	+	+	0.1	0.8	1.3
CF_4	+	+	+	+	+	+
Others*	0.2	3.6	6.6	7.6	8.8	9.4
Total	**0.9**	**24.0**	**34.0**	**42.1**	**49.6**	**56.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

* Others include HFC-152a, HFC-227ea, HFC-4310mee, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C_6F_{14}.

Note: Totals may not sum due to independent rounding.

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 has been increasing from small amounts in 1990 to 56.7 Tg CO_2 Eq. in 1999. This increase was the result of efforts to phase-out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely accelerate in the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases, however, may help to offset this anticipated increase in emissions.

Methodology and Data Sources

The EPA used a detailed vintaging model of ODS-containing equipment and products to estimate the actual—versus potential—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, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for more than 40 different end-uses, the model produces estimates of annual use and emissions of each compound. Details on the Vintaging Model are contained in Annex I.

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 the 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.

Table 3-32: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	1995	1996	1997	1998	1999
HFC-23	+	2	5	10	17	25
HFC-32	+	+	3	7	11	17
HFC-125	+	478	675	889	1,116	1,289
HFC-134a	564	14,345	18,962	23,478	26,854	30,340
HFC-143a	+	111	209	334	488	676
HFC-236fa	+	+	+	15	120	213
CF_4	+	+	+	+	+	1
Others*	M	M	M	M	M	M

M (Mixture of Gases)

+ Does not exceed 0.5 Mg

* Others include HFC-152a, HFC-227ea, HFC-4310mee and PFC/PFPEs, which are a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

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. In 1999, the United States was the largest producer of primary aluminum, with 16 percent of the world total (USGS 2000). The United States was also a major importer of primary aluminum. The production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related 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 cover gas or a fluxing and degassing agent in experimental and specialized casting operations. In its application as a cover gas, SF_6 is mixed with nitrogen or carbon dioxide and injected above the surface of molten aluminum; as a fluxing and degassing agent, SF_6 is mixed with argon, nitrogen, and/or chlorine and blown through molten aluminum. These practices are not employed extensively by primary aluminum producers and are probably isolated to the secondary casting firms. The aluminum industry in the United States and Canada is estimated to use 230 Mg of SF_6 per year (Maiss and Brenninkmeijer 1998); however, this estimate is highly uncertain.

Historically, SF_6 from aluminum activities has been omitted from models of global SF_6 emissions, with the caveat that any emissions would be insignificant (Ko et al. 1993, Victor and MacDonald 1998). Emissions are thought to be slight since the concentration of SF_6 in the mixtures is small and a portion of the SF_6 is decomposed in the process (MacNeal et al. 1990, Gariepy and Dube 1992, Ko et al. 1993, Ten Eyck and Lukens 1996, Zurecki 1996). Emissions of SF_6 have not been estimated for aluminum production.

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 5.6 Tg CO_2 Eq. (5,555 Gg) in 1999 (see Table 3-33). The CO_2 emissions from this source, however, are accounted for under the non-energy use portion of CO_2 from Fossil Fuel Combustion of petroleum coke and tar pitch in the Energy chapter. Thus, to avoid double counting, CO_2 emissions from aluminum production are not included in totals for the Industrial Processes chapter. They are provided here for informational purposes only.

In addition to CO_2 emissions, the aluminum production industry is 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 48 percent since 1990. Since 1990, emissions of CF_4 and C_2F_6 have declined 46 and 58 percent, respectively, to 9.0 Tg CO_2 Eq. of CF_4 (1.38 Gg CF_4) and 1.1 Tg CO_2 Eq. of C_2F_6 (0.12 Gg C_2F_6) in 1999, as shown in Table 3-34 and Table 3-35. 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. The EPA supports aluminum smelters with these efforts through the Voluntary Aluminum Industrial Partnership (VAIP).

U.S. primary aluminum production for 1999—totaling 3,779 thousand metric tons—increased slightly from 1998. This increase is attributed to the reintroduction of previously idled production capacity and the start up of new production capacity (USGS 2000). The transportation industry remained the largest domestic consumer of aluminum, accounting for about 37 percent (USGS 2000). According to the U.S. Geological Survey (2000), overall consumption in the United States will continue to grow, driven by strong demand for aluminum in manufacturing passenger cars and light trucks. However, annual domestic production is expected to decline in 2000. The high cost of electric power in various regions of the country has prompted several production curtailments at U.S. smelters.

Methodology

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

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

The CO_2 emission factor employed was estimated from the production 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). Based upon the mass balance for a

Table 3-33: CO_2 Emissions from Aluminum Production

Year	Tg CO_2 Eq.	Gg
1990	6.0	5,951
1995	5.0	4,961
1996	5.3	5,258
1997	5.3	5,296
1998	5.5	5,458
1999	5.6	5,555

Table 3-34: PFC Emissions from Aluminum Production (Tg CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	16.7	2.5	19.3
1995	10.0	1.3	11.2
1996	10.3	1.3	11.6
1997	9.7	1.2	10.8
1998	9.0	1.1	10.1
1999	9.0	1.1	10.0

Note: Totals may not sum due to independent rounding.

Table 3-35: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.6	0.3
1995	1.5	0.1
1996	1.6	0.1
1997	1.5	0.1
1998	1.4	0.1
1999	1.4	0.1

"typical" aluminum smelter (Drexel University Project Team 1996), the emission factor was set at 1.5 metric tons CO_2 per metric ton of aluminum smelted. 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 chapter.[20] Thus, to avoid double counting, CO_2 emissions from aluminum production are not included in totals for the Industrial Processes chapter.

PFC emissions from aluminum production were estimated using a per unit production emission factor that is expressed as a function of operating parameters (anode effect frequency and duration), as follows:

PFC (CF_4 or C_2F_6) kg/metric ton Al = S × Anode Effect Minutes/Cell-Day

where,

S = Slope coefficient

Anode Effect Minutes/Cell-Day = Anode Effect Frequency × Anode Effect Duration

The slope coefficient was established for each smelter based on actual field measurements, where available, or default coefficients by technology-type based on field measurements. Once established, the slope coefficient was used along with smelter anode effect data, collected by aluminum companies and reported to the VAIP, to estimate emissions factors over time. Emissions factors were multiplied by annual production to estimate annual emissions at the smelter level. Emissions were then aggregated across smelters to estimate national emissions. The methodology used to estimate emissions is consistent with the methodologies recommended by the *Good Practice Guidance* (IPCC 2000).

Data Sources

Primary aluminum production data for 1990 through 1999 (see Table 3-36) were obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000). The USGS requested data from the 12 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).

Table 3-36: 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
1997	3,603
1998	3,713
1999	3,779

PFC emission estimates were provided by the EPA in cooperation with participants in the Voluntary Aluminum Industrial Partnership (VAIP) program.

Uncertainty

There is uncertainty 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 more accurate 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.

For PFC emission estimates, the uncertainty in the aluminum production data is relatively low (± 1 to 2 percent) compared to the uncertainty in the emissions factors (± 10 to 50 percent). Uncertainty in the emissions factors arises from the lack of comprehensive data for both the slope coefficients and anode effect data. Currently, insufficient measurement data exist to quantify a relationship between PFC emissions and anode effect minutes for all smelters. Future inventories will incorporate additional data reported by aluminum companies and ongoing research into PFC emissions from aluminum production.

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[20] Although the carbon contained in the anode is considered a non-energy use of petroleum coke or tar pitch and the CO_2 emissions it generates should be included in the Industrial Processes chapter, information needed to distinguish individual non-energy uses of fossil fuels is-unfortunately not available in DOE/EIA fuel statistics.

Emissions of SF_6 from aluminum fluxing and degassing have not been estimated. Uncertainties exist as to the quantity of SF_6 used by the aluminum industry and its rate of destruction in its uses as a degassing agent or cover gas.

HCFC-22 Production

Trifluoromethane (HFC-23 or CHF_3) is generated as a by-product during the manufacture of chlorodifluoromethane (HCFC-22), which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Since 1990, production and use of HCFC-22 has increased significantly as it has replaced chlorofluorocarbons (CFCs) in many applications. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses is scheduled to be phased out by 2020 under the U.S. Clean Air Act.[21] Feedstock production, in contrast, is permitted to continue indefinitely.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where $x + y = 5$), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. HCl is recovered as a useful byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 is generally vented to the atmosphere as an unwanted by-product, or may be captured for use in a limited number of applications.

Emissions of HFC-23 in 1999 were estimated to be 30.4 Tg CO_2 Eq. (2.6 Gg). This quantity represents a 13 percent decrease from emissions in 1990 (see Table 3-37). Despite a 19 percent increase in production since 1990, the intensity of HFC-23 emissions (the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined significantly.

In the future, production of HCFC-22 in the United States is expected to decline as non-feedstock HCFC production is phased-out. Feedstock production is anticipated to continue growing, mainly for manufacturing fluorinated polymers. U.S. producers of HCFC-22 are participating in a voluntary program with the EPA to reduce HFC-23 emissions.

Methodology

The 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.

The methodology employed for estimating emissions was based upon measurements of critical feed components at individual HCFC-22 production plants. Individual producers also measured HFC-23 concentrations in their output stream by gas chromatography. Using measurements of feed components and HFC-23 concentrations in output 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.

Table 3-37: HFC-23 Emissions from HCFC-22 Production

Year	Tg CO_2 Eq.	Gg
1990	34.8	3.0
1995	27.1	2.3
1996	31.2	2.7
1997	30.1	2.6
1998	40.0	3.4
1999	30.4	2.6

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[21] 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]

Data Sources

Emission estimates were provided by the EPA's Climate Protection 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 accounted for the declining intensity of HFC-23 emissions over time. The use of a constant emission factor would not have allowed for such accounting. More simplistic emission estimates generally assume that HFC-23 emissions are between 2 and 4 percent of HCFC-22 production on a mass ratio basis. By 1996, the rate of HFC-23 generated in the United States as a percent of HCFC-22 produced dropped, on average, below 2 percent.

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), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

Plasma etching is performed to provide pathways for the conducting material to connect individual circuit components in the silicon, using HFCs, PFCs, SF_6 and other gases in plasma. The etching process creates fluorine atoms that react at the semiconductor surface according to prescribed patterns to selectively remove substrate material. A single semiconductor wafer may require as many as 100 distinct process steps that utilize these gases. Chemical vapor deposition chambers, used for depositing materials that will act as insulators and wires, are cleaned periodically using PFCs and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. However, due to the low destruction efficiency (high dissociation energy) of PFCs, a portion of the gas flowing into the chamber flows unreacted through the chamber and, unless emission abatement technologies are used, this portion is emitted into the atmosphere. In addition to emissions of unreacted gases, these compounds can also be transformed in the plasma processes into a different HFC or PFC compound, which is then exhausted into the atmosphere. For example, when either CHF_3 or C_2F_6 is used in cleaning or etching, CF_4 is generated and emitted as a process by-product.

For 1999, it was estimated that total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were 6.8 Tg CO_2 Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 3-38 below. The rapid growth of this industry and the increasing complexity of semiconductor products, which use more PFCs in the production process, led to an increase in emissions of over 130 percent since 1990. However, the growth rate in emissions has slowed since 1997 due in part to an industry slow down and possibly to the initial implementation of PFC emission reduction methods such as process optimization. In the future, emissions are expected to stabilize and ultimately decline over the next decade due to global industry efforts to reduce emissions.

Table 3-38: Emissions of Fluorinated Greenhouse Gases from Semiconductor Manufacture

Year	Tg CO_2 Eq.
1990	2.9
1995	5.5
1996	7.0
1997	7.0
1998	6.8
1999	6.8

Methodology

Emissions have been estimated using two sets of data. For 1990 through 1994, emissions were estimated based on the historical consumption of silicon (square centimeters), the estimated average number of interconnecting layers in the chips produced, and an estimated per-layer emission factor. (The number of layers per chip, and hence the PFC emissions per square centimeter of silicon, increases as the line-width of the chip decreases.) The average number of layers per chip was based on industry estimates of silicon consumption by line-width and of the number of layers per line-width. The per-layer emission factor was based on the total annual emissions reported by the participants in the PFC Emission Reduction Partnership for the Semiconductor Industry. For the three years for which gas sales data are available (1992 to 1994), the estimates derived using this method are within 10 percent of the estimates derived using gas sales data and average values for emission factors and global warming potentials (GWPs).

For 1995 through 1999, emissions were estimated based on the total annual emissions reported by the participants in the PFC Emission Reduction Partnership for the Semiconductor Industry. Partners estimate their emissions using a range of methods. The partners with relatively high emissions typically multiply estimates of their PFC consumption by process-specific emission factors that they have either measured or obtained from tool suppliers. To estimate total U.S. emissions from semiconductor manufacturing, based on reported partner emissions, a per-plant emission factor was estimated for the partners. This per-plant emission factor was then applied to PFC-using plants operated by semiconductor manufacturers who were not partners, considering the varying characteristics of the plants operated by partners and non-partners (e.g., typical plant size and employed linewidth technology). The resulting estimate of non-partner emissions was added to the emissions reported by the partners to obtain total U.S. emissions.

Data Sources

Aggregate emissions estimates from the semiconductor manufacturers participating in the PFC Emission Reduction Partnership were used to develop the 1995 through 1999 national emission estimate. Estimates of the numbers of plants operated by partners and non-partners, and information on the characteristics of those plants, were derived from the International Fabs on Disk (1999) database. Estimates of silicon consumed by line-width from 1990 through 1994 were derived from information from VLSI Research (1998), and the number of layers per line-width was obtained from the Semiconductor Industry Association's National Technology Roadmap (1997).

Uncertainty

Emission estimates for this source are improving, but are still relatively uncertain. Emissions vary depending upon the total amount of gas used and the tool and process employed. Much of this information is tracked by semiconductor manufacturers participating in the EPA's PFC Emission Reduction Partnership; however, there is some uncertainty associated with the data collected. In addition, not all semiconductor manufacturers track this information, so when it is extrapolated to total U.S. emissions, the uncertainty related to gas use and emission rates is much greater.

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 (Science and Policy Associates 1997). 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 switch gear through seals, especially from older equipment. It can also be released during equipment installation and when equipment is opened for servicing, which typically occurs every few years. In the past, some utilities vented SF_6 to the atmosphere during servicing; however, increased awareness and the relatively high cost of the gas have reduced this practice. In the United States, the voluntary partnership—SF_6 Emissions Reduction Partnership for Electric Power Systems—is working with utilities to reduce their emissions and will likely contribute to a reduction of emissions over time.

Emissions of SF_6 from electrical transmission and distribution systems were estimated to be 25.7 Tg CO_2 Eq. (1.1 Gg) in 1999. This quantity amounts to a 25 percent increase over the estimate for 1990 (see Table 3-39).

Table 3-39: SF_6 Emissions from Electrical Transmission and Distribution

Year	Tg CO_2 Eq.	Gg
1990	20.5	0.9
1995	25.7	1.1
1996	25.7	1.1
1997	25.7	1.1
1998	25.7	1.1
1999	25.7	1.1

Methodology

Emissions of SF_6 were estimated using a top-down, or production-based approach. Specifically, emissions were calculated based upon the following factors: 1) the estimated U.S. production capacity for SF_6, 2) the estimated use of this production capacity, 3) the fraction of U.S. SF_6 production estimated to be sold annually to fill or refill electrical equipment, and 4) the fraction of these sales estimated to replace emitted gas.

Based on information gathered from chemical manufacturers, it was estimated that in 1994 U.S. production capacity for SF_6 was approximately 3,000 metric tons. It was assumed that plants were operating at 90 percent capacity, which was consistent with industry averages and implied that 2,700 metric tons of SF_6 were produced in 1994. It was further assumed that 75 percent of U.S. SF_6 sales were made to electric utilities and electrical transmission and distribution equipment manufacturers. This assumption is consistent with the estimate—given in Ko, et al. (1993)—that worldwide, 80 percent of SF_6 sales is for electrical transmission and distribution systems. Seventy-five percent of annual U.S. production in 1994 was 2,000 metric tons.

Finally, it was assumed that approximately 50 percent of this production, or 1,000 metric tons, replaced gas emitted into the atmosphere in 1994. This amount is equivalent to 25.7 Tg CO_2 Eq. (when rounding is performed at the end of the calculation). The estimate is based on information showing that emissions rates from electric equipment have been significant and atmospheric measurements indicating that most of the SF_6 produced internationally since the 1950s has been released. Emissions from electrical equipment are known to have occurred from the service and disposal of the equipment and leaks during operation. Leaks from older equipment were reported to release up to 50 percent of the equipment's charge per year, although leaks from newer equipment were reported to release considerably less (e.g., less than 1 percent of the charge per year).

It was assumed that emissions have remained constant at 25.7 Tg CO_2 Eq. since 1995.

Data Sources

Emission estimates were provided by EPA's Climate Protection Division in cooperation with U.S. electric utilities and chemical producers.

Uncertainty

There is currently little verifiable data for estimating SF_6 emissions from electrical transmission and distribution systems. Neither U.S. gas consumption nor emission monitoring data were available. In 1999, the EPA launched a voluntary program to reduce emissions of SF_6 from equipment used to transmit and distribute electricity such as high voltage circuit breakers, substations, transformers, and transmission lines. The EPA anticipates that better information on SF_6 emissions will be available in the future and expects to update SF_6 emission estimates. The updated estimates will be derived from the SF_6 emissions data reported by the Voluntary SF_6 Emissions Reduction Partnership. It is expected that new data will reveal that emissions from electrical transmission and distribution have declined in recent years.

Magnesium Production and Processing

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a covergas to prevent the violent oxidation of molten magnesium in the presence of air. A dilute gaseous mixture of SF_6 with dry air and/or carbon dioxide is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A minute portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and some magnesium fluoride. In accordance with current IPCC guidance (IPCC 2000), it is assumed that the amount of SF_6 reacting in magnesium industry application is negligible and thus all SF_6 used is emitted into the atmosphere. Sulfur hexafluoride has been used in this application around the world for the last twenty years. It has largely replaced salt fluxes, sulfur dioxide (SO_2), and boron trifluoride (BF_3), which are drastically more toxic and corrosive than SF_6.

Table 3-40: SF_6 Emissions from Magnesium Production and Processing

Year	Tg CO_2 Eq.	Gg
1990	5.5	0.2
1995	5.5	0.2
1996	5.6	0.2
1997	7.5	0.3
1998	6.3	0.3
1999	6.1	0.3

For 1999, a total of 6.1 Tg CO_2 Eq. (0.3 Gg) of SF_6 was estimated to have been emitted by the magnesium industry (see Table 3-40). There are no significant plans for expansion of primary magnesium production in the United States, but demand for magnesium metal by U.S. casting companies is growing as auto manufacturers design more lightweight magnesium parts into vehicle models. Foreign magnesium producers are expected to meet the growing U.S. demand for primary magnesium.

Methodology

Emission estimates for the magnesium industry were revised this year to incorporate information provided by EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. EPA's magnesium industry partner companies represent 100 percent of U.S. primary production and approximately 60 percent of the casting sector. U.S. magnesium metal production (primary and secondary) and consumption data from 1993 to 1999 are available from the U.S. Geological Survey (USGS).[22] Emissions were estimated by multiplying average industry emission factors (kg SF_6/tonne Mg produced or processed) by the amount of metal produced or consumed in the six major processes that require SF_6 melt protection; 1) primary production, 2) secondary production, 3) die casting, 4) gravity casting, 5) wrought products and, 6) anodes. The emission factors are derived from EPA partner companies' reports, technical publications (Gjestland and Magers 1996), and expert judgement. 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 tonne of magnesium.

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[22] http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis

Data Sources

Emission estimates were provided by EPA's Climate Protection Division in cooperation with the U.S. EPA SF_6 Emission Reduction Partnership for the Magnesium Industry and the USGS.

Uncertainty

There are a number of uncertainties in these estimates, including the assumption that SF_6 does not react nor decompose during use. It is possible that the melt surface reactions and high temperatures associated with molten magnesium would cause some gas degradation.

Box 3-1: Potential Emission Estimates of HFCs, PFCs, and SF_6

Emissions of HFCs, PFCs and SF_6 from industrial processes can be estimated in two ways, either as potential emissions or as actual emissions. Emission estimates in this chapter are "actual emissions," which are defined by the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* as estimates that take into account the time lag between consumption and emissions. In contrast, "potential emissions" are defined to be equal to the amount of a chemical consumed in a country, minus the amount of a chemical recovered for destruction or export in the year of consideration. Potential emissions will generally be greater for a given year than actual emissions, since some amount of chemical consumed will be stored in products or equipment and will not be emitted to the atmosphere until a later date, if ever. Because all chemicals consumed will eventually be emitted into the atmosphere, in the long term the cumulative emission estimates using the two approaches should be equivalent unless the chemical is captured and destroyed. Although actual emissions are considered to be the more accurate estimation approach for a single year, estimates of potential emissions are provided for informational purposes.

Separate estimates of potential emissions were not made for industrial processes that fall into the following categories:

- *By-product emissions.* Some emissions do not result from the consumption or use of a chemical, but are the unintended by-products of another process. For such emissions, which include emissions of CF_4 and C_2F_6 from aluminum production and of HFC-23 from HCFC-22 production, the distinction between potential and actual emissions is not relevant.
- *Potential emissions that equal actual emissions.* For some sources, such as magnesium production and processing, it is assumed that there is no delay between consumption and emission and that no destruction of the chemical takes place. It this case, actual emissions equal potential emissions.
- *Emissions that are not easily defined.* In some processes, such as semiconductor manufacture, the gases used in the process may be destroyed or transformed into other compounds, which may also be greenhouse gases. It is therefore not logical to estimate potential emissions based on consumption of the original chemical.

Table 3-41 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances and SF_6 emissions from electrical transmission and distribution and other miscellaneous sources such as tennis shoes and sound insulating windows.[23] Potential emissions associated with the substitution for ozone depleting substances were calculated through a combination of the EPA's Vintaging Model and information provided by U.S. chemical manufacturers. For other SF_6 sources, estimates were based on an assumed U.S. SF_6 production capacity and plant utilization to estimate total sales. The portion of this amount used for magnesium processing and assumed to be used for semiconductor manufacture were subtracted.

Table 3-41: 1999 Potential and Actual Emissions of HFCs, PFCs, and SF_6 from Selected Sources (Tg CO_2 Eq.)

Source	Potential	Actual
Substitution of Ozone Depleting Substances	181.4	56.7
Aluminum Production	-	10.0
HCFC-22 Production	-	30.4
Semiconductor Manufacture	-	6.8
Magnesium Production and Processing	6.1	6.1
Other SF_6 Sources*	61.0	25.7

- Not applicable
*Includes Electrical Transmission and Distribution and, in the case of potential emissions, other miscellaneous sources.

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[23] See Annex P for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

As is the case for other sources of SF_6 emissions, verifiable SF_6 consumption data for magnesium production and processing in United States were not available. Sulfur hexafluoride may also be used as a covergas for the casting of molten aluminum with a high magnesium content; however, it is unknown to what extent this technique is used in the United States.

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 1999 are reported in Table 3-42.

Methodology and Data Sources

The emission estimates for this source were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1999* (EPA 2000). Emissions were calculated either for individual categories or for many categories 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 categories from various agencies. Depending on the 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 1997). 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 3-42: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999
NO_x	**921**	**842**	**977**	**992**	**924**	**930**
Chemical & Allied Product Manufacturing	152	144	113	115	117	119
Metals Processing	88	89	75	80	80	80
Storage and Transport	3	5	14	15	15	15
Other Industrial Processes	343	362	397	417	424	426
Miscellaneous*	335	242	377	365	289	290
CO	**9,502**	**5,291**	**7,227**	**8,831**	**5,612**	**5,604**
Chemical & Allied Product Manufacturing	1,074	1,109	955	972	981	981
Metals Processing	2,395	2,159	1,455	1,550	1,544	1,522
Storage and Transport	69	22	64	64	65	65
Other Industrial Processes	487	566	509	528	535	543
Miscellaneous*	5,479	1,435	4,244	5,716	2,487	2,492
NMVOCs	**3,110**	**2,805**	**2,354**	**2,793**	**2,352**	**2,281**
Chemical & Allied Product Manufacturing	575	599	351	352	357	358
Metals Processing	111	113	66	71	71	70
Storage and Transport	1,356	1,499	1,169	1,204	1,204	1,125
Other Industrial Processes	364	409	383	397	402	407
Miscellaneous*	705	185	385	769	318	320

* 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 Residue 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. Surface coatings accounted for just under a majority of NMVOC emissions from solvent use—44 percent in 1999—while "non-industrial"[2] uses accounted for about 36 percent and degreasing applications for 8 percent. Overall, solvent use accounted for approximately 27 percent of total U.S. emissions of NMVOCs in 1999, and decreased 16 percent since 1990.

Although NMVOCs are not considered direct 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 uses 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 industrial applications also 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 1990 to 1999 are reported in Table 4-1.

Methodology

Emissions were calculated by aggregating solvent use data based on information relating to solvent uses from different applications 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.

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[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 chapter.

[2] "Non-industrial" uses include cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

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

Activity	1990	1995	1996	1997	1998	1999
NO_x	**1**	**3**	**3**	**3**	**3**	**3**
Degreasing	+	+	+	+	+	+
Graphic Arts	+	1	1	1	1	1
Dry Cleaning	+	+	+	+	+	+
Surface Coating	1	2	2	2	2	2
Other Industrial Processes[a]	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+
CO	**4**	**5**	**1**	**1**	**1**	**1**
Degreasing	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+
Dry Cleaning	+	1	+	+	+	+
Surface Coating	+	1	1	1	1	1
Other Industrial Processes[a]	4	3	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+
NMVOCs	**5,217**	**5,609**	**4,963**	**5,098**	**4,668**	**4,376**
Degreasing	675	716	546	566	337	337
Graphic Arts	249	307	260	266	272	266
Dry Cleaning	195	209	140	148	151	152
Surface Coating	2,289	2,432	2,153	2,228	1,989	1,938
Other Industrial Processes[a]	85	87	96	100	101	103
Non-Industrial Processes[b]	1,724	1,858	1,768	1,790	1,818	1,581

[a] Includes rubber and plastics manufacturing, and other miscellaneous applications.

[b] Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

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, 1900-1999* (EPA 2000). Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of solvent purchased) as an indicator of emissions. National activity data were collected for individual applications 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 1997). 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.

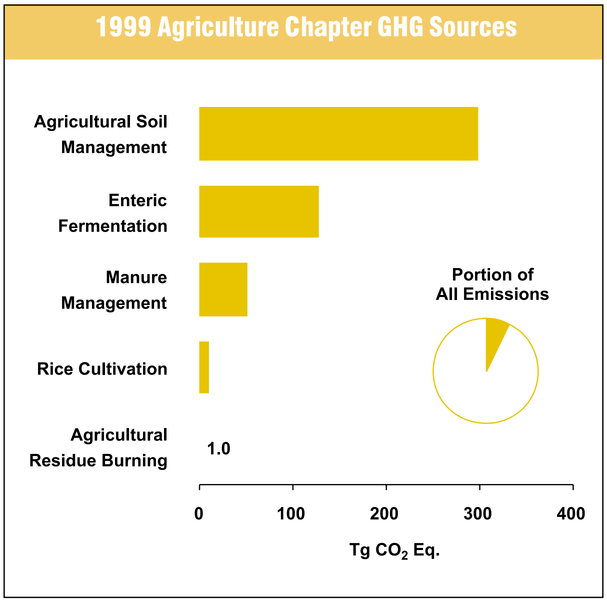
Uncertainty

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. This chapter provides an assessment of non-carbon dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and agricultural residue burning (see Figure 5-1). Carbon dioxide emissions and removals from agriculture-related land-use activities, such as conversion of grassland to cultivated land, are discussed in the Land-Use Change and Forestry chapter.

Figure 5-1



1999 Agriculture Chapter GHG Sources

In 1999, agricultural activities were responsible for emissions of 488.8 Tg CO_2 Eq., or 7.2 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 21 and 6 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 residue burning were minor sources of methane. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 69 percent. Manure management and agricultural residue burning were also smaller sources of N_2O emissions.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture chapter. Between 1990 and 1999, CH_4 emissions from agricultural activities increased by 4.7 percent while N_2O emissions increased by 10.7 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).

Table 5-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999
CH_4	**165.1**	**177.4**	**172.3**	**172.4**	**173.4**	**172.9**
Enteric Fermentation	129.5	136.3	132.2	129.6	127.5	127.2
Manure Management	26.4	31.0	30.7	32.6	35.2	34.4
Rice Cultivation	8.7	9.5	8.8	9.6	10.1	10.7
Agricultural Residue Burning	0.5	0.5	0.6	0.6	0.6	0.6
N_2O	**285.4**	**302.1**	**311.8**	**317.4**	**317.9**	**315.9**
Agricultural Soil Management	269.0	285.4	294.6	299.8	300.3	298.3
Manure Management	16.0	16.4	16.8	17.1	17.2	17.2
Agricultural Residue Burning	0.4	0.4	0.4	0.4	0.5	0.4
Total	**450.5**	**479.5**	**484.1**	**489.8**	**491.4**	**488.8**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999
CH_4	**7,862**	**8,446**	**8,205**	**8,208**	**8,259**	**8,232**
Enteric Fermentation	6,166	6,492	6,295	6,172	6,072	6,057
Manure Management	1,256	1,477	1,463	1,553	1,677	1,638
Rice Cultivation	414	452	419	455	481	509
Agricultural Residue Burning	25	24	28	29	30	28
N_2O	**921**	**975**	**1,006**	**1,024**	**1,026**	**1,019**
Manure Management	52	53	54	55	55	55
Agricultural Soil Management	868	921	950	967	969	962
Agricultural Residue Burning	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding.

Enteric Fermentation

Methane (CH_4) is produced as part of 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, 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 domesticated animal types, 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 products that can be utilized by the animal. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest methane emissions among all animal types.

Non-ruminant domesticated animals (e.g., pigs, horses, mules, rabbits, and guinea pigs) also produce methane emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants have significantly lower methane emissions on a per-animal basis 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 emissions. 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 emission estimates from enteric fermentation are shown in Table 5-3 and Table 5-4. Total livestock methane emissions in 1999 were 127.2 Tg CO_2 Eq. (6,057 Gg) decreasing slightly since 1998. Beef cattle remain the largest contributor of methane emissions from enteric fermentation, accounting for 75 percent of emissions in 1999. Emissions from dairy cattle in 1999 accounted for 21 percent of total emissions, and the remaining 4 percent of emissions can be attributed to horses, sheep, swine, and goats.

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. Cattle production systems in the United States are better characterized in comparison with other livestock management systems. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimating emissions for cattle. Emission estimates for other domesticated animals were handled using a less detailed approach (i.e., IPCC Tier 1).

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 livestock population, feeding practices and production characteristics was used to estimate emissions from cattle populations.

The methodology for estimating emissions from enteric fermentation involves the four steps indicated below.

Step 1: Characterize the Cattle Population

National cattle population statistics were disaggregated into the following cattle sub-populations:

Dairy Cattle

- Calves
- Heifer Replacements
- Cows

Table 5-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1995	1996	1997	1998	1999
Beef Cattle	94.7	103.0	100.4	97.8	95.8	95.4
Dairy Cattle	28.7	27.5	26.1	26.0	25.9	26.1
Horses	2.1	2.3	2.3	2.3	2.3	2.3
Sheep	1.9	1.5	1.4	1.3	1.3	1.2
Swine	1.7	1.9	1.8	1.8	2.0	1.9
Goats	0.3	0.3	0.3	0.2	0.2	0.2
Total	**129.5**	**136.3**	**132.2**	**129.6**	**127.5**	**127.2**

Note: Totals may not sum due to independent rounding.

Table 5-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1995	1996	1997	1998	1999
Beef Cattle	4,511	4,902	4,781	4,658	4,561	4,544
Dairy Cattle	1,369	1,308	1,241	1,240	1,234	1,245
Horses	102	108	109	111	111	111
Sheep	91	72	68	64	63	58
Swine	81	88	84	88	93	89
Goats	13	12	13	11	10	10
Total	**6,166**	**6,492**	**6,295**	**6,172**	**6,072**	**6,057**

Note: Totals may not sum due to independent rounding.

Beef Cattle

- Calves
- Heifer Replacements
- Heifer and Steer Stockers
- Animals in Feedlots
- Cows
- Bulls

Calf birth estimates, end of year population statistics, detailed feedlot placement information, and slaughter weight data were used in the model to initiate and track cohorts of individual animal types having distinct emissions profiles. The key variables tracked for each of the cattle population categories are described in Annex J. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain.

Step 2: Characterize Cattle Nutrition

Diet characteristics were estimated by State and region for U.S. dairy, beef, and feedlot cattle, and were used to calculate Digestible Energy (DE) values and methane conversion rates (Y_m) for each population category. The IPCC recommends Y_m values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for all other cattle. Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed, rather than using the recommended IPCC values. The diet characterizations and estimation of DE and Y_m values were based on contact with State agricultural extension specialists, a review of published forage quality studies, expert opinion, and modeling of animal physiology. See Annex J for more details on the method used to characterize cattle diets in the United States.

Step 3: Determine Cattle Emissions

In order to estimate methane emissions from cattle, the population was divided into region, age, sub-type (e.g., calves, heifer replacements, cows, etc.), and production (i.e., pregnant, lactating, etc.) groupings to more fully capture any differences in methane emissions from these animal types. Cattle diet characteristics developed under Step 2 were used to develop regional emission factors for each sub-category. Tier 2 equations from IPCC (2000) were used to produce methane emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, and steer and heifer feedlot step-up diet animals. To estimate emissions from cattle, population data were multiplied by the emission factor for each cattle type. More details can be found in Annex J.

Step 4: Determine Other Livestock Emissions

Emission 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 from 1990 through 1999. 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 less than that for cattle.

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

Data Sources

Annual cattle population data were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (1995a-d, 1996b, 1997, 1998a, 1999a-c,f-g, 2000a,c,d). DE and Y_m values were used to calculate emissions from cattle populations. DE and Y_m for dairy and beef cows, and for beef stockers, were calculated from diet characteristics using a model simulating ruminant digestion in growing and/or lactating cattle (Donovan and Baldwin 1999). For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. Values from EPA (1993) were used for dairy replacement heifers. Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. Annual livestock population data for other livestock types, except horses, as well as feedlot placement information were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1998b-c, 1999d,e,h, 2000b,e). Horse data were obtained from the Food and Agriculture Organization (FAO) statistical database (FAO 2000). Methane emissions from sheep, goats, pigs, and horses were estimated by using emission factors utilized in Crutzen et al. (1986). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology is the same as that recommended by IPCC (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).

Uncertainty

The basic uncertainties associated with estimating emissions from enteric fermentation are the range of emission factors possible for the different animal types and the number of animals with a particular emissions profile that exist during the year. Although determining an emission factor for all possible cattle sub-groupings and diet characterizations in the United States is not possible, the enteric fermentation model that was used estimates the likely emission factors for the major animal types and diets. The model generates estimates for dairy and beef cows, dairy and beef replacements, beef stockers, and feedlot animals. The analysis departs from the recommended IPCC (2000) DE and Y_m values to account for diets for these different animal types regionally. Based on expert opinion and peer reviewer recommendations, it is believed that the values supporting the development of emission factors for the animal types studied are appropriate for the situation in the United States.

In addition to the uncertainty associated with developing emission factors for different cattle population categories based on estimated energy requirements and diet characterizations, there is uncertainty in the estimation of animal populations by animal type. The model estimates the movement of animal cohorts through the various monthly age and weight classes by animal type. Several inputs affect the precision of this approach, including estimates of births by month, weight gain of animals by age class, and placement of animals into feedlots based on placement statistics and slaughter weight data. However, it is believed that the model accurately characterizes the U.S. cattle population and fully captures the potential differences in emission factors between different animal types.

Manure Management

The management of livestock manure can produce anthropogenic 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 nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.

When livestock or poultry manure are 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 the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or pits) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. A number of other factors related to how the manure is handled also affect the amount of CH_4 produced: 1) ambient temperature and moisture affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for methane formation; 2) methane production generally increases with rising temperature and residency time; and 3) for non-liquid based manure systems, moist conditions (which are a function of rainfall and humidity) favor CH_4 production. Although the majority of manure is handled as a solid, producing little CH_4, the general trend in manure management, particularly for large dairy and swine producers, is one of increasing use of liquid systems. In addition, use of daily spread systems at smaller dairies is decreasing, due to new regulations limiting the application of manure nutrients, which has resulted in an increase of manure managed and stored on site at these smaller dairies.

The composition of manure also affects the amount of methane produced. Manure composition varies by animal type and diet. The greater the energy content and digestibility of the feed, the greater the potential for CH_4 emissions. For example, feedlot cattle fed a high energy grain diet generate manure with a high CH_4-producing capacity. Range cattle fed a low energy diet of forage material produce manure with about 70 percent of the CH_4-producing potential of feedlot cattle manure. In addition, there is a trend in the dairy industry for dairy cows to produce more milk per year. These high-production milk cows tend to produce more volatile solids in their manure as milk production increases, which increases the probability of CH_4 production.

The production of nitrous oxide from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For N_2O emissions to occur, the manure must first be handled aerobically where ammonia nitrogen is converted to nitrites (nitrification), and then handled anaerobically where the nitrite is converted to N_2O (denitrification). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but can also undergo saturation to create pockets of anaerobic conditions. For example, manure at cattle drylots is deposited on soil, oxidized to nitrite and nitrate nitrogen, and has the potential to encounter saturated conditions following rain events.

Certain N_2O emissions are accounted for and discussed under Agricultural Soil Management. These are emissions from livestock manure and urine deposited on pasture, range, or paddock lands, as well as emissions from manure and urine that is spread onto fields either directly as "daily spread" or after it is removed from manure management systems (e.g., lagoon, pit, etc.)

Table 5-5, Table 5-6, and Table 5-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category. Estimates for methane emissions in 1999 were 34.4 Tg CO_2 Eq. (1,638 Gg), 30 percent above emissions in 1990. The majority of the increase in methane emissions over the time series was from swine and dairy cow manure and is attributed to shifts by the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use flush or scrape liquid systems to manage and store manure. Thus the shift towards larger facilities is translated into an increasing use of liquid manure management systems. This shift was accounted for by incorporating State-specific weighted methane conversion factor (MCF) values calculated from the 1992 and 1997 farm-size distribution reported in the *Census of Agriculture* (USDA 1999e). In 1999, swine CH_4 emissions decreased from 1998 due to a decrease in swine animal populations.

As stated previously, dairies are moving away from daily spread systems. Therefore, more manure is managed and stored on site, contributing to additional CH_4 emissions over the time series. The CH_4 estimates also account for changes in volatile solids production from dairy cows correlated to their generally increasing milk production. A description of the methodology is provided in Annex K.

Total N_2O emissions from manure management systems in 1999 were estimated to be 17.2 Tg CO_2 Eq. (55 Gg). The 7 percent increase in N_2O emissions from 1990 to 1999 can be partially attributed to a shift in the poultry industry away from the use of liquid manure management systems, in favor of litter-based systems and high rise houses. In addition, there was an overall increase in the population of poultry and swine, although swine populations declined slightly in 1993, 1995, 1996, and 1999 from previous years. The population of beef cattle in feedlots, which tend to store and manage manure on site, also increased.[1] Although dairy cow populations went down overall, the population of dairies managing and storing manure on site—as opposed to using pasture, range, or paddock or daily spread systems—went up. Therefore, the increase in dairies using on-site storage to manage their manure results in increased N_2O emissions. As stated previously, N_2O emissions from livestock manure deposited on pasture, range, or paddock land and manure immediately applied to land in daily spread systems are accounted for under Agricultural Soil Management.

Methodology

The methodologies presented in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) form the basis of the CH_4 and N_2O emissions estimates for each animal type. The calculation of emissions requires the following information:

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[1] Methane emissions were mostly unaffected by this increase in the beef cattle population because feedlot cattle primarily use solid storage systems, which produce little methane.

Table 5-5: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Animal Type	1990	1995	1996	1997	1998	1999
CH_4	**26.4**	**31.0**	**30.7**	**32.6**	**35.2**	**34.4**
Dairy Cattle	8.9	11.1	11.2	11.8	12.2	12.5
Beef Cattle	3.2	3.5	3.4	3.4	3.4	3.3
Swine	11.1	13.2	12.8	14.1	16.2	15.3
Sheep	0.1	0.1	+	+	+	+
Goats	+	+	+	+	+	+
Poultry	2.6	2.6	2.6	2.6	2.7	2.6
Horses	0.6	0.6	0.6	0.7	0.7	0.7
N_2O	**16.0**	**16.4**	**16.8**	**17.1**	**17.2**	**17.2**
Dairy Cattle	4.2	4.0	3.9	3.9	3.8	3.8
Beef Cattle	4.9	5.3	5.1	5.4	5.5	5.5
Swine	0.3	0.3	0.3	0.4	0.4	0.4
Sheep	+	+	+	+	+	+
Goats	+	+	+	+	+	+
Poultry	6.3	6.5	7.2	7.2	7.2	7.2
Horses	0.2	0.2	0.2	0.2	0.2	0.2
Total	**42.4**	**47.4**	**47.5**	**49.7**	**52.4**	**51.6**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 5-6: CH_4 Emissions from Manure Management (Gg)

Animal Type	1990	1995	1996	1997	1998	1999
Dairy Cattle	422	527	532	561	583	593
Beef Cattle	150	165	164	162	160	159
Swine	527	630	610	670	770	728
Sheep	3	2	2	2	2	2
Goats	1	1	1	1	1	1
Poultry	125	122	123	126	130	124
Horses	29	31	31	31	31	31
Total	**1,256**	**1,477**	**1,463**	**1,553**	**1,677**	**1,638**

Note: Totals may not sum due to independent rounding.

Table 5-7: N_2O Emissions from Manure Management (Gg)

Animal Type	1990	1995	1996	1997	1998	1999
Dairy Cattle	14	13	13	12	12	12
Beef Cattle	16	17	16	17	18	18
Swine	1	1	1	1	1	1
Sheep	+	+	+	+	+	+
Goats	+	+	+	+	+	+
Poultry	20	21	23	23	23	23
Horses	1	1	1	1	1	1
Total	**52**	**53**	**54**	**55**	**55**	**55**

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

- Animal population data (by animal type and State)
- Amount of nitrogen produced (amount per head times number of head)
- Amount of volatile solids produced (amount per head times number of head)
- 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)
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems

Both CH_4 and N_2O emissions were estimated by first determining activity data, including animal population, waste characteristics, and manure management system usage. For swine and dairy cattle, manure management system usage was determined for different farm size categories using data from USDA (USDA 1996b, 1998d, 2000h) and EPA (ERG 2000). For beef cattle and poultry, manure management system usage data was not tied to farm size (ERG 2000, USDA 2000i). For other animal types, manure management system usage was based on previous EPA estimates (EPA 1992).

Next, "base" methane conversion factors (MCFs) and N_2O emissions factors were determined for all manure management systems. Base MCFs for dry systems and base N_2O emission factors for all systems were set equal to default IPCC factors (IPCC 2000). Base MCFs for liquid/slurry and deep pit systems were calculated using the average annual ambient temperature for the climate zone where the animal populations are located. For anaerobic lagoon systems, the base MCFs were calculated based on the average monthly ambient temperature, the carryover of volatile solids in the system from month to month due to long storage times exhibited by these systems, and a factor to account for management and design practices that result in the loss of volatile solids from the system.

For each animal group—except sheep, goats, and horses—the base emission factors were weighted to incorporate the distribution of management systems used within each State to create an overall State-specific weighted emission factor. To calculate this weighted factor, the percent of manure for each animal group managed in a particular system in a State was multiplied by the emission factor for that system and State, and then summed for all manure management systems in the State.

Methane emissions were estimated by calculating the volatile solids (VS) production for all livestock. For each animal group except dairy cows, VS production was calculated using a national average VS production rate from the *Agricultural Waste Management Field Handbook* (USDA 1996b), which was then multiplied by the average weight of the animal and the State-specific animal population. For dairy cows, the national average VS constant was replaced with a mathematical relationship between milk production and VS, which was then multiplied by State-specific average annual milk production (USDA 2000j). The resulting VS for each animal group was then multiplied by the maximum methane producing capacity of the waste (B_o), and the State-specific methane conversion factors.

Nitrous oxide emissions were estimated by determining total Kjeldahl nitrogen (TKN)[2] production for all livestock wastes using livestock population data and nitrogen excretion rates. For each animal group, TKN production was calculated using a national average nitrogen excretion rate from the *Agricultural Waste Management Field Handbook* (USDA 1996b), which was then multiplied by the average weight of the animal and the State-specific animal population. State-specific weighted N_2O emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate N_2O emissions.

See Annex K for more detailed information on the methodology and data used to calculate methane and nitrous oxide emissions from manure management.

Data Sources

Animal population data for all livestock types, except horses and goats, were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a-

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

g). Horse population data were obtained from the FAOSTAT database (FAO 2000). Goat population data were obtained from the Census of Agriculture (USDA 1999d). Information regarding poultry turnover (i.e., slaughter) rate was obtained from State Natural Resource Conservation Service (NRCS) personnel (Lange 2000). Dairy cow and swine population data by farm size for each State, used for the weighted MCF and emission factor calculations, were obtained from the *Census of Agriculture*, which is conducted every five years (USDA 1999e).

Manure management system usage data for dairy and swine operations were obtained from USDA's Centers for Epidemiology and Animal Health (USDA 1996b, 1998d, 2000h) for small operations and from preliminary estimates for EPA's Office of Water regulatory effort for large operations (ERG 2000). Data for poultry layers were obtained from a voluntary United Egg Producers' survey (UEP 1999), previous EPA estimates (EPA 1992), and USDA's Animal Plant Health Inspection Service (USDA 2000i). Data for beef feedlots were also obtained from EPA's Office of Water (ERG 2000). Manure management system usage data for other livestock were taken from previous EPA estimates (EPA 1992). Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations, and data provided by those personnel (Poe et al. 1999). These organizations include State NRCS offices, State extension services, State universities, USDA National Agriculture Statistics Service (NASS), and other experts (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, and Wright 2000). Additional information regarding the percent of beef steer and heifers on feedlots was obtained from contacts with the national USDA office (Milton 2000).

Volatile solids and nitrogen excretion rate data from the USDA Agricultural Waste Management Field Handbook (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types. In addition, annual NASS data for average milk production per cow per State (USDA 2000j) were used to calculate State-specific volatile solids production rates for dairy cows for each year. Nitrous oxide emission factors and MCFs for dry systems were taken from *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). Methane conversion factors for liquid/slurry systems were calculated based on average ambient temperatures of the counties in which animal populations were located.

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 regional location and the exact methane generating characteristics of each type of manure management system. Because of significant shifts toward larger swine and dairy farms, it is believed that increasing amounts of manure are being managed in liquid manure management systems. The existing estimates reflect these shifts in the weighted MCFs based on the 1992 and 1997 farm-size data. However, the assumption of a direct relationship between farm size and liquid system usage may not apply in all cases and may vary based on geographic location. In addition, the CH_4 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.

IPCC (2000) published default CH_4 conversion factors of 0 to 100 percent for anaerobic lagoon systems, which reflects the wide range in performance that may be achieved with these systems. There exist relatively few data points on which to determine country-specific MCFs for these systems. In the United States, many livestock waste treatment systems classified as anaerobic lagoons are actually holding ponds that are substantially organically overloaded and therefore not producing methane at the same rate as a properly designed lagoon. In addition, these systems may not be well operated, contributing to higher loading rates when sludge is allowed to enter the treatment portion of the lagoon or the lagoon volume is pumped too low to allow treatment to occur. Rather than setting the MCF for all anaerobic lagoon systems in the United States based on data available from optimized lagoon systems, an MCF methodology was developed that more closely matches observed system performance and accounts for the affect of temperature on system performance.

However, there is uncertainty related to the new methodology. The MCF methodology used includes a factor to account for management and design practices that result in the loss of volatile solids from the management system. This factor is currently estimated based on data from anaerobic lagoons in temperate climates, and from only three systems. However, this methodology is intended to account for systems across a range of management practices. Future work in gathering measurement data from animal waste lagoon systems across the country will contribute to the verification and refinement of this methodology. It will also be evaluated whether lagoon temperatures differ substantially from ambient temperatures and whether a lower bound estimate of temperature should be established for use with this methodology.

The IPCC provides a suggested MCF for poultry waste management operations of 1.5 percent. Additional study is needed in this area to determine if poultry high rise houses promote sufficient aerobic conditions to warrant a lower MCF.

The default N_2O emission factors published in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) were 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 nitrous oxide at different rates, although a single N_2O emission factors was used for both system types. In addition, there are little data available to determine the extent to which nitrification-denitrification occurs in animal waste management systems. Ammonia concentrations that are present in poultry and swine systems suggest that the N_2O emission estimates may be high. Current research to measure N_2O from liquid manure systems also suggests that these emissions may be overstated. At this time, there are insufficient data available to develop U.S.-specific N_2O emission factors; however, this is an area of on-going research, and warrants further study as more data become available.

Although an effort was made to introduce the variability in volatile solids production due to differences in diet for dairy cows, additional work is needed to establish the relationship between milk production and volatile solids production. In addition, the corresponding dairy methane emissions may be underestimated because milk production was unable to be correlated to specific manure management systems in each State. A methodology to assess variability in swine volatile solids production would be useful in future inventory estimates.

Uncertainty also exists with the maximum CH_4 producing potential of volatile solids excreted by different animal groups (i.e., B_o). The B_o values used in the CH_4 calculations are published values for U.S. animal waste. However, there are several studies that provide a range of B_o values for certain animals, including dairy and swine. Separate B_o values for dairy cows and dairy heifers were chosen to better represent the feeding regimens of these animal groups. For example, dairy heifers do not receive an abundance of high energy feed and consequently, dairy heifer manure will not produce as much CH_4 as manure from a milking cow. However, the data available for B_o values are sparse, and do not necessarily reflect the rapid changes that have occurred in this industry with respect to feed regimens. Further investigation to these waste characteristics is an area for further improvement.

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. Once the environment becomes anaerobic, methane is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the methane produced is oxidized by aerobic methanotrophic 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 un-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), the lower stems and roots of the rice plants are dead so the primary methane transport pathway to the atmosphere is blocked. The quantities of methane released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with more shallow flooding depths. 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. Mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence methane emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, and seeding and weeding practices). The factors that determine the amount of organic material that is available to decompose (i.e., organic fertilizer use, soil type, rice variety,[3] and cultivation practices) are the most important variables influencing methane emissions over an entire growing season because the total amount of methane released depends primarily on the amount of organic substrate available. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of methane production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to methane, that time is short relative to a growing season, so the dependence of emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence methane emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate, and ammonium sulfate) appear to inhibit methane formation.

Rice is cultivated in seven States: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Soil types, soil temperatures, rice varieties, and cultivation practices for rice vary from State to State, and even from farm to farm. However, most rice farmers utilize organic fertilizers in the form of rice residue from the previous crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields, usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of Arkansas, southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop. This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, the amount of organic material that is available for decomposition is considerably higher than with the first (i.e., primary) crop. Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop.

Rice cultivation is a small source of methane in the United States (Table 5-8 and Table 5-9). In 1999, methane emissions from rice cultivation were 10.7 Tg CO_2 Eq. (509 Gg)—only about 2 percent of total U.S. methane emissions. Although annual emissions fluctuated up and down between the years 1990 and 1999, there was a general increase over the nine year period due to an increase in harvested area. Between 1990 and 1999, total emissions increased by 23 percent.

The factors that affect the rice acreage harvested in any year vary from State to State. In Florida, the State having the smallest harvested rice area, rice acreage is largely a function of sugarcane acreage. Sugarcane fields are flooded each year after harvest to control pests, and on this flooded land a rice crop is grown along with a ratoon crop of sugarcane (Schueneman 1997). In Mis-

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[3] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

Table 5-8: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	1995	1996	1997	1998	1999
Arkansas	2.5	2.8	2.5	2.9	3.2	3.5
California	1.5	1.8	1.9	2.0	1.8	2.1
Florida	0.1	0.1	0.1	0.1	0.1	0.1
Louisiana	2.7	2.8	2.6	2.9	3.0	3.0
Mississippi	0.5	0.6	0.5	0.5	0.6	0.7
Missouri	0.2	0.3	0.3	0.3	0.4	0.5
Texas	1.2	1.0	1.0	0.8	0.9	0.8
Total	**8.7**	**9.5**	**8.8**	**9.6**	**10.1**	**10.7**

Note: Totals may not sum due to independent rounding.

Table 5-9: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1995	1996	1997	1998	1999
Arkansas	121	135	118	140	154	16
California	72	85	91	94	87	98
Florida	3	5	5	4	4	4
Louisiana	127	133	125	136	145	144
Mississippi	26	30	22	25	28	34
Missouri	10	14	12	15	18	23
Texas	55	50	47	40	44	40
Total	**414**	**452**	**419**	**455**	**481**	**509**

Note: Totals may not sum due to independent rounding.

souri, rice acreage is affected by weather (e.g., rain during the planting season may prevent the planting of rice), the price differential between soybeans and rice (i.e., if soybean prices are higher, then soybeans may be planted on some of the land which would otherwise have been planted in rice), and government support programs (Stevens 1997). The price differential between soybeans and rice also affects rice acreage in Mississippi. 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 therefore harvested area, are affected 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 Louisiana, rice area is influenced by government programs, weather conditions (e.g., rainfall during the planting season), as well as the price differential between rice and corn and other crops (Saichuk 1997). Arkansas rice area has been influenced in the past by government programs. However, due to the phase-out of these programs nationally, which began in 1996, spring commodity prices have had a greater effect on the amount of land planted in rice in recent years (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. Because season lengths are quite 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, an earlier 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 extension agents 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 continuously flooded, flooding season lengths varied considerably among States; therefore, emissions were calculated separately for each State.

Emissions from ratooned and primary areas are estimated separately. Information on ratoon flooding season lengths was collected from agricultural extension agents in the States that practice ratooning, and emission factors for both the primary season and the ratoon season were derived from published results of field experiments in the United States.

Data Sources

The harvested rice areas for the primary and ratoon crops in each State are presented in Table 5-10. Data for 1990 through 1999 for all States except Florida were taken from *U.S. Department of Agriculture's National Agriculture Statistics Data—Published Estimates Database* (USDA 2000). Harvested rice areas in Florida from 1990 to 1999 were obtained from Tom Schueneman (1999b, 1999c, 2000), a Florida Agricultural Extension Agent. Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each State. In Arkansas, ratooning occurred only in 1998 and 1999, when the ratooned area was less than 1 percent of the primary area (Slaton 1999a, 2000). In Florida, the ratooned area was 50 percent of the primary area from 1990 to 1998 (Schueneman 1999a) and about 65 percent of the primary area in 1999 (Schueneman 2000). In the other two States in which ratooning is practiced (i.e., Louisiana and Texas), the percentage of the primary area that was ratooned was constant over the entire 1990 to 1999 period. In Louisiana it was 30 percent (Linscombe 1999a, Bollich 2000), and in Texas it was 40 percent (Klosterboer 1999a, 2000).

Information about flooding season lengths was obtained from agricultural extension agents in each State (Beck 1999, Guethle 1999, Klosterboer 1999b, Linscombe 1999b, Scardaci 1999a and 1999b, Schueneman 1999b, Slaton 1999b, Street 1999a and 1999b). These data were assumed to apply to 1990 through 1999, and are presented in Table 5-11.

To determine what daily methane emission factors should be used for the primary and ratoon crops, methane flux information from rice field measurements in the United States was collected. Experiments which involved the application of nitrate or sulfate fertilizers, or other substances believed to suppress methane formation, as well as experiments in which measurements were not made over an entire flooding season or in which floodwaters were drained mid-season, were excluded from the analysis. This process left ten field experiments from California (Cicerone et al. 1992), Texas (Sass et al. 1990, 1991a, 1991b, 1992), and Louisiana (Lindau et al. 1991, Lindau and Bollich 1993, Lindau et al. 1993, Lindau et al. 1995, Lindau et al. 1998).[4] These experimental results were then sorted by season and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The results for the primary crop showed no consistent correlation between emission rate and type or magnitude of fertilizer application. Although individual experiments have shown a significant increase in emissions when organic fertilizers are added, when the results were combined, emissions from fields that received organic fertilizers were not found to be, on average, higher

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[4] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the reasons just mentioned. In addition, one measurement from the ratooned fields (i.e., the 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 (IPCC/UNEP/OECD/IEA 1997).

Table 5-10: Rice Areas Harvested (Hectares)

State/Crop	1990	1995	1996	1997	1998	1999
Arkansas						
Primary	485,633	542,291	473,493	562,525	617,159	665,722
Ratoon*	NO	NO	NO	NO	202	202
California	159,854	188,183	202,347	208,822	193,444	216,512
Florida						
Primary	4,978	9,713	8,903	7,689	8,094	7,229
Ratoon	2,489	4,856	4,452	3,845	4,047	4,673
Louisiana						
Primary	220,558	230,676	215,702	235,937	250,911	249,292
Ratoon	66,168	69,203	64,711	70,781	75,273	74,788
Mississippi	101,174	116,552	84,176	96,317	108,458	130,716
Missouri	32,376	45,326	38,446	47,349	57,871	74,464
Texas						
Primary	142,857	128,693	120,599	104,816	114,529	104,816
Ratoon	57,143	51,477	48,240	41,926	45,811	41,926
Total	**1,273,229**	**1,386,969**	**1,261,068**	**1,380,008**	**1,475,799**	**1,570,340**

Note: Totals may not sum due to independent rounding.

* Arkansas ratooning occurred only in 1998 and 1999.

NO (Not Occurring)

Table 5-11: Rice Flooding Season Lengths (Days)

State/Crop	Low	High
Arkansas		
Primary	60	80
Ratoon	30	40
California	100	145
Florida		
Primary	90	110
Ratoon	40	60
Louisiana		
Primary	90	120
Ratoon	70	75
Mississippi	68	82
Missouri	80	100
Texas		
Primary	60	80
Ratoon	40	60

that those from fields that receive synthetic fertilizer only. In addition, there appeared to be no correlation between fertilizer application rate and emission rate, either for synthetic or organic fertilizers. These somewhat surprising results are probably due to other variables that have not been taken into account, such as timing and mode of fertilizer application, soil type, cultivar type, and other cultivation practices. There were limited results from ratooned fields. Of those that received synthetic fertilizers, there was no consistent correlation between emission rate and amount of fertilizer applied. All the ratooned fields that received synthetic fertilizer had emission rates that were higher than the one ratoon experiment in which no synthetic fertilizer was applied. Given these results, the lowest and highest emission rates measured in primary fields that received synthetic fertilizer only—which bounded the results from fields that received both synthetic and organic fertilizers—were used as the emission factor range for the primary crop, and the lowest and highest emission rates measured in all the ratooned fields were used as the emission factor range for the ratoon crop. These ranges are 0.020 to 0.609 g/m^2-day for the primary crop, and 0.301 to 0.933 g/m^2-day for the ratoon crop.

Uncertainty

The largest uncertainty in the calculation of CH$_4$ emissions from rice cultivation is associated with the emission factors. Daily average emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This variability is due to differences in cultivation practices, particularly the type, amount, and mode of fertilizer application; differences in cultivar type; and differences in soil and climatic conditions. By separating primary from ratooned areas, this Inventory has accounted for some of this. A range for both the primary (0.315 g/m^{2}day ±93 percent) and ratoon crop (0.617

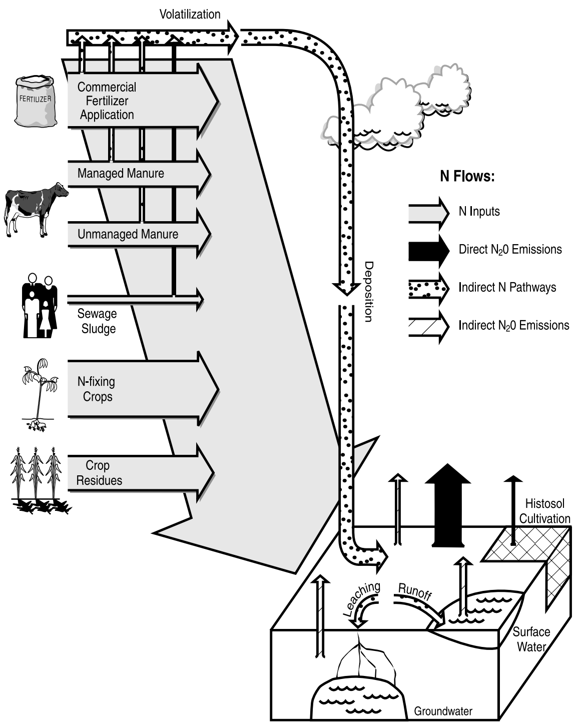
g/m^{2}day ±51 percent) has been used in these calculations to reflect the remaining uncertainty. Based on this range, total methane emissions from rice cultivation in 1999 were estimated to have been approximately 1.6 to 19.8 Tg CO_2 Eq. (76 to 943 Gg), or 10.7 Tg CO_2 Eq. ±85 percent.

Two other sources of uncertainty are the flooding season lengths and ratoon areas 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. Even within a State, flooding seasons can vary by county and cultivar type (Linscombe 1999a). Data on the areas ratooned each year are not compiled regularly, so expert judgement was used to estimate these areas.

The last source of uncertainty is in the practice of flooding outside of the normal rice season. According to agriculture extension agents, all of the rice-growing States practice this on some part of their rice acreage, ranging from 5 to 33 percent of the rice acreage. Fields are flooded for a variety of reasons: to provide habitat for waterfowl, to provide ponds for crawfish production, and to aid in rice straw decomposition. To date, methane flux measurements have not been undertaken in these flooded areas, so this activity is not included in the emission estimates presented here.

Figure 5-2

Sources of N_2O Emissions from Agricultural Soils



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from agricultural soils in the United States. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also shown with arrows. On the lower right-hand side is a cut-away view of a representative section of managed soil; histosol cultivation is represented here.

Agricultural Soil Management

Nitrous oxide (N_2O) is produced naturally in soils through the microbial processes of nitrification and denitrification.[5] 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 (Figure 5-2). Direct additions occur through various soil management practices and from the deposition of manure on soils by animals on pasture, range, and paddock (i.e., by animals whose manure is not managed). Soil management practices that add nitrogen to soils include fertilizer use, application of managed livestock manure, disposal of sewage sludge, production of nitrogen-fixing crops, application of crop residues, and cultivation of histosols (i.e., soils with a high organic matter content, otherwise known as organic soils).[6] Indirect additions of nitrogen to soils occur through two mechanisms: 1) volatilization and subsequent atmospheric

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[5] Nitrification and denitrification are two processes within the nitrogen cycle that are brought about by certain microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4) to nitrate (NO_3), and denitrification is the anaerobic microbial reduction of nitrate to dinitrogen gas (N_2). Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well understood mechanism (Nevison 2000).

[6] Cultivation of histosols does not, *per se*, "add" nitrogen to soils. Instead, the process of cultivation enhances mineralization of old, nitrogen-rich organic matter that is present in histosols, thereby enhancing N_2O emissions from histosols.

deposition of applied nitrogen;[7] and 2) surface runoff and leaching of applied nitrogen into groundwater and surface water. 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 associated with these other fluxes, they have not been estimated.

Agricultural soil management is the largest source of N_2O in the United States.[8] Estimated emissions from this source in 1999 are 298.3 Tg CO_2 Eq. (962 Gg), or approximately 69 percent of total U.S. N_2O emissions. Although annual agricultural soil management emissions fluctuated between 1990 and 1999, there was a general increase in emissions over the ten-year period (Table 5-12 and Table 5-13).[9] This general increase in emissions was due primarily to an increase in synthetic fertilizer use, manure production, and crop production over this period. The year-to-year fluctuations are largely a reflection of annual variations in synthetic fertilizer consumption and crop production. Over the ten-year period, total emissions of N_2O from agricultural soil management increased by approximately 11 percent. Estimated emissions, by subsource, are provided in Table 5-14, Table 5-15, and Table 5-16.

Methodology

The methodology used to estimate emissions from agricultural soil management is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). The *Revised 1996 IPCC Guidelines* divide this N_2O source category into three components: (1) direct emissions from managed soils due to applied nitrogen and cultivation of histosols; (2) direct emissions from soils due to the deposition of manure by livestock on pasture, range, and paddock; and (3) indirect emissions from soils induced by applied nitrogen.

Annex L provides more detailed information on the methodologies and data used to calculate N_2O emissions from each of these three components.

Direct N_2O Emissions from Managed Soils

Direct N_2O emissions from managed soils are composed of two parts, which are estimated separately and then summed. These two parts are 1) emissions due to nitrogen applications, and 2) emissions from histosol cultivation.

Estimates of direct N_2O emissions from nitrogen applications were based on the total amount of nitrogen that is applied to soils annually through the following practices: (a) the application of synthetic and organic commercial fertilizers, (b) the application of livestock manure through both daily spread operations and through the eventual application of manure that had been stored in manure management systems, (c) the application of sewage sludge, (d) the production of nitrogen-fixing crops, and (e) the application of crop residues. For each of these practices, the annual amounts of nitrogen applied were estimated as follows:

a) Synthetic and organic commercial fertilizer nitrogen applications were derived from annual fertilizer consumption data and the nitrogen content of the fertilizers.

b) Livestock manure nitrogen applications were based on the assumption that all livestock manure is applied to soils except for two components: 1) a small portion of poultry manure that is used as a livestock feed supplement; and 2) the manure from pasture, range, and paddock livestock. The manure nitrogen data were derived from animal population and weight statistics, information on manure management system usage, annual nitrogen excretion rates for each animal type, and information on the fraction of poultry litter that is used as a livestock feed supplement.

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[7] These processes entail volatilization of applied nitrogen as ammonia (NH_3) and oxides of nitrogen (NO_x), transformations of these gases within the atmosphere (or upon deposition), and deposition of the nitrogen primarily in the form of particulate ammonium (NH_4), nitric acid (HNO_3), and oxides of nitrogen.

[8] Note that the emission estimates for this source category include applications of nitrogen to *all* soils, but the term "Agricultural Soil Management" is kept for consistency with the reporting structure of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

[9] Emission estimates for all years are presented in Annex L.

Table 5-12: N_2O Emissions from Agricultural Soil Management (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999
Direct	**195.1**	**206.4**	**213.9**	**219.4**	**220.1**	**218.0**
Managed Soils	154.4	162.4	170.0	176.8	178.4	176.6
Pasture, Range, & Paddock Livestock	40.7	44.0	43.9	42.6	41.8	41.4
Indirect	73.9	79.0	80.7	80.4	80.2	80.3
Total	**269.0**	**285.4**	**294.6**	**299.8**	**300.3**	**298.3**

Note: Totals may not sum due to independent rounding.

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

Activity	1990	1995	1996	1997	1998	1999
Direct	**629**	**666**	**690**	**708**	**710**	**703**
Managed Soils	498	524	549	570	575	570
Pasture, Range, & Paddock Livestock	131	142	142	138	135	133
Indirect	**238**	**255**	**260**	**259**	**259**	**259**
Total	**868**	**921**	**950**	**967**	**969**	**962**

Note: Totals may not sum due to independent rounding.

Table 5-14: Direct N_2O Emissions from Managed Soils (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999
Commercial Fertilizers*	55.4	59.2	61.2	61.3	61.4	61.8
Livestock Manure	12.7	13.2	13.4	13.7	13.8	13.8
Sewage Sludge	0.5	0.7	0.7	0.7	0.7	0.7
N Fixation	58.6	62.0	64.0	68.2	69.3	68.2
Crop Residue	23.3	23.4	26.9	29.1	29.3	28.3
Histosol Cultivation	3.9	3.9	3.9	3.9	3.9	3.9
Total	**154.4**	**162.5**	**170.1**	**176.9**	**178.5**	**176.7**

Note: Totals may not sum due to independent rounding.
* Excludes sewage sludge and livestock manure used as commercial fertilizers.

Table 5-15: Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure (Tg CO_2 Eq.)

Animal Type	1990	1995	1996	1997	1998	1999
Beef Cattle	35.2	38.9	39.0	37.8	37.0	36.7
Dairy Cows	1.7	1.5	1.4	1.3	1.3	1.2
Swine	+	+	+	+	+	+
Sheep	+	+	+	+	+	+
Goats	+	+	+	+	+	+
Poultry	+	+	+	+	+	+
Horses	2.5	2.7	2.7	2.7	2.7	2.7
Total	**40.7**	**44.0**	**43.9**	**42.6**	**41.8**	**41.4**

Note: Totals may not sum due to independent rounding.
\+ Less than 0.5 Tg CO_2 Eq.

Table 5-16: Indirect N_2O Emissions (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999
Volatilization & Atm. Deposition	**11.7**	**12.5**	**12.7**	**12.6**	**12.6**	**12.6**
Commercial Fertilizers*	4.9	5.3	5.4	5.5	5.5	5.5
Livestock Manure	6.6	7.1	7.1	7.0	7.0	6.9
Sewage Sludge	+	+	+	+	+	+
Surface Leaching & Runoff	**62.2**	**66.5**	**68.0**	**67.8**	**67.6**	**67.7**
Commercial Fertilizers*	36.9	39.5	40.8	40.9	40.9	41.2
Livestock Manure	24.9	26.5	26.6	26.4	26.1	26.0
Sewage Sludge	+	0.5	0.5	0.6	0.6	0.6
Total	**73.9**	**79.0**	**80.7**	**80.4**	**80.2**	**80.3**

Note: Totals may not sum due to independent rounding.
* Excludes sewage sludge and livestock manure used as commercial fertilizers.
+ Less than 0.5 Tg CO_2 Eq.

c) Sewage sludge nitrogen applications were derived from estimates of annual U.S. sludge production, the nitrogen content of the sludge, and periodic surveys of sludge disposal methods.

d) The amounts of nitrogen made available to soils through the cultivation of nitrogen-fixing crops were based on estimates of the amount of nitrogen in aboveground plant biomass, which were derived from annual crop production statistics, mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents of the plant biomass.

e) Crop residue nitrogen applications were derived from information about which residues are typically left on the field, the fractions of residues left on the field, annual crop production statistics, mass ratios of aboveground residue to crop product, and dry matter fractions and nitrogen contents of the residues.

After the annual amounts of nitrogen applied were estimated for each practice, each amount of nitrogen was reduced by the fraction that is assumed to volatilize according to the *Revised 1996 IPCC Guidelines* and the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. The net amounts left on the soil from each practice were then summed to yield total unvolatilized applied nitrogen, which was multiplied by the IPCC default emission factor for nitrogen applications.

Estimates of annual N_2O emissions from histosol cultivation were based on estimates of the total U.S. acreage of histosols cultivated annually. To estimate annual emissions, these areas were multiplied by the IPCC default emission factor for temperate histosols.[10]

Total annual emissions from nitrogen applications, and annual emissions from histosol cultivation, were then summed to estimate total direct emissions from managed soils.

Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure

Estimates of N_2O emissions from this component are based on amounts of nitrogen in the manure that is deposited annually on soils by livestock in pasture, range, and paddock. Estimates of annual manure nitrogen from these livestock were derived from animal population and weight statistics; information on the fraction of the total population of each animal type that is on pasture, range, or paddock; and annual nitrogen excretion rates for each animal type. The annual amounts of manure nitrogen from each animal type were summed over all animal types to yield total pasture, range, and paddock manure nitrogen, which was then multiplied by the IPCC default emission factor for pasture, range, and paddock nitrogen to estimate N_2O emissions.

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[10] Note that the IPCC default emission factors for histosols have been revised in the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). The revised default emission factor for temperate histosols (IPCC 2000) was used in these calculations.

Indirect N_2O Emissions from Soils

Indirect emissions of N_2O are composed of two parts, which are estimated separately and then summed. These two parts are 1) emissions resulting from volatilization and subsequent deposition of the nitrogen in applied fertilizers, applied sewage sludge, and all livestock manure, and 2) leaching and runoff of nitrogen in applied fertilizers, applied sewage sludge, and all livestock manure.[11] The activity data (i.e., nitrogen in applied fertilizers, applied sewage sludge, and all livestock manure) are the same for both parts, and were estimated in the same way as for the direct emission estimates.

To estimate the annual amount of applied nitrogen that volatilizes, the annual amounts of applied synthetic fertilizer nitrogen, applied sewage sludge nitrogen, and all livestock manure nitrogen, were each multiplied by the appropriate IPCC default volatilization fraction. The three amounts of volatilized nitrogen were then summed, and the sum was multiplied by the IPCC default emission factor for volatilized/deposited nitrogen.

To estimate the annual amount of nitrogen that leaches or runs off, the annual amounts of applied synthetic fertilizer nitrogen, applied sewage sludge nitrogen, and all livestock manure nitrogen were each multiplied by the IPCC default leached/runoff fraction. The three amounts of leached/runoff nitrogen were then summed, and the sum was multiplied by the IPCC default emission factor for leached/runoff nitrogen.

Total annual indirect emissions from volatilization, and annual indirect emissions from leaching and runoff, were then summed to estimate total indirect emissions of N_2O from managed soils.

Data Sources

The activity data used in these calculations were obtained from numerous sources. Annual synthetic and organic fertilizer consumption data for the United States were obtained from annual publications on commercial fertilizer statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999). Fertilizer nitrogen contents were taken from these same publications or Terry (1997). Livestock population data were obtained from USDA publications (USDA 1994b,c; 1995a,b; 1998a,c; 1999a-e; 2000a-g), the FAOSTAT database (FAO 2000), and Lange (2000). Manure management information was obtained from Poe et al. (1999), Safley et al. (1992), and personal communications with agricultural experts (Anderson 2000, Deal 2000, Johnson 2000, Miller 2000, Milton 2000, Stettler 2000, Sweeten 2000, Wright 2000). Livestock weight data were obtained from Safley (2000), USDA (1996, 1998d), and ASAE (1999); daily rates of nitrogen excretion from ASAE (1999) and USDA (1996); and information about the fraction of poultry litter used as a feed supplement from Carpenter (1992). Data collected by the U.S. EPA were used to derive annual estimates of land application of sewage sludge (EPA 1993, Bastian 1999). The nitrogen content of sewage sludge was taken from National Research Council (1996). Annual production statistics for nitrogen-fixing crops were obtained from USDA reports (USDA 1994a, 1997, 1998b, 1999f, 2000i), a book on forage crops (Taylor and Smith 1995, Pederson 1995, Beuselinck and Grant 1995, Hoveland and Evers 1995), and personal communications with forage experts (Cropper 2000, Gerrish 2000, Hoveland 2000, Evers 2000, and Pederson 2000). Mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents for nitrogen-fixing crops were obtained from Strehler and Stützle (1987), Barnard and Kristoferson (1985), Karkosh (2000), Ketzis (1999), and IPCC/UNEP/OECD/IEA (1997). Annual production statistics for crops whose residues are left on the field were obtained from USDA reports (USDA 1994a, 1997, 1998b, 1999f). Aboveground residue to crop mass ratios, residue dry matter fractions, and residue nitrogen contents were obtained from Strehler and Stützle (1987), Turn et al. (1997), and Ketzis (1999). Estimates of the fractions of residues left on the field were based on information provided by Karkosh (2000), and on information about rice residue burning (see the Agricultural Residue Burning section). The annual areas of cultivated histosols were estimated from 1982, 1992, and 1997 statistics in USDA's 1992 and 1997 National Resources Inventories (USDA 1994d and 2000h, as cited in Paustian 1999 and Sperow 2000, respectively).

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[11] Total livestock manure nitrogen is used in the calculation of indirect N_2O emissions because all manure nitrogen, regardless of how the manure is managed or used, is assumed to be subject to volatilization and leaching and runoff.

All emission factors, volatilization fractions, and the leaching/runoff fraction were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

Uncertainty

The amount of N_2O emitted from managed soils depends not only on N inputs, but also on a large number of variables, including organic carbon availability, O_2 partial pressure, soil moisture content, pH, and soil temperature. However, the effect of the combined interaction of these other variables on N_2O flux is complex and highly uncertain. Therefore, the IPCC default methodology, which is used here, is based only on N inputs and does not utilize these other variables. As noted in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), this is a generalized approach that treats all soils as being under the same conditions. The estimated ranges around the IPCC default emission factors provide an indication of the uncertainty in the emission estimates due to this simplified methodology. Most of the emission factor ranges are about an order of magnitude, or larger. Developing an emission estimation methodology that explicitly utilizes these other variables will require more scientific research, and will likely involve the use of process models.

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 non-commercial fertilizers (other than the estimated manure and crop residues) have 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. The livestock excretion values, while based on detailed population and weight statistics, were derived using simplifying assumptions concerning the types of management systems employed. Statistics on sewage sludge applied to soils were not available on an annual basis; annual production and application estimates were based on two data points that were calculated from surveys that yielded uncertainty levels as high as 14 percent (Bastian 1999). The production statistics for the nitrogen-fixing crops that are forage legumes are highly uncertain because statistics are not compiled for these crops except for alfalfa, and the alfalfa statistics include alfalfa mixtures. Conversion factors for the nitrogen-fixing crops were based on a limited number of studies, and may not be representative of all conditions in the United States. Data on crop residues left on the field are not available, so expert judgement was used to estimate the amount of residues applied to soils. And finally, the estimates of cultivated histosol areas are uncertain because they are from a natural resource inventory that was not explicitly designed as a soil survey. However, these areas are consistent with those used in the organic soils component of the Land-Use Change and Forestry Chapter. Also, all histosols were assigned to the temperate climate regime; however, some of these areas are in subtropical areas, and therefore may be experiencing somewhat higher emission rates.[12]

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 left on or plowed back into the field, composted and then applied to soils, 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 oxides (NO_x), which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States; therefore, emissions from this source are minor. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, corn, barley, soybeans,

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[12] As discussed in Annex L, these issues regarding histosols will be researched in future U.S. Inventories.

and peanuts, and of these residues, less than 5 percent is burned each year, except for rice.[13] Annual emissions from this source over the period 1990 through 1999 averaged approximately 0.6 Tg CO_2 Eq. (28 Gg) of CH_4, 0.4 Tg CO_2 Eq. (1 Gg) of N_2O, 740 Gg of CO, and 33 Gg of NO_x (see Table 5-17 and Table 5-18).

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) ×(Residue/Crop Product Ratio)×(Fraction of Residues Burned *in situ*) ×(Dry Matter Content of the Residue)×(Burning Efficiency)×(Carbon Content of the Residue)× (Combustion Efficiency)[14]

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

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

Data Sources

The crop residues that are 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

Table 5-17: Emissions from Agricultural Residue Burning (Tg CO_2 Eq.)

Gas/Crop Type	1990	1995	1996	1997	1998	1999
CH_4	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	+	+	+
Sugarcane	+	+	+	+	+	+
Corn	0.2	0.2	0.3	0.3	0.3	0.3
Barley	+	+	+	+	+	+
Soybeans	0.1	0.1	0.1	0.2	0.2	0.2
Peanuts	+	+	+	+	+	+
N_2O	**0.4**	**0.4**	**0.4**	**0.4**	**0.5**	**0.4**
Wheat	+	+	+	+	+	+
Rice	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+
Soybeans	0.2	0.2	0.2	0.3	0.3	0.3
Peanuts	+	+	+	+	+	+
Total	**0.9**	**0.9**	**1.0**	**1.0**	**1.1**	**1.0**

\+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

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[13] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Data Sources" discussion below).

[14] 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 5-18: Emissions from Agricultural Residue Burning (Gg)*

Gas/Crop Type	1990	1995	1996	1997	1998	1999
CH_4	**25**	**24**	**28**	**29**	**30**	**28**
Wheat	5	4	4	5	5	4
Rice	2	2	3	2	2	2
Sugarcane	1	1	1	1	1	1
Corn	11	10	13	12	13	13
Barley	1	1	1	1	1	+
Soybeans	6	6	7	8	8	8
Peanuts	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**
Wheat	+	+	+	+	+	+
Rice	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+
Corn	+	+	+	+	+	+
Barley	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+
CO	**668**	**641**	**735**	**750**	**776**	**740**
Wheat	137	109	114	124	128	115
Rice	65	65	73	55	53	49
Sugarcane	18	20	19	21	22	23
Corn	282	263	328	328	347	336
Barley	16	13	15	13	13	11
Soybeans	148	167	183	207	211	203
Peanuts	2	2	2	2	2	2
NO_x	**28**	**28**	**32**	**33**	**34**	**33**
Wheat	4	3	3	3	3	3
Rice	2	2	3	2	2	2
Sugarcane	+	+	+	+	+	+
Corn	7	6	8	8	8	8
Barley	1	+	+	+	+	+
Soybeans	14	16	17	20	20	19
Peanuts	+	+	+	+	+	+

* Full molecular weight basis.

\+ Does not exceed 0.5 Gg

Note: Totals may not sum due to independent rounding.

burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

Crop production data were taken from the USDA's *Field Crops, Final Estimates 1987-1992, 1992-1997* (USDA 1994, 1998) and *Crop Production 1999 Summary* (USDA 2000). The production data for the crop types whose residues are burned are presented in Table 5-19.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, 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). Estimates of the percentage of rice acreage on which residue burning took place were obtained on a State-by-State basis from agricultural extension agents in each of the seven rice-producing States (Bollich 2000; Guethle 1999, 2000; Fife 1999; California Air Resources Board 1999; Klosterboer 1999a, 1999b, 2000; Linscombe 1999a, 1999b; Najita 2000; Schueneman 1999a, 1999b; Slaton 1999a, 1999b, 2000; Street 1999a, 1999b, 2000) (see Table 5-20 and Table 5-21). The estimates provided for Arkansas and Florida remained constant over the entire 1990 through 1999 period, while the estimates for all other States varied over the time series. For California, it was assumed that the annual percents of rice acreage burned in Sacramento Valley are representative of burning in the entire State, because the Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). The annual percents of rice acreage burned in Sacramento Valley were obtained from a report of the California Air Resources

Table 5-19: Agricultural Crop Production (Thousand Metric Tons of Product)

Crop	1990	1995	1996	1997	1998	1999
Wheat	74,292	59,404	61,980	67,534	69,327	62,662
Rice[a]	7,080	7,887	7,784	8,300	8,530	9,546
Sugarcane	25,525	27,922	26,729	28,766	30,896	32,406
Corn[b]	201,534	187,970	234,518	233,864	247,882	239,719
Barley	9,192	7,824	8,544	7,835	7,667	6,137
Soybeans	52,416	59,174	64,780	73,176	74,598	71,928
Peanuts	1,635	1,570	1,661	1,605	1,798	1,755

[a] Does not include rice production in Florida because rice residues are not burned in Florida (see Table 5-20).
[b] Corn for grain (i.e., excludes corn for silage).

Table 5-20: Percentage of Rice Area Burned by State

State	Percent Burned 1990-1998	Percent Burned 1999
Arkansas	10	10
California	variable[a]	23
Florida[b]	0	0
Louisiana	6	0
Mississippi	5	10
Missouri	3.5	5
Texas	1	2

[a] Values provided in Table 5-21.
[b] Burning of crop residues is illegal in Florida.

Table 5-21: Percentage of Rice Area Burned

Year	California	United States
1990	75	16
1995	59	15
1996	63	17
1997	34	12
1998	33	11
1999	23	9

Board (1999). These values declined over the 1990 through 1999 period because of a legislated reduction in rice straw burning (see Table 5-21). To derive the national percentage of rice acreage burned each year, the acreages burned in each State were summed and then divided by total U.S. rice harvested area (Table 5-21).

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The datum for sugarcane is from University of California (1977). Residue dry matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry matter content was obtained from Strehler and Stützle (1987). Peanut dry matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System. The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue carbon content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The nitrogen content of soybeans is from Barnard and Kristoferson (1985). The nitrogen content of peanuts is from Ketzis (1999). These data are listed in Table 5-22. 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 (see Table 5-23) 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, as well as 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 in the future.

Table 5-22: Key Assumptions for Estimating Emissions from Agricultural Residue Burning*

Crop	Reisduce/Crop Ration	Fraction of Residue Burned	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction
Wheat	1.3	0.03	0.93	0.4428	0.0062
Rice	1.4	variable	0.91	0.3806	0.0072
Sugarcane	0.8	0.03	0.62	0.4235	0.0040
Corn	1.0	0.03	0.91	0.4478	0.0058
Barley	1.2	0.03	0.93	0.4485	0.0077
Soybeans	2.1	0.03	0.87	0.4500	0.0230
Peanuts	1.0	0.03	0.86	0.4500	0.0106

* The burning efficiency and combustion efficiency for all crops were assumed to be 0.93 and 0.88, respectively.

Other sources of uncertainty include the residue/crop product mass 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.

Table 5-23: Greenhouse Gas Emission Ratios

Gas	Emission Ratio
CH_4[a]	0.004
CO[a]	0.060
N_2O[b]	0.007
NO_x[b]	0.121

[a] Mass of carbon compound released (units of C) relative to mass of total carbon released from burning (units of C).

[b] Mass of nitrogen compound released (units of N) relative to mass of total nitrogen released from burning (units of N).

6. Land-Use Change and Forestry

This chapter provides an assessment of the net carbon dioxide (CO_2) flux caused by 1) changes in forest carbon stocks; 2) changes in agricultural soil carbon stocks; and 3) changes in yard trimming carbon stocks in landfills. Seven components of forest carbon stocks are analyzed: trees, understory, forest floor, forest soils, logging residues, wood products, and landfilled wood. The estimated CO_2 flux from each of these forest components is based on carbon stock estimates developed by the USDA Forest Service, using methodologies that are consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Changes in agricultural soil carbon stocks include mineral and organic soil carbon stock changes due to agricultural land use and land management (i.e., use and management of cropland and grazing land), and emissions of CO_2 due to the application of crushed limestone and dolomite to agricultural soils. The methods in the *Revised 1996 IPCC Guidelines* were used to estimate all three components of changes in agricultural soil carbon stocks. Changes in yard trimming carbon stocks in landfills were estimated using EPA's method of analyzing life cycle greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). Note that the chapter title "Land-Use Change and Forestry" has been used to retain consistency with IPCC reporting structure; however, the chapter covers land-use activities, as well as land-use change and forestry activities. Therefore, except in table titles, the term "land use, land-use change, and forestry" will be used in the remainder of this chapter.

Unlike the assessments in other chapters, which are based on annual activity data, the flux estimates in this chapter, with the exception of emissions from liming and carbon storage associated with yard trimmings disposed in landfills, are based on periodic activity data in the form of forest and land use surveys. Carbon dioxide fluxes from forest carbon stocks and from agricultural soils are calculated on an average annual basis over five or ten year periods. The resulting annual averages are applied to years between surveys. As a result of this data structure, estimated CO_2 fluxes are constant over multi-year intervals. In addition, because the most recent national forest and land use surveys were completed for the year 1997, the estimates of the CO_2 flux from forest carbon stocks are based in part on modeled projections of stock estimates for years since 1997.

Estimated total annual net CO_2 flux from land use, land-use change, and forestry in 1999 is 990.4 Tg CO_2 Eq. (270 Tg C) net sequestration (Table 6-1 and Table 6-2). This represents an offset of approximately 15 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net sequestration declined by about 7 percent between 1990 and 1999. This decline is primarily due to increasing forest harvests and land-use changes, which resulted in decreasing net sequestration rates for forests.

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

Component	1990	1995	1996	1997	1998	1999
Forests	(1,001.7)	(938.3)	(942.7)	(903.5)	(897.2)	(905.7)
Agricultural Soils	(40.4)	(68.8)	(68.9)	(69.0)	(77.3)	(77.0)
Landfilled Yard Trimmings	(17.8)	(12.0)	(10.0)	(9.4)	(8.8)	(7.7)
Total Net Flux	**(1,059.9)**	**(1,019.1)**	**(1,021.6)**	**(981.9)**	**(983.3)**	**(990.4)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding. Lightly shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

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

Component	1990	1995	1996	1997	1998	1999
Forests	(273)	(256)	(257)	(246)	(245)	(247)
Agricultural Soils	(11)	(19)	(19)	(19)	(21)	(21)
Landfilled Yard Trimmings	(5)	(3)	(3)	(3)	(2)	(2)
Total Net Flux	**(289)**	**(278)**	**(279)**	**(268)**	**(268)**	**(270)**

Note: 1 Tg C = 1 Tg Carbon = 1 million metric tons carbon. This table has been included to facilitate comparison with previous U.S. Inventories. Parentheses indicate net sequestration. Totals may not sum due to independent rounding. Lightly shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Changes in Forest Carbon Stocks

The United States covers roughly 2,263 million acres, of which 33 percent (747 million acres) is forest land (Smith and Sheffield 2000). Forest land acreage has remained fairly constant during the last several decades. Between 1977 and 1987, forest land declined by approximately 5.9 million acres, and then between 1987 and 1997, the area increased by about 9.2 million acres. Although these changes in forest area are in opposite directions, they represent average annual fluctuations of only about 0.1 percent.

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)
- Forest floor (i.e., fine woody debris, tree litter, and humus)
- Down dead wood (i.e., logging residue and other dead wood on the ground)
- 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 accumulate 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. For this reason, the term "apparent flux" is used in this chapter. 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., net sequestration) of carbon during the 1990s. Due to improvements in U.S. agricultural productivity, the rate of forest 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 taken out of crop production, primarily between 1920 and 1950, and were allowed to revert to forests 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 have been 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 forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, 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 over the last century.

U.S. forest components and harvested wood components were estimated to account for an average annual net sequestration of 940.1 Tg CO_2 Eq. (256.4 Tg C) over the period 1990 through 1999 (Table 6-3 and Table 6-4).[1] This net sequestration is a reflection of net forest growth and increasing forestland area. The rate of annual sequestration, however, declined by about 10 percent between 1990 and 1999. This is due to increasing harvests and land-use changes over this period (Haynes 2000, Smith and Sheffield 2000). The relatively large shift in annual net sequestration from 1996 to 1997 is the result of calculating average annual forest fluxes from periodic, rather than annual, activity data.

Table 6-5 presents the carbon stock estimates for forests (i.e., trees, understory, forest floor, and forest soil), wood products, and landfilled wood. 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). Logging residue stocks were not available because these fluxes were not calculated as a difference between stocks, but as a difference between wood cut and wood removed from the site for processing.

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[1] This average annual net sequestration is based on the entire time series (1990 through 1999), rather than the abbreviated time series presented in Table 6-3 and Table 6-4.

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

Description	1990	1995	1996	1997	1998	1999
Apparent Forest Flux	**(791.6)**	**(735.2)**	**(735.2)**	**(690.8)**	**(690.8)**	**(690.8)**
Trees	(414.0)	(384.6)	(384.6)	(387.6)	(387.6)	(387.6)
Understory	(5.1)	(5.1)	(5.1)	(4.0)	(4.0)	(4.0)
Forest Floor	(57.6)	(55.4)	(55.4)	(51.0)	(51.0)	(51.0)
Forest Soils	(251.5)	(226.6)	(226.6)	(184.8)	(184.8)	(184.8)
Logging Residues	(63.4)	(63.4)	(63.4)	(63.4)	(63.4)	(63.4)
Apparent Harvested Wood Flux	**(210.1)**	**(203.1)**	**(207.5)**	**(212.7)**	**(206.4)**	**(214.9)**
Wood Products	(47.7)	(53.9)	(56.1)	(58.6)	(52.1)	(61.6)
Landfilled Wood	(162.4)	(149.2)	(151.4)	(155.1)	(154.4)	(153.3)
Total Flux	**(1,001.7)**	**(938.3)**	**(942.7)**	**(903.5)**	**(897.2)**	**(905.7)**

Note: Parentheses indicate net carbon "sequestration" (i.e., 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. Lightly shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Totals may not sum due to independent rounding.

Table 6-4: Net CO_2 Flux from U.S. Forests (Tg C)

Description	1990	1995	1996	1997	1998	1999
Apparent Forest Flux	**(216)**	**(201)**	**(201)**	**(188)**	**(188)**	**(188)**
Trees	(113)	(105)	(105)	(106)	(106)	(106)
Understory	(1)	(1)	(1)	(1)	(1)	(1)
Forest Floor	(16)	(15)	(15)	(14)	(14)	(14)
Forest Soils	(69)	(62)	(62)	(50)	(50)	(50)
Logging Residues	(17)	(17)	(17)	(17)	(17)	(17)
Apparent Harvested Wood Flux	**(57)**	**(55)**	**(57)**	**(58)**	**(56)**	**(59)**
Wood Products	(13)	(15)	(15)	(16)	(14)	(17)
Landfilled Wood	(44)	(41)	(41)	(42)	(42)	(42)
Total Flux	**(273)**	**(256)**	**(257)**	**(246)**	**(245)**	**(247)**

Note: Note: 1 Tg C = 1 Tg Carbon = 1 million metric tons carbon. This table has been included to facilitate comparison with previous U.S. Inventories. Parentheses indicate net carbon "sequestration" (i.e., 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. Lightly shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Totals may not sum due to independent rounding.

Table 6-5: U.S. Forest Carbon Stock Estimates (Tg C)

Description	1987	1992	1997	2000
Forests (excluding logging residue)	**36,251**	**37,243**	**38,160**	**38,672**
Trees	12,709	13,273	13,798	14,115
Understory	557	564	571	574
Forest Floor	3,350	3,428	3,504	3,545
Forest Soils	19,635	19,978	20,287	20,438
Logging Residues	NA	NA	NA	NA
Harvested Wood	**1,920**	**2,198**	**2,479**	**2,651**
Wood Products	1,185	1,245	1,319	1,366
Landfilled Wood	735	953	1,159	1,285

NA (Not Available)

Note: Forest carbon stocks do not include forest stocks in Alaska, Hawaii, or U.S. territories, 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. Lightly shaded areas indicate values based on a combination of historical data and projections. All other estimates are based on historical data only. Logging residue is not available because logging residue flux is predicted from differences between wood harvested and wood removed from the site. Totals may not sum due to independent rounding.

Methodology

The methodology for estimating annual net forest carbon flux in the United States is based on periodic surveys rather than annual activity data. In addition, because the most recent survey was compiled for 1997, projected data, rather than complete historical data, were used to derive some of the annual flux estimates. A description of the assumptions underlying this projection is given in Haynes (2000). The projection reflects assumptions about variables that affect wood demand and supply, such as population and technological changes; policies regulating forests and their management are assumed fixed.

The carbon budget of forest ecosystems in the United States was estimated using a core model, FORCARB, and several subroutines that calculate additional information, including carbon in wood products (Plantinga and Birdsey 1993, Birdsey et al. 1993, Birdsey and Heath 1995, and Heath et al. 1996). FORCARB is part of an integrated system of models consisting of an area change model (Alig 1985), a timber market model (TAMM; Adams and Haynes 1980), a pulp and paper model (NAPAP; Ince 1994) and an inventory projection model (ATLAS; Mills and Kincaid 1992). Through linkage with these models, FORCARB estimates carbon stocks on private timberlands as a function of management intensity and land-use change. ATLAS does not yet include public timberlands, and harvesting on public lands is not particularly responsive to price, so forest inventory and harvest data for public timberlands are developed exogenously and then used as inputs to the modeling system to estimate carbon stocks on public timberlands (Heath 1997b). Average annual net carbon flux on timberlands is estimated by taking the difference between carbon stocks, and dividing by the length of the period between stock estimates.

The current version of FORCARB partitions carbon storage in the forest into five separate components: trees, understory vegetation, forest floor, forest soils, and logging residues. The tree component includes all above-ground and below-ground portions of all live and dead trees, including the merchantable stem, limbs, tops, cull sections, stump, foliage, bark and rootbark, and coarse tree roots (greater than 2 mm). Understory vegetation includes all live vegetation other than live trees. The forest floor includes litter and fine woody debris. The soil component includes all organic carbon in mineral horizons to a depth of one meter, excluding coarse tree roots. Logging residue is the portion of the harvested wood that is left on the site, i.e., not removed for processing.

The FORCARB model essentially converts merchantable volumes from the model linkages into carbon and predicts carbon in other ecosystem components—such as soil and forest floor—based on other data from forest inventories and additional information from intensive-site ecosystem studies. Estimates of average carbon storage by age or volume class of forest stands—analogous to a forest yield table—are made for each ecosystem component for forest classes defined by region, forest type, productivity class, and land-use history. Equations that estimate carbon stocks in the forest floor, soil, and understory vegetation for each forest class are incorporated in the model. Logging residue is calculated as the difference between the carbon in wood harvested (cut) and wood removed from the site for processing at the mill. Additional details about estimating carbon storage for different regions, forest types, site productivity class, and past land use are provided in Birdsey (1996).

The methodology for reserved forest lands and other forest lands differs from that described above for timberlands.[2] Forest carbon stocks on non-timberland forests were estimated based on average per area carbon estimates derived from timberlands. Reserved forests were assumed to contain the same average per area carbon stocks as timberlands of the same forest type, region, and owner group. These averages were multiplied by the areas in the forest statistics, and then aggregated for a national total. Average carbon stocks per area were

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[2] Forest land in the United States 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 1997, there were about 503 million acres of timberlands, which represented 67 percent of all forest lands (Smith and Sheffield 2000). Forest land classified as timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 33 percent of forest land is classified as reserved forest land, which is forest land withdrawn from timber use by statute or regulation, or other forest land, which includes forests on which timber is growing at a rate less than 20 cubic feet per acre per year.

derived for other forest land by estimating carbon stocks per area for timberlands in the lowest productivity class that is surveyed. These estimates were multiplied by 80 percent to simulate the effects of lower productivity. The results indicated these non-timberland forests are in equilibrium, and therefore contribute little to the flux estimates.

Estimates of carbon in wood products and wood discarded in landfills are based on the methods described in Skog and Nicholson (1998), and aggregation as described in Heath et al. (1996). The disposition of harvested wood carbon removed from the forest can be described in four general pools: products in use, discarded wood in landfills, emissions from wood burned for energy, and emissions from decaying wood or wood burned in which energy was not captured. The apparent fluxes presented here represent the net amounts of carbon that are stored in wood product and landfilled wood pools (i.e., inputs to the pools minus emissions from, or transfers out of, the pools). Annual historical estimates and projections of detailed product production were used to divide consumed roundwood into product, wood mill residue, and pulp mill residue. The carbon decay rates for products and landfills were estimated, and applied to the respective pools. The results were aggregated for national estimates.

The apparent fluxes from wood product and landfilled wood pools include exports and exclude imports. Carbon in exported wood is tracked using the same disposal rates as in the United States. Over the period 1990 through 1999, carbon in exported wood accounts for an average of 21.3 Tg CO_2 Eq. net storage per year, with little variation from year to year. For comparison, imports—which are not included in the harvested wood apparent flux estimates—increase from 26.4 to 44.7 Tg CO_2 Eq. net storage per year from 1990 to 1999.

The methodology described above is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The IPCC identifies two approaches to developing estimates of net carbon flux from Land-Use Change and Forestry: 1) using average annual statistics on land use, 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.[3] Although there are 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 carbon stocks used in this Inventory to calculate forest carbon fluxes are based on areas, volumes, growth, harvests, and utilization factors derived from the forest inventory data collected by the USDA Forest Service. Compilations of these data for 1987, 1992, and 1997 are given in Waddell et al. (1989), Powell et al. (1993), and Smith and Sheffield (2000), respectively. The timber volume data include timber stocks on forest land classified as timberland, reserved forest land, or other forest land in the contiguous United States, but do not include stocks on forest land in Alaska, Hawaii, or the U.S. territories, or stocks on non-forest land (e.g., urban trees).[4] The timber volume data include estimates by tree species, size class, and other categories. The forest inventory data are augmented or converted to

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[3] Again, the product estimates in this study do not account for carbon stored in imported wood products. However, they do include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

Box 6-1: Comparison to forest carbon stock and flux estimates in the United States Submission on Land Use, Land-Use Change, and Forestry

On August 1, 2000, the U.S. government submitted a document to the UNFCCC on methodological issues related to the treatment of carbon sinks under Articles 3.3 and 3.4 of the Kyoto Protocol (U.S. Department of State 2000). This document, entitled *United States Submission on Land Use, Land-Use Change and Forestry* (i.e., the U.S. Submission on LULUCF), was submitted in response to a request of the Subsidiary Body for Scientific and Technological Advice (SBSTA). The U.S. Submission on LULUCF contains estimates of carbon stocks and flux from forest lands, croplands, and grazing lands. The estimates of forest carbon stocks and flux presented in this Inventory are slightly different from those presented in the U.S. Submission on LULUCF for two reasons: 1) the SBSTA requested stock and flux estimates for a different set of forest areas and activities than are accounted for in national greenhouse gas inventories required under the UNFCCC; and 2) both the estimates presented here, and those presented in the U.S. Submission on LULUCF, reflect interim results of forest carbon modeling refinements that are underway at the USDA Forest Service. These differences are discussed more fully below.

First, the U.S. Submission on LULUCF is concerned with only timberlands, and with carbon fluxes due to activities since 1990. The *U.S. Inventory on Greenhouse Gas Emissions and Sinks* covers timberlands, reserved forests, and other forests; and *U.S. Inventory on Greenhouse Gas Emissions and Sinks* flux estimates for any particular year include fluxes due to activities in that year, as well as fluxes due to activities in previous years (i.e., delayed fluxes). Carbon stocks on reserved forests and other forests are believed to be stable, so their inclusion in the Inventory only affects carbon stocks, not fluxes. The inclusion of fluxes due to activities prior to 1990 in the Inventory results in higher annual emission estimates (i.e., lower net sequestration) for harvested wood and logging residue pools compared to the U.S. Submission.

Second, the methodologies used to estimate harvested wood and soil carbon pools vary between the two documents. The harvested wood carbon pools in the U.S. Submission on LULUCF are based on disposition coefficients that were derived using the method of Skog and Nicholson (1998) and a run of the integrated forestry model system (FORCARB/TAMM/ATLAS/NAPAP) with 1992 and earlier forest inventory data as inputs. The estimates of harvested wood carbon pools used in the Inventory are also based on the method of Skog and Nicholson (1998), but with a rerun of the integrated forestry model system with the 1997 forest inventory data as input. Also, the carbon stocks in the U.S. Submission were derived using a new soils method, which is not yet available for reserved forests and other forests, so an older method was used in the Inventory. This resulted in higher soil carbon stock estimates in the U.S. Submission compared to the Inventory, but did not affect the estimated fluxes.

carbon following the methods described in the methodology section. Soil carbon estimates are based on data from the STATSGO database (USDA 1991). Carbon stocks in wood products in use and wood stored in landfills are based on historical data from the USDA Forest Service (Powell et al. 1993, Smith and Sheffield 2000), and historical data as implemented in the framework underlying the NAPAP (Ince 1994) and TAMM/ATLAS (Adams and Haynes 1980, Mills and Kincaid 1992) models.

Uncertainty

This section discusses uncertainties in the results, given the methods and data used. There are likely sampling and measurement errors associated with forest survey data that underlie the forest carbon estimates. These surveys are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. Although newer inventories are being conducted annually in every state, much of the data currently used may have been collected over more than one year in a state, and data associated with a particular year may actually have been collected over several previous years. Thus, there is uncertainty in the year associated with the forest inventory data. In addition, the forest survey data that are currently available exclude timber stocks on forest land in Alaska, Hawaii, and the U.S. territories, and trees on non-forest land (e.g., urban trees). However, net carbon fluxes from these stocks are believed to be minor. The assumptions that were used to calculate carbon stocks in reserved forests and other forests in the coterminous United States also contribute to

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[4] Although forest carbon stocks in Alaska, Hawaii, and U.S. territories are large compared to the U.S. total, net carbon fluxes from forest stocks in these areas are believed to be minor. Net carbon fluxes from urban tree growth are also believed to be minor.

the uncertainty. Although the potential for uncertainty is large, the sample design for the forest surveys contributes to limiting the error in carbon flux. Re-measured permanent plot estimates are correlated, and greater correlation leads to decreased uncertainties in change estimates. For example, in a study on the uncertainty in the forest carbon budget of U.S. private timberlands, Smith and Heath (2000) estimated that the uncertainty of the flux increased about 3.5 times when the correlation coefficient dropped from 0.95 to 0.5.

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. 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 (e.g., 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. For example, Moore et al. (1981) found that harvest may lead to a 20 percent loss of soil carbon, while Johnson (1992) found little or no net change in soil carbon following harvest. Heath and Smith (2000) noted that the experimental design in a number of soil studies was such that the usefulness of the studies may be limited in determining harvesting effects on soil carbon. Soil carbon impact estimates need to be very precise because even small changes in soil carbon may sum to large differences over large areas.

Recent studies have looked at quantifying the amount of uncertainty in national-level carbon budgets based on the methods adopted here. Smith and Heath (2000) and Heath and Smith (2000a) report on an uncertainty analysis they conducted on carbon sequestration in private timberlands. These studies are not strictly comparable to the estimates in this chapter because they used an older version of the FORCARB model, and were based on older data. However, the magnitudes of the uncertainties should be instructive. Their results indicate that the carbon flux of private timberlands, not including harvested wood, was approximately the average carbon flux (271 Tg CO_2 Eq. per year) ±15 percent at the 80 percent confidence level for the period 1990 through 1999. The flux estimate included the tree, soil, understory vegetation, and forest floor components only. The uncertainty in the carbon inventory of private timberlands for 2000 was approximately 5 percent at the 80 percent confidence level. It is expected that the uncertainty should be greater for all forest lands (i.e., private and public timberlands, and reserved and other forest land).

Changes in Agricultural 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 such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net flux of carbon to or from soils. In addition, the application of carbonate minerals to soils through liming operations results in emissions of CO_2. The IPCC methodology for estimation of net CO_2 flux from agricultural soils (IPCC/UNEP/OECD/IEA 1997) is divided into three categories of land-use/land-management activities: 1) agricultural land-use and land-management activities on mineral soils; 2) agricultural land-use and land-management activities on organic soils; and 3) liming of soils. Mineral soils and organic soils are treated separately because each responds differently to land-use practices.

Mineral soils contain comparatively low amounts of organic matter, much of which is concentrated near the soil surface. Typical well-drained mineral surface soils contain from 1 to 6 percent organic matter (by weight); mineral subsoils contain even lower amounts of organic matter (Brady and Weil 1999). When mineral soils undergo conversion from their native state to agricultural use, as much as half of the soil organic carbon can be lost to the atmosphere. The rate and ultimate magnitude of carbon loss will depend on native vegetation, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40 to 60 percent of the carbon loss generally occurs within the first 10 years following conversion; after that, carbon stocks continue to decline but at a much slower rate. In temperate regions, carbon loss can continue for several decades. Eventually, the soil will reach a new equilibrium that reflects a balance between carbon accumulation from plant biomass and carbon loss through oxidation. Any changes in land-use or management practices that result in increased biomass production or decreased oxidation (e.g., crop rotations, cover crops, application of organic amendments and manure, and reduction or elimination of tillage) will result in a net accumulation of soil organic carbon until a new equilibrium is achieved.

Organic soils, which are also referred to as histosols, include all soils with more than 20 to 30 percent organic matter by weight (depending on clay content) (Brady and Weil 1999). The organic matter layer of these soils is also typically extremely deep. Organic soils form under waterlogged conditions, in which decomposition of plant residues is retarded. When organic soils are cultivated, tilling or mixing of the soil aerates the soil, thereby accelerating the rate of decomposition and CO_2 generation. Because of the depth and richness of the organic layers, carbon loss from cultivated organic soils can continue over long periods of time. Conversion of organic soils to agricultural uses typically involves drainage as well, which also causes 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 (i.e., 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).

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 applied limestone and dolomite to degrade completely.

Of the three activities, use and management of mineral soils was by far the most important in terms of contribution to total flux during the 1990 through 1999 period (see Table 6-6). Carbon sequestration in mineral soils in 1999 was estimated at about 109.3 Tg CO_2 Eq., while emissions from organic soils were estimated at about 22.4 Tg CO_2 Eq. and emissions from liming were estimated at about 9.9 Tg CO_2 Eq. Together, the three activities accounted for net sequestration of 77.0 Tg CO_2 Eq. in 1999. Total annual net CO_2 flux was negative each year over the 1990 to 1999 period. Between 1990 and 1999, total net carbon sequestration in agricultural soils increased by 90 percent.

The flux estimates and analysis for this source are restricted to CO_2 fluxes associated with the use and management of agricultural 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

Table 6-6: Net CO_2 Flux From Agricultural Soils (Tg CO_2 Eq.)

Description	1990	1995	1996	1997	1998	1999
Mineral Soils	(71.9)	(100.1)	(100.1)	(100.1)	(109.3)	(109.3)
Organic Soils	22.0	22.4	22.4	22.4	22.4	22.4
Liming of Soils	9.5	8.9	8.9	8.7	9.6	9.9
Total Net Flux	**(40.4)**	**(68.8)**	**(68.9)**	**(69.0)**	**(77.3)**	**(77.0)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding. Lightly shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

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 greenhouse gas fluxes that result from these activities.[5]

Methodology and Data Sources

The methodologies used to calculate CO_2 emissions from use and management of mineral and organic soils and from liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), except where noted below.

The estimates of annual net CO_2 flux from mineral soils were taken from Eve et al. (2000a) and U.S. Department of State (2000). The approach used to derive these estimates is described in Eve et al. (2000b). Total mineral soil carbon stock estimates for 1982, 1992, and 1997 were developed by applying the default IPCC carbon stock and carbon adjustment factors (with one exception), to cropland and grazing land area estimates, classified by climate, soil type, and management regime. The exception is the base factor for lands set aside for less than 20 years. The IPCC default value is 0.8, but recent research in the United States (Paustian et al. 2001, Follett et al. 2001, Huggins et al. 1997, and Gebhart et al. 1994) indicates that 0.9 is a more accurate factor for the United States. Therefore, 0.9 was used instead of 0.8 for the base factor for grassland set aside through the Conservation Reserve Program. Areas of non-federal cropland and grazing land, by soil type and land management regime, in 1982, 1992, and 1997 were taken from USDA (2000a).[6] These were assigned to climatic regions using the climate mapping program in Daly et al. (1994). Estimates of tillage practices were derived from data collected by the Conservation Technology Information Center (CTIC).[7] The carbon flux estimate for 1990 is based on the change in stocks between 1982 and 1992, and the carbon flux estimate for 1995 through 1997 is based on the change in stocks between 1982 and 1997. The IPCC base, tillage, and input factors were adjusted to account for use of a ten-year and a fifteen-year accounting period, rather than the 20-year period used in the *IPCC Guidelines*. The carbon flux estimate for 1998 and 1999 is based on the change in stocks between 1982 and a projection for 2008. The 2008 projection is based on the estimated 1997 stock, adjusted to account for additional acres expected to be enrolled in the Conservation Reserve Program by 2008 (USDA 2000b).

The estimates of annual CO_2 emissions from organic soils were also taken from Eve et al. (2000a) and U.S. Department of State (2000), and are based on an approach described in Eve et al. (2000b). The IPCC methodology for organic soils utilizes annual CO_2 emission factors, rather than a stock change approach. Following the IPCC methodology, only organic soils under intense management were included, and the default IPCC rates of carbon loss were applied to the total 1992 and 1997 areas for the climate/land-use categories defined in the IPCC Guidelines. The area estimates were derived from the same climatic, soil, and land-use/land management databases that were used in the mineral soil calculations (Daly et al. 1994, USDA 2000a). The annual flux estimated for 1992 is applied to 1990, and the annual flux estimated for 1997 is applied to 1995 through 1999.

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[5] However, methane emissions due to flooding of rice fields are included, as are nitrous oxide emissions from agricultural soils. These are addressed under the Rice Cultivation and Agricultural Soil Management sections, respectively, of the Agriculture chapter.

[6] Soil carbon stocks on federal grazing lands were assumed to be stable, and so are not included in the flux estimates.

[7] See <www.ctic.purdue.edu>.

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 (see Table 6-7) 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 in the same year in which the minerals are applied. The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys* (Tepordei 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000; USGS 2000). To develop these data, USGS (U.S. Bureau of Mines prior to 1997) 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 were 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, data were not available in 1990, 1992, and 1999 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 1999 data, the 1998 fractions were applied to a 1999 estimate of total crushed stone found in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2000* (USGS 2000).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the U.S. Geological Survey from 1995 to the present. In 1994, the "Crushed Stone" chapter in *Minerals Yearbook* began rounding (to the nearest thousand) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Uncertainty

Uncertainties in the flux estimates for mineral and organic soils result from both the activity data and the carbon stock and adjustment factors. Each of the datasets used in deriving the area estimates has a level of uncertainty that is passed on through the analysis, and the aggregation of data over large areas necessitates a certain degree of generalization. The default IPCC values used for estimates of mineral soil carbon stocks under native vegetation, as well as for the base, tillage and input factors, carry with them high degrees of uncertainty, as these values represent broad regional averages based on expert judgment. Moreover, measured carbon loss rates from cultivated organic soils vary by as much as an

Table 6-7: Quantities of Applied Minerals (Thousand Metric Tons)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Limestone	19,012	20,312	17,984	15,609	16,686	17,297	17,479	16,539	14,882	15,375
Dolomite	2,360	2,618	2,232	1,740	2,264	2,769	2,499	2,989	6,389	6,600

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[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.

order of magnitude. In addition, this methodology does not take into account changes in carbon stocks due to pre-1982 land use and land-use change.

Uncertainties in the estimates of emissions from liming also result from both the methodology and the activity data. It can take several years for agriculturally-applied limestone and dolomite to degrade completely. The IPCC method assumes that the amount of mineral applied in any year is equal to the amount that degrades in that year, so annual application rates can be used to derive annual emissions. Further research is required to determine actual degradation rates, which would vary with varying soil and climatic conditions. However, application rates are fairly constant over the entire time series, so this assumption may not contribute significantly to overall uncertainty.

There are several sources of uncertainty in the limestone and dolomite activity data. When reporting data to the USGS (or U.S. Bureau of Mines), some producers do not distinguish between limestone and dolomite. In these cases, data are reported as limestone, so this could lead to an overestimation of limestone and an underestimation of dolomite. In addition, the total quantity of crushed stone listed each year in the *Minerals Yearbook* excludes American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands. The *Mineral Industry Surveys* further excludes Alaska and Hawaii from its totals.

Changes in Yard Trimming Carbon Stocks in Landfills

As is the case with landfilled forest products, carbon contained in landfilled yard trimmings can be stored indefinitely. In the United States, yard trimmings (i.e., grass clippings, leaves, branches) comprise a significant portion of the municipal waste stream. In 1990, the EPA estimated discards of yard trimmings to landfills at over 21 million metric tons (EPA 1999). Since then, programs banning or discouraging disposal, coupled with a dramatic rise in the number of composting facilities, have decreased the disposal rate for yard trimmings. In 1999, the landfill disposal of yard trimmings was about 9 Tg (EPA 1999). The decrease in the yard trimmings landfill disposal rate has resulted in a decrease in the rate of landfill carbon storage from about 17.8 Tg CO_2 Eq. in 1990 to 7.7 Tg CO_2 Eq. in 1999 (see Table 6-8).

Methodology

Table 6-8: Net CO_2 from Landfilled Yard Trimmings

Year	Tg CO_2 Eq.
1990	(17.8)
1995	(12.0)
1996	(10.0)
1997	(9.4)
1998	(8.8)
1999	(7.7)

Note: Parentheses indicate net storage. Lightly shaded area indicates values based on projections.

The methodology for estimating carbon storage is based on a life cycle analysis of greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). According to this methodology, carbon storage is the product of the mass of yard trimmings disposed, on a wet weight basis, and a storage factor. The storage factor, which is the fraction of total carbon that is assumed to be stored permanently, is based on a series of experiments designed to evaluate methane generation and residual organic material in landfills (Barlaz 1997). These experiments analyzed grass, leaves, branches, and other materials, and were designed to promote biodegradation by providing ample moisture and nutrients.

For purposes of this analysis, the composition of yard trimmings was assumed to consist of 50 percent grass clippings, 25 percent leaves, and 25 percent branches on a wet weight basis. A different storage factor was used for each component. The weighted average carbon storage factor is 0.23 (metric ton of carbon stored indefinitely per metric ton [wet weight] of yard trimmings landfilled), as shown in Table 6-9.

Data Sources

The yard trimmings discard rate was taken from the EPA report *Characterization of Municipal Solid Waste in the U.S.: 1998 Update* (EPA 1999), which provides

Table 6-9: Composition of Yard Trimmings in MSW and Carbon Storage Factor (Gg C/Gg yard trimmings)

Component	Percent	Storage Factor
Grass	50	0.13
Leaves	25	0.43
Branches	25	0.23
Total/Weighted Average	**100**	**0.23**

Table 6-10: Yard Trimmings Disposal to Landfills

Year	Gg (wet weight)
1990	21,200
1991	20,800
1992	20,400
1993	18,200
1994	16,200
1995	14,300
1996	12,000
1997	11,200
1998	10,500
1999	9,200

Note: Lightly shaded area indicates values based on projections.

estimates for 1990 through 1998 and forecasts for 2000 and 2005. Yard trimmings discards for 1999 were projected using the EPA (1999) forecast of generation and recovery rates (i.e., decrease of 6 percent per year, increase of 8 percent per year, respectively) for 1999 through 2000. This report does not subdivide discards of individual materials into volumes landfilled and combusted, although it does provide an estimate of the overall distribution of solid waste between these two management methods (i.e., 76 percent and 24 percent, respectively) for the waste stream as a whole.[9] Thus, yard trimmings disposal to landfills is the product of the quantity discarded and the proportion of discards managed in landfills (see Table 6-10). The carbon storage factors were obtained from EPA (1998).

Uncertainty

The principal source of uncertainty for the landfill carbon storage estimates stems from an incomplete understanding of the long-term fate of carbon in landfill environments. Although there is ample field evidence that many landfilled organic materials remain virtually intact for long periods, the quantitative basis for predicting long-term storage is based on limited laboratory results under experimental conditions. In reality, there is likely to be considerable heterogeneity in storage rates, based on 1) actual composition of yard trimmings (e.g., oak leaves decompose more slowly than grass clippings) and 2) landfill characteristics (e.g., availability of moisture, nitrogen, phosphorus, etc.) Other sources of uncertainty include the estimates of yard trimmings disposal rates, which are based on extrapolations of waste composition surveys, and the extrapolation of a value for 1999 disposal from estimates for the period from 1990 through 1998.

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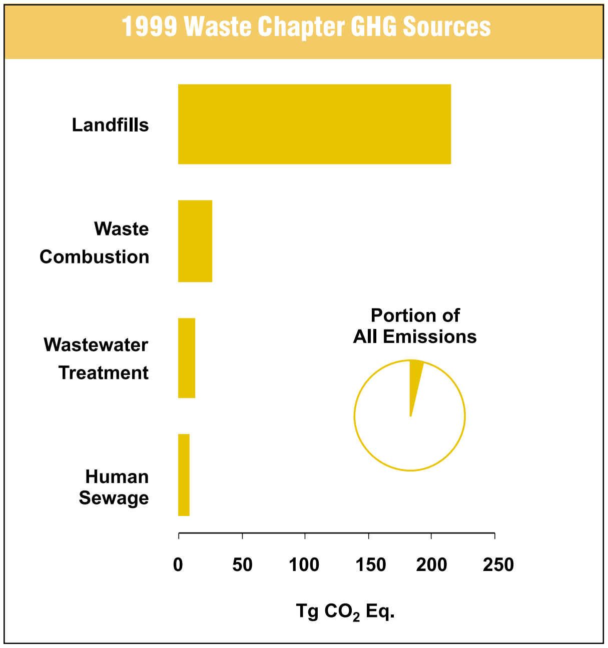
[9] Note that this calculation uses a different proportion for combustion than an earlier calculation in the Waste Combustion section of the Waste chapter. The difference arises from different sources of information with different definitions of what is included in the solid waste stream.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills are the nation's largest source of anthropogenic methane (CH_4) emissions, accounting for 35 percent of the U.S. total.[1] Waste combustion is the second largest source in this sector, emitting carbon dioxide (CO_2) and nitrous oxide (N_2O). 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 N_2O emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by each of these sources, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Overall, in 1999, waste activities generated emissions of 261.3 Tg CO_2 Eq., or 3.9 percent of total U.S. greenhouse gas emissions.

Figure 7-1



Landfills

Landfills are the largest anthropogenic source of methane (CH_4) emissions in the United States. In 1999, landfill emissions were approximately 214.6 Tg CO_2 Eq. (10,221 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Over 2,200 operational landfills exist in the United States (BioCycle 2000), with the largest landfills receiving most of the waste and generating the majority of the methane.

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[1] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land-Use Change and Forestry chapter.

Table 7-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999
CH_4	**228.5**	**234.7**	**231.0**	**229.8**	**225.7**	**226.9**
Landfills	217.3	222.9	219.1	217.8	213.6	214.6
Wastewater Treatment	11.2	11.8	11.9	12.0	12.1	12.2
CO_2	**17.6**	**23.1**	**24.0**	**25.7**	**25.1**	**26.0**
Waste Combustion	17.6	23.1	24.0	25.7	25.1	26.0
N_2O	**7.4**	**8.5**	**8.1**	**8.2**	**8.3**	**8.4**
Human Sewage	7.1	8.2	7.8	7.9	8.1	8.2
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2
Total	**253.4**	**266.2**	**263.1**	**263.6**	**259.2**	**261.3**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999
CH_4	**10,879**	**11,175**	**11,002**	**10,943**	**10,748**	**10,803**
Landfills	10,346	10,614	10,435	10,371	10,171	10,221
Wastewater Treatment	533	561	567	572	577	583
CO_2	**17,572**	**23,065**	**23,968**	**25,674**	**25,145**	**25,960**
Waste Combustion	17,572	23,065	23,968	25,674	25,145	25,960
N_2O	**24**	**27**	**26**	**26**	**27**	**27**
Human Sewage	23	27	25	26	26	26
Waste Combustion	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding.

Methane emissions result from the decomposition of organic landfill materials such as paper, food scraps, and yard trimmings. This decomposition process is a natural mechanism through which microorganisms derive energy. After being placed in a landfill, organic waste is initially digested by aerobic (i.e., in the presence of oxygen) bacteria. After the oxygen supply has been depleted, the remaining waste is consumed by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These 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 bacteria convert these fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent methane, by volume.[2] Methane production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

Between 1990 and 1999, net methane emissions from landfills were relatively constant (see Table 7-3 and Table 7-4). The roughly constant emissions estimates are a result of two offsetting trends: (1) the amount of MSW in landfills contributing to methane emissions increased, thereby increasing the potential for emissions; and (2) the amount of landfill gas collected and combusted by landfill operators also increased, thereby reducing emissions.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of MSW in landfills, which is related to total MSW landfilled annually for the last 30 years; (2) composition of the waste-in-place; (3) the amount of methane that is recovered and either flared or used for energy purposes; and (4) the amount of methane oxidized in landfills instead of being released into the atmosphere. The estimated total quantity of waste-in-place contributing to emissions increased from about 4,926 Gg in 1990 to 6,036 Gg in 1999, an in-

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[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is composed of non-methane volatile organic compounds (NMVOCs).

Table 7-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**
MSW Landfills	221.1	254.8	261.0	267.1	272.7	279.6
Industrial Landfills	15.3	17.5	17.8	18.2	18.5	19.0
Recovered						
Gas-to-Energy	(14.7)	(21.8)	(24.3)	(28.8)	(36.1)	(42.7)
Flared	(4.5)	(27.6)	(35.3)	(38.8)	(41.5)	(41.2)
Net Emissions	**217.3**	**222.9**	**219.1**	**217.8**	**213.6**	**214.6**

Note: Totals may not sum due to independent rounding.

Table 7-4: CH_4 Emissions from Landfills (Gg)

Activity	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**
MSW Landfills	10,531	12,133	12,427	12,720	12,985	13,315
Industrial Landfills	731	833	850	868	883	904
Recovered						
Gas-to-Energy	(702)	(1,037)	(1,159)	(1,372)	(1,720)	(2,034)
Flared	(213)	(1,314)	(1,683)	(1,846)	(1,977)	(1,964)
Net Emissions	**10,346**	**10,614**	**10,435**	**10,371**	**10,171**	**10,221**

Note: Totals may not sum due to independent rounding.

Box 7-1: Biogenic Emissions and Sinks of Carbon

For many countries, CO_2 emissions from the combustion or degradation of biogenic materials are important because of the significant amount of energy they derive from biomass (e.g., burning fuelwood). The fate of biogenic materials is also important when evaluating waste management emissions (e.g., the decomposition of paper). The carbon contained in paper was originally stored in trees during photosynthesis. Under natural conditions, this material would eventually degrade and cycle back to the atmosphere as CO_2. The quantity of carbon that these degradation processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic greenhouse gas sources. But the focus of the United Nations Framework Convention on Climate Change is on anthropogenic emissions—emissions resulting from human activities and subject to human control—because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and enhancing the atmosphere's natural greenhouse effect.

Carbon dioxide emissions from biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis are considered to mimic the closed loop of the natural carbon cycle—that is, they return to the atmosphere CO_2 that was originally removed by photosynthesis. However, CH_4 emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills, and are consequently included in this Inventory.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. Landfilling of forest products and yard trimmings results in long-term storage of about 70 Tg CO_2 Eq. and 7 to 18 Tg CO_2 Eq. per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in the Land-Use Change and Forestry chapter, as recommended in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) regarding the tracking of carbon flows.

Box 7-2: Recycling and Greenhouse Gas Emissions and Sinks

U.S. waste management patterns changed dramatically in the 1990s in response to changes in economic and regulatory factors. Perhaps the most significant change from a greenhouse gas perspective was the increase in the national average recycling rate, which climbed from 16 percent in 1990 to 28 percent in 1997 (EPA 1999).

This change has affected emissions in several ways, primarily by reducing emissions from waste and energy activities, as well as by enhancing forestry sinks. The impact of increased recycling on greenhouse gas emissions can be best understood when emissions are considered from a life cycle perspective (EPA 1998). When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed and managed as waste. The substitution of recycled inputs for virgin inputs reduces three types of emissions throughout the product life cycle. First, manufacturing processes involving recycled inputs generally require less energy than those using virgin inputs. Second, the use of recycled inputs leads to reductions in process non-energy emissions (e.g., perfluorocarbon emissions from aluminum smelting). Third, recycling reduces disposal and waste management emissions, including methane from landfills and nitrous oxide and non-biogenic carbon dioxide emissions from combustion. In addition to greenhouse gas emission reductions from manufacturing and disposal, recycling of paper products—which are the largest component of the U.S. wastestream—results in increased forest carbon sequestration. When paper is recycled, fewer trees are needed as inputs in the manufacturing process; reduced harvest levels result in older average forest ages, with correspondingly more carbon stored.

crease of 23 percent (see Annex M). During this period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 915 Gg of methane was recovered and combusted (i.e., used for energy or flared) from landfills. In 1999, the estimated quantity of methane recovered and combusted increased to 3,998 Gg.

Over the next several years, the total amount of MSW generated is expected to increase slightly. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, 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 1996 regulation that requires large MSW landfills to collect and combust landfill gas (see 40 CFR Part 60, Subparts Cc and WWW).

Methodology

Based on available information, methane emissions from landfills were estimated to equal the methane produced from municipal landfills, minus the methane recovered and combusted, minus the methane oxidized before being released into the atmosphere, plus the methane produced by industrial landfills.

The methodology for estimating CH_4 emissions from municipal landfills is based on a model that updates the population of U.S. landfills each year. 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 (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, year of closure, and design capacity. 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 M.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, and a database compiled by the EPA's Landfill Methane Outreach Program (LMOP). Based on the information provided by vendors, the methane combusted by the 487 flares in operation from 1990 to 1999 were estimated. This quantity likely under-estimates flaring. The EPA believes that more than 700 flares exist in the United States, and is working with the Solid Waste Association of North America (SWANA) to better characterize flaring activities. Additionally, the LMOP database provided sufficient data on landfill gas flow and energy generation for 273 of the approximately 315 operational landfill gas-to-energy projects (LFGTE). If both flare data and LFGTE recovery data for a particular landfill were available, then the emissions recovery was based on the LFGTE data, which provides actual landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given size flare. Given that each LFGTE project was likely to also have had a flare, EPA avoided double counting reductions from flares and LFGTE projects by subtracting from the emissions reductions associated with flares, those emissions reductions associated with LFGTE projects.[3]

Emissions from industrial landfills were assumed to be equal to 7 percent of the total methane emissions from municipal landfills. The amount of methane oxidized was assumed to be 10 percent of the methane generated (Liptay et al. 1998). To calculate net methane emissions, both methane recovered and methane oxidized were subtracted from methane generated at municipal and industrial landfills.

Data Sources

The landfill population model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA's Office of Solid Waste (EPA 1988). National landfill waste disposal data for 1991 through 1999 were obtained from *BioCycle* (2000).[4] Documentation on the landfill methane emissions methodology employed is available in the EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993). Information on flares was obtained from vendors, and information on landfill gas-to-energy projects was obtained from the LMOP database.

Uncertainty

Several types of uncertainties are associated with the estimates of methane emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is lacking on the area landfilled and total waste-in-place—the fundamental factors that affect methane production. In addition, 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 in the landfill methane emission rate is estimated to be roughly ±30 percent.

Waste Combustion

Combustion is used to manage both municipal solid wastes (MSW) and hazardous wastes. Combustion of either type of waste results in conversion of the organic inputs to carbon dioxide (CO_2). According to the IPCC Guidelines, when the CO_2 is of fossil origin, it is counted as an anthropogenic emission in national inventories. Thus, the emissions from waste combustion are driven by estimating the quantity of waste combusted, the fraction of the waste that is carbon, and the fraction of the carbon that is of fossil origin.

MSW is composed of garbage and non-hazardous solids. Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), and have their net carbon flows accounted for under the Land-Use Change and Forestry chapter (see Box 7-1). However, some components—plastics, synthetic rubber, and synthetic fibers—are of fossil origin. Plastics in the U.S. wastestream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, like carpets, and in non-durable goods, such as clothing and footwear. Fibers in MSW are predominantly from clothing and home furnishings. Tires are also considered a "non-hazardous" waste and are included in the estimate, though waste disposal practices for tires differ from the rest of MSW.

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[3] Due to the differences in referencing landfills and incomplete data on the national population of flares, matching flare vendor data with the LMOP LFGTE data was problematic and EPA was not able to identify a flare for each of the LFGTE projects. Because each LFGTE project likely has a flare, the aggregate flare estimate of emission reductions was reduced by the LFGTE projects for which a specific flare could not be identified. This approach eliminated the potential for double counting emissions reductions at landfills with both flares and a LFGTE project.

[4] At the time this section was prepared, BioCycle had not yet published its 1999 estimate for the percent of the total waste landfilled, so the previous year's figure (61 percent) was used.

In 1999, it was estimated that nearly 34 million metric tons of MSW were combusted in the United States (EPA 1999). Carbon dioxide emissions have risen 46 percent since 1990, to an estimated 20.5 Tg CO_2 Eq. (20,470 Gg) in 1999, as the volume of plastics in MSW has increased (see Table 7-5 and Table 7-6). In addition to CO_2, MSW combustion is a source of nitrous oxide (N_2O) emissions (De Soete 1993). Nitrous oxide emissions from MSW combustion were estimated to be 0.2 Tg CO_2 Eq. (1 Gg) in 1999, and have not changed significantly since 1990.

Hazardous wastes are defined by the EPA under the Resource Conservation and Recovery Act (RCRA).[5] Industrial wastes, such as rejected products, spent reagents, reaction by-products, and sludges from wastewater or air pollution control, are federally regulated as hazardous wastes if they are found to be ignitable, corrosive, reactive, or toxic according to standardized tests or studies conducted by the EPA.

Hazardous wastes must be treated prior to disposal according to the federal regulations established under the authority of RCRA. Combustion is one of the most common techniques for hazardous waste treatment, particularly for those wastes that are primarily organic in composition or contain primarily organic contaminants. Generally speaking, combustion devices fall into two categories: incinerators that burn waste solely for the purpose of waste management, and boilers and industrial furnaces (BIFs) that burn waste in part to recover energy from the waste. The EPA's Office of Solid Waste requires biennial reporting of hazardous waste management activities, and these reports provide estimates of the amount of hazardous waste burned for incineration or energy recovery. Table 7-7 presents estimates of CO_2 emissions from hazardous waste combustion based on these estimates and assumptions about the composition of the wastes and efficiency of the combustion process.

Methodology

CO_2 from Plastics Combustion

In the report, *Characterization of Municipal Solid Waste in the United States* (EPA 2000c), the flows of plastics in the U.S. wastestream are reported for seven resin categories. The 1998 quantity generated, recovered, and discarded for each resin is shown in Table 7-8. The report

Table 7-5: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Tg CO_2 Eq.)

Gas/Waste Product	1990	1995	1996	1997	1998	1999
CO_2	**14.0**	**18.2**	**19.1**	**20.8**	**19.9**	**20.5**
Plastics	10.3	11.1	11.5	12.5	12.9	13.3
Synthetic Rubber in Tires	0.2	1.4	1.5	1.7	1.1	1.2
Carbon Black in Tires	0.3	2.1	2.3	2.6	1.7	1.8
Synthetic Rubber in MSW	1.6	1.7	1.7	1.8	1.8	1.9
Synthetic Fibers	1.5	1.9	2.0	2.1	2.2	2.3
N_2O	**0.3**	**0.3**	**0.3**	**0.3**	**0.2**	**0.2**
Total	**14.3**	**18.4**	**19.3**	**21.0**	**20.1**	**20.7**

Table 7-6: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Waste Product	1990	1995	1996	1997	1998	1999
CO_2	**14,014**	**18,154**	**19,061**	**20,770**	**19,871**	**20,470**
Plastics	10,320	11,077	11,459	12,484	12,929	13,297
Synthetic Rubber in Tires	227	1,353	1,517	1,711	1,134	1,190
Carbon Black in Tires	348	2,077	2,329	2,627	1,741	1,827
Synthetic Rubber in MSW	1,584	1,708	1,737	1,807	1,833	1,870
Synthetic Fibers	1,535	1,938	2,018	2,141	2,233	2,285
N_2O	**1**	**1**	**1**	**1**	**1**	**1**

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[5] [42 U.S.C. §6924, SDWA §3004]

Table 7-7: CO_2 Emissions from Hazardous Waste Combustion

Year	Tg CO_2 Eq.	Gg
1990	3.6	3,557
1995	4.9	4,911
1996	4.9	4,908
1997	4.9	4,904
1998*	5.3	5,274
1999*	5.5	5,490

*Projection based on 1989 to 1997 trend.

does not provide estimates for individual materials landfilled and combusted, although it does provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and combusted, total discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. wastestream (76 percent and 24 percent, respectively).

Fossil fuel-based CO_2 emissions for 1998 were calculated as the product of plastic combusted, carbon content, and combustion efficiency (see Table 7-9). The carbon content of each of the six types of plastics is listed, with the value for "other plastics" assumed equal to the weighted average of the six categories. The fraction oxidized was assumed to be 98 percent.

Emissions for 1990 through 1997 were calculated using the same approach. Estimates of the portion of plastics in the wastestream in 1999 were not available; therefore, they were projected by assuming a 3 percent annual growth rate in generation and a 5.4 percent growth rate for recovery, based on reported trends (EPA 1999).

CO_2 from Combustion of Synthetic Rubber and Carbon Black in Tires

Emissions from tire combustion require two pieces of information: the amount of tires combusted and the carbon content of the tires. The *Scrap Tire Use/Disposal Study 1998/1999 Update* (STMC 1999) reports that 114 million of the 270 million scrap tires generated in 1998 (approximately 42 percent of generation) were used for fuel purposes. Using STMC estimates of average tire composition and weight, the weight of synthetic rubber and carbon black in scrap tires was determined. Synthetic rub-

Table 7-8: 1998 Plastics in the Municipal Solid Waste Stream by Resin (Gg)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	2,023	4,500	1,243	4,844	2,576	1,969	3,139	**20,294**
Recovery	354	399	0	127	154	18	45	**1,098**
Discard	1,669	4,101	1,243	4,717	2,422	1,950	3,094	**19,196**
Landfill	1,269	3,116	945	3,585	1,841	1,482	2,351	**14,589**
Combustion	401	984	298	1,132	581	468	742	**4,607**
Recovery*	17%	9%	0%	3%	6%	1%	1%	**5%**
Discard*	83%	91%	100%	97%	94%	99%	99%	**95%**
Landfill*	63%	69%	76%	74%	71%	75%	75%	**72%**
Combustion*	20%	22%	24%	23%	23%	24%	24%	**23%**

*As a percent of waste generation.

Note: Totals may not sum due to independent rounding. Abbreviations: PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE/LLDPE ((linear) low density polyethylene), PP (polypropylene), PS (polystyrene).

Table 7-9: 1998 Plastics Combusted (Gg), Carbon Content (%), and Carbon Combusted (Gg)

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Quantity Combusted	401	984	298	1,132	581	468	742	**4,607**
Carbon Content of Resin	63%	86%	38%	86%	86%	92%	66%[a]	**-**
Carbon in Resin Combusted	250	844	115	970	498	432	489	**3,598**
Emissions (Tg CO_2 Eq.)[b]	0.9	3.0	0.4	3.5	1.8	1.6	1.8	**12.9**

[a] Weighted average of other plastics produced in 1998 production.

[b] Assumes a fraction oxidized of 98 percent.

ber in tires was estimated to be 90 percent carbon by weight, based on the weighted average carbon contents of the major elastomers used in new tire consumption (see Table 7-10).[6] Carbon black is 100 percent carbon. Multiplying the proportion of scrap tires combusted by the total carbon content of the synthetic rubber and carbon black portion of scrap tires yielded CO_2 emissions, as shown in Table 7-11. Note that the disposal rate of rubber in tires (0.4 Tg/yr) is smaller than the consumption rate for tires shown in Table 7-10 (1.3 Tg/yr); this is due to the fact that much of the rubber is lost through tire wear during the product's lifetime and due to the lag time between consumption and disposal of tires.

CO_2 from Combustion of Synthetic Rubber in Municipal Solid Waste

Similar to the methodology for scrap tires, CO_2 emissions from synthetic rubber in MSW were estimated by multiplying the amount of rubber combusted by an average rubber carbon content. The amount of rubber in the MSW stream was estimated from data provided in the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c). The report organizes rubber found in MSW into three product categories: other durables (not including tires), non-durables (which includes clothing and footwear and other non-durables), and containers and packaging. Since there was negligible recovery for these product types, all the waste generated can be considered discarded. Similar to the plastics method, discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. wastestream (76 percent and 24 percent, respectively). The report aggregates rubber and leather in the MSW stream; an assumed rubber content percentage was assigned to each product type, as shown in Table 7-12.[7] A carbon content of 85 percent was assigned to synthetic rubber for all product types, according to the weighted average carbon content of rubber consumed for non-tire uses (See Table 7-10). For 1999, waste generation values were not provided in the report. Generation was forecast by multiplying the 1998 Rubber and Leather waste generation by the 1990 through 1998 average annual growth rate for that product category.

Table 7-10: Elastomers Consumed in 1998 (Gg)

Elastomer	Consumed	Carbon Content	Carbon Equivalent
Styrene butadiene rubber solid	**908**	**91%**	**828**
For Tires	743	91%	677
For Other Products*	165	91%	151
Polybutadiene	**561**	**89%**	**499**
For Tires	404	89%	359
For Other Products	157	89%	140
Ethylene Propylene	**320**	**86%**	**274**
For Tires	10	86%	8
For Other Products	310	86%	266
Polychloroprene	**69**	**59%**	**40**
For Tires	0	59%	0
For Other Products	69	59%	40
Nitrile butadiene rubber solid	**87**	**77%**	**67**
For Tires	1	77%	1
For Other Products	86	77%	67
Polyisoprene	**78**	**88%**	**69**
For Tires	65	88%	57
For Other Products	13	88%	12
Others	**369**	**88%**	**324**
For Tires	63	88%	56
For Other Products	306	88%	268
Total	**2,392**	**-**	**2,101**

*Used to calculate carbon content of non-tire rubber products in municipal solid waste.
- Not applicable

CO_2 from Combustion of Synthetic Fibers

Carbon dioxide emissions from synthetic fibers were estimated as the product of the amount of synthetic fiber discarded annually and the average carbon content of synthetic fiber. Fiber in the MSW stream was estimated from data provided in the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c) for textiles. The amount of synthetic fiber in MSW was estimated by subtracting the amount recovered from the waste generated (see Table 7-13). As with the other materials in the MSW stream, discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. wastestream (76 percent and 24 percent, respectively). It was assumed that approximately 55 percent of the fiber was synthetic in origin, based on information received from the Fiber Economics Bureau (DeZan 2000).

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[6] 1,158,000 Tg for the carbon content of tires divided by 1,285,000 Tg for the mass of tires, equals 90 percent.

[7] As a biogenic material, the combustion of leather is assumed to have no net carbon dioxide emissions.

Table 7-11: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Combustion in 1998

Material	Weight of Material (Tg)	Carbon Content	Percent Combusted	Emissions (Tg CO_2 Eq.)*
Synthetic Rubber	0.4	90%	42%	1.1
Carbon Black	0.5	100%	42%	1.7
Total	**0.8**	**-**	**-**	**2.9**

* Assumes a fraction oxidized of 98 percent.
- Not applicable

Table 7-12: Rubber and Leather in Municipal Solid Waste in 1998

Product Type	Generation (Gg)	Synthetic Rubber (%)	Carbon Content (%)	Emissions (Tg CO_2 Eq.)*
Durables (not Tires)	**2,141**	**100%**	**85%**	**1.6**
Non-Durables	**744**	**100%**	**85%**	**0.2**
Clothing and Footwear	526	25%	85%	0.1
Other Non-Durables	218	75%	85%	0.1
Containers and Packaging	**18**	**100%**	**85%**	**+**
Total	**2,903**	**-**	**-**	**1.8**

* Assumes a fraction oxidized of 98 percent.
+ Less than 0.05 Tg CO_2 Eq.
- Not applicable

Table 7-13: Textiles in MSW (Gg)

Year	Generation	Recovery	Discards	Combustion
1990	5,271	599	4,672	1,121
1991	5,599	622	4,977	1,195
1992	5,948	647	5,302	1,272
1993	6,319	672	5,647	1,355
1994	6,713	699	6,015	1,444
1995	6,713	816	5,897	1,415
1996	7,004	862	6,142	1,474
1997	7,475	962	6,514	1,563
1998	7,802	1,007	6,795	1,631
1999*	7,989	1,035	6,954	1,669

*Projected using 1998 data and the 1997 to 2000 Average Annual Growth Rate for Generation (EPA 1999).

An average carbon content of 70 percent was assigned to synthetic fiber using the production-weighted average of the carbon contents of the four major fiber types (polyester, nylon, olefin, and acrylic) produced in 1998 (see Table 7-14). The equation relating CO_2 emissions to the amount of textiles combusted is shown below. Since 1999 values were not provided in the *Characterization* report, generation and recovery were forecast by applying their respective average annual growth rates for 1990 through 1998 to the 1998 values.

CO_2 Emissions from the Combustion of Synthetic Fibers = Annual Textile Combustion (Gg)× (Percent of Total Fiber that is Synthetic)× (Average Carbon Content of Synthetic Fiber)× ($44g\ CO_2/12g\ C$)

N_2O from Municipal Solid Waste Combustion

Estimates of N_2O emissions from MSW combustion in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emis-

Table 7-14: Synthetic Fiber Production in 1998

Fiber	Proection (Tg)	Carbon Content	Carbon Equivalent (Tg CO_2 Eq.)
Polyester	1.8	63%	4.1
Nylon	1.3	64%	3.0
Olefin	1.3	86%	4.1
Acrylic	0.2	68%	0.5
Total	**4.6**	**-**	**11.7**

- Not applicable

sion Factors (EPA 1997). According to this methodology, emissions of N_2O from MSW combustion are the product of the mass of MSW combusted, an emission factor of N_2O emitted per unit mass of waste combusted, and an N_2O emissions control removal efficiency. For MSW combustion in the United States, an emission factor of 30 g N_2O/metric ton MSW, and an estimated emissions control removal efficiency of zero percent were used. No information was available on the mass of waste combusted in 1999, so this was extrapolated, using least-squares linear regression, from the times series for 1990 through 1998.

CO_2 from Hazardous Waste Combustion

Hazardous wastes combusted are reported to the EPA, which stores the information in its Biennial Reporting System (BRS) database. Combusted wastes are identified based on management system types M041 through M049 (incineration) and M051 through M059 (energy recovery). Combusted quantities are grouped into four representative waste form categories based on the form codes reported in the BRS: aqueous liquids, organic liquids and sludges, organic solids, and inorganic solids. For this analysis, energy recovery was considered separately from incineration because regulations and practical considerations require wastes that are burned for energy recovery to have higher heating values than wastes sent to incineration. Based on these determinations, combusted waste quantities were grouped into categories representing the two types of combustion (incineration and energy recovery) and the four major waste forms.

To relate hazardous waste quantities to carbon emissions, "fuel equivalent" factors were derived for hazardous waste by assuming that they are simple mixtures of a common fuel, water, and noncombustible ash. For liquids and sludges, crude oil is used as the fuel equivalent and coal is used to represent solids.

Fuel equivalent factors were multiplied by the tons of waste burned to obtain the tons of fuel equivalent. Multiplying the tons of fuel equivalent by the appropriate carbon content factors from Marland and Rotty (1984) yields tons of carbon emitted. Implied carbon content is calculated by dividing the tons of carbon emitted by the associated tons of waste burned.

This analysis was repeated for each of the BRS reporting years (odd numbered years from 1989 through 1997) assuming a constant average waste composition (see in Table 7-15) and fraction oxidized over the period. To obtain estimates for even numbered years, the average of the previous and subsequent years was used. A least-squares linear regression from the time series 1989 through 1997 was used for 1998 and 1999.

Table 7-15: Assumed Composition of Combusted Hazardous Waste by Weight (Percent)

Waste Type	Water	Noncombustibles	Fuel Equivalent
Energy Recovery			
Aqueous Waste	90	5	5
Organic Liquids and Sludges	30	10	60
Organic Solids	20	20	60
Inorganic Solids	20	40	40
Incineration			
Aqueous Waste	90	5	5
Organic Liquids and Sludges	40	20	40
Organic Solids	20	40	40
Inorganic Solids	20	70	10

Data Sources

For each of the CO_2 emissions methods used to calculate emissions from MSW combustion, there are generally two types of activity data needed: the quantity of product combusted and the carbon content of the product. For plastics, synthetic rubber in MSW, and synthetic fibers, the amount of material in MSW and its portion combusted was taken from the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c).

For synthetic rubber and carbon black in scrap tires, this information was provided by the *Scrap Tire Use/Disposal Study 1998/1999 Update* (STMC 1999).

Average carbon contents for the "Other" plastics category, synthetic rubber in scrap tires, synthetic rubber in MSW, and synthetic fibers have been calculated from recent production statistics which divide their respective markets by chemical compound. The plastics production data set was taken from the website of the American Plastics Council (APC 2000); synthetic rubber production was taken from the website of the International Institute of Synthetic Rubber Producers (IISRP 2000); and synthetic fiber production was taken from the website of the Fiber Economics Bureau (FEB 2000). Personal communications with the APC (Eldredge-Roebuck 2000) and the FEB (DeZan 2000) validated the website information. All three sets of production data can also be found in Chemical and Engineering News, "Facts & Figures for the Chemical Industry." Lastly, information about scrap tire composition was taken from the Scrap Tire Management Council's webpage entitled "Scrap Tire Facts and Figures" (STMC 2000).

The assumption of 98 as the fraction of carbon oxidized, which applies to all municipal solid waste combustion categories for CO_2 emissions, was reported in the EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 1998).

The N_2O emission estimates are based on different data sources. The N_2O emissions are a function of total waste combusted, as reported in the April 1999 issue of *BioCycle* (Glenn 1999). Table 7-16 provides MSW generation and percentage combustion data for the total wastestream. The emission factor of N_2O emissions per quantity of MSW combusted was taken from Olivier (1993).

Waste quantity data for hazardous wastes were obtained from the EPA's Biennial Reporting System (BRS) database for reporting years 1989, 1991, 1993, 1995, and 1997 (EPA 2000a). Combusted waste quantities were obtained from Form GM (Generation and Management) for wastes burned on site and Form WR (Wastes Received) for waste received from off-site for combustion. Carbon emission factors for equivalent fuels were obtained from Marland and Rotty (1984). All other estimates were assumed based on expert judgment.

Table 7-16: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted

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
1997	309,075,035	9.0
1998	340,090,022	7.5
1999	353,986,624	7.5

Uncertainty

There is uncertainty associated with the emissions estimates for both MSW and hazardous waste combustion. For MSW combustion, uncertainty arises from both the assumptions applied to the data and the quality of the data itself. For hazardous wastes, the primary source of uncertainty surrounds the composition of combusted wastes.

- *MSW Combustion Rate:* A source of uncertainty affecting both fossil CO_2 and N_2O emissions is the estimate of the MSW combustion rate. The EPA (1999) estimates of materials generated, discarded, and combusted embody considerable uncertainty associated with the material flows methodology used to generate them. Similarly, the *BioCycle* (Glenn 1999) estimate of total waste combustion—used for the N_2O emissions estimate—is based on a survey of State officials, who use differing definitions of solid waste and who draw from a variety of sources of varying reliability and accuracy. Despite the differences in methodology and data sources, the two references—the EPA's Office of Solid Waste (EPA 1999) and *BioCycle* (Glenn 1999)—provide estimates of total solid waste combusted that are relatively consistent (see Table 7-17).
- *Fraction Oxidized:* Another source of uncertainty for the CO_2 emissions estimate is fraction oxidized. Municipal waste combustors vary considerably in their efficiency as a function of waste type, moisture content, combustion conditions, and other factors. The value of 98 percent assumed here may not be representative of typical conditions.

Table 7-17: U.S. Municipal Solid Waste Combusted by Data Source (Metric Tons)

Year	EPA	BioCycle
1990	28,939,680	30,652,316
1991	30,236,976	25,479,677
1992	29,656,638	29,132,773
1993	29,865,024	27,857,295
1994	29,474,928	29,310,956
1995	32,241,888	29,658,643
1996	32,740,848	29,726,819
1997	32,294,240	27,816,753
1998	NA	25,506,752
1999	NA	NA

NA (Not Available)

- *Use of 1998 Data on MSW Composition:* The materials that draw on the *Characterization* report (EPA 2000b) for data incur uncertainty in their 1999 emissions estimates. Emissions have been calculated from activity that has been extrapolated from reported 1998 values using average annual growth rates.
- *Average Carbon Contents:* Average carbon contents are applied to the mass of "Other" plastics combusted, synthetic rubber in tires and MSW, and synthetic fibers. These average values have been estimated from the average carbon content of the known products recently produced. The true carbon content of the combusted waste may differ from this estimate depending on differences in the formula between the known and unspecified materials, and differences between the composition of the material disposed and that produced. For rubber, this uncertainty is probably very small since the major elastomers' carbon contents range from 77 to 91 percent; for plastics, where carbon contents range from 29 to 92 percent, it may be more significant. Overall, this is a small source of uncertainty.
- *Synthetic/Biogenic Assumptions:* A portion of the fiber and rubber in MSW is biogenic in origin. Assumptions have been made concerning the allocation between synthetic and biogenic materials based primarily on expert judgement.
- *Combustion Conditions Affecting N_2O Emissions:* Because insufficient data exist to provide detailed estimates of N_2O emissions for individual combustion facilities, the estimates presented are highly uncertain. The emission factor for N_2O from MSW combustion facilities used in the analysis is a default value used to estimate N_2O emissions from facilities worldwide (Olivier 1993). As such, it has a range of uncertainty that spans an order of magnitude (between 25 and 293 g N_2O/metric ton MSW combusted) (Watanabe, et al. 1992). Due to a lack of information on the control of N_2O emissions from MSW combustion facilities in the United States, the estimate of zero percent for N_2O emissions control removal efficiency is also uncertain.
- *Hazardous Waste:* The greatest uncertainty in the hazardous waste combustion analysis is introduced by the assumptions about the composition of combusted hazardous wastes, including the characterization that hazardous wastes are similar to mixtures of water, noncombustibles, and fuel equivalent. Another limitation is the assumption that all of the carbon that enters hazardous waste combustion is emitted—some small fraction is likely to be sequestered in combustion ash—but given that the destruction and removal efficiency for hazardous organics is required to meet or exceed 99.99 percent, this is a minor source of uncertainty. Carbon emission estimates from hazardous waste should be considered central value estimates that are likely to be accurate to within ±50 percent.

Wastewater Treatment

Wastewater is treated to remove soluble organic matter, suspended solids, pathogenic organisms and other chemical contaminants. Soluble organic matter is generally removed using biological processes in which microorganisms consume organic waste for maintenance and generation of new cells. The resulting biomass is removed from the wastewater prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic and anaeriobic conditions. The biodegradation of soluble organic material in wastewater treatment systems produces methane when it occurs under anaerobic conditions. The amount of methane produced is driven by the extent to which the organic material is broken down under anaerobic versus aerobic conditions. During collection and treatment, wastewater may be incidentally or deliberately managed under anaerobic conditions. In addition, the biomass (sludge) produced by the microorganisms that have consumed the wastewater's soluble organic material may be further biodegraded under aerobic or 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 contained under anaerobic conditions.

The organic content, expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD), 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. COD refers to the amount of oxygen consumed under specified conditions in the oxidation of the organic and oxidizable inorganic matter and is a parameter typically used to characterize industrial wastewater. Under anaerobic conditions and with all other conditions, such as temperature, being the same, wastewater with higher BOD or COD concentrations will produce more methane than wastewater with lower BOD or COD.

In 1999, methane emissions from domestic or municipal wastewater treatment were 12.2 Tg CO_2 Eq. (583 Gg). Emissions have increased since 1990 in response to the increase in the U.S. human population. Since estimates of emissions from industrial wastewater contain only emissions from the pulp and paper industry at this time, these emissions are not included in totals. In 1999, methane emissions from industrial wastewater treatment were 0.2 Tg CO_2 Eq. (8 Gg). In the future, more research will be conducted to analyze and quantify methane emissions from wastewater treatment processes at other industries.

Table 7-18 and Table 7-19 provide emission estimates from domestic and industrial wastewater treatment.

Methodology

Domestic wastewater methane emissions are estimated using the default IPCC methodology (IPCC 2000). The total population for each year was multiplied by a per capita wastewater BOD production rate to determine total wastewater BOD produced. It was assumed that, per capita, 0.065 kilograms of wastewater BOD5[8] 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 0.6 kg CH_4/kg BOD5.

Table 7-18: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999
Domestic	11.2	11.8	11.9	12.0	12.1	12.2
Industrial*	0.2	0.2	0.2	0.2	0.2	0.2
Total	**11.2**	**11.8**	**11.9**	**12.0**	**12.1**	**12.2**

* Industrial activity only includes the pulp and paper industry.
Note: Emissions from industrial wastewater treatment are not included in totals.

Table 7-19: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990	1995	1996	1997	1998	1999
Domestic	533	561	567	572	577	583
Industrial*	7	8	8	8	8	8
Total	**533**	**561**	**567**	**572**	**577**	**583**

* Industrial activity only includes the pulp and paper industry.
Note: Emissions from industrial wastewater treatment are not included in totals.

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[8] The 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972).

A top-down approach was used to develop estimates of methane emissions from industrial wastewater according to the methodology described in the IPCC *Good Practice Guidance* (IPCC 2000). Information on industrial wastewater sources contained in the IPCC *Good Practice Guidance* was used to help identify industries that were likely to have significant methane emissions from industrial wastewater. Industries were chosen that typically had both a high volume of wastewater generated and a high BOD or COD wastewater load. Five industries that met these criteria were:

- Pulp and paper manufacturing
- Food and beverage production
- Textile (natural) manufacturing
- Petroleum refineries
- Organic chemical manufacturing

Estimates of methane from petroleum refining wastewater processes are included elsewhere in this document under the category for petroleum systems. Regarding the other listed industries, national data on total BOD loadings were available only for the pulp and paper industry. Future efforts will attempt to include the other identified industries.

There are approximately 565 pulp and paper manufacturing facilities in the United States (EPA 1997a). Of these, 316 facilities operate wastewater treatment systems that discharge directly to receiving streams. These facilities do not discharge to a Publicly Owned Treatment Works (POTW). Wastewater discharges to POTWs are captured under domestic wastewater treatment. About 25 percent of the direct discharging pulp and paper facilities use fully-aerated activated sludge treatment, about 50 percent use aerated and non-aerated stabilization basins, while the remainder use other types of treatment. Industry experts (NCASI 2000) estimate that approximately 1 percent of direct discharging pulp and paper facilities operate anaerobic treatment systems from which methane (biogas) may be emitted.

Methane emissions for industrial wastewater treatment in the pulp and paper industry were calculated by multiplying an emission factor by one percent of the national BOD removal from the wastewater treatment process at direct discharging pulp and paper mills. National BOD removal from industrial wastewater treatment by the pulp and paper industry was calculated using reported national values for raw wastewater load BOD from direct discharging mills and wastewater effluent load BOD from direct discharging mills (EPA 1993). The effluent load was subtracted from the raw wastewater load to estimate national BOD removal. The national BOD removal value was then multiplied by the emission factor of 0.6 kg CH_4/kg BOD to estimate national methane emissions for 1990. Emissions for the years 1991 through 1999 were then calculated by projecting the 1990 national BOD removal value using 1991 through 1999 annual production values for the pulp and paper industry.

Data Sources

National population data for 1990 to 1999 were supplied by the U.S. Census Bureau (2000). The emission factor (0.6 kg CH_4/kg BOD5) employed for both domestic and industrial wastewater treatment was taken from IPCC (2000). Per-capita production of BOD5 for domestic wastewater was obtained from the EPA (1997b).

Table 7-20 provides U.S. population and wastewater BOD data.

A time series of methane emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post Directory 1992-1999). The relative proportion of the post-1990 year's production to the 1990 base year production was used to adjust the 1990 BOD removal value to the other years in the time series.

Table 7-20: U.S. Population (Millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD5
1990	249.4	5,920
1991	252.0	5,984
1992	254.9	6,052
1993	257.7	6,118
1994	260.2	6,179
1995	262.7	6,238
1996	265.2	6,296
1997	267.7	6,356
1998	270.2	6,415
1999	272.6	6,473

Table 7-21 provides U.S. pulp and paper production and wastewater BOD data.

Table 7-21: U.S. Pulp and Paper Production (Million Metric Tons) and Wastewater BOD Removed (Gg)

Year	Population	BOD5
1990	128.9	1,200
1991	129.2	1,203
1992	134.5	1,253
1993	134.1	1,249
1994	139.3	1,297
1995	140.9	1,312
1996	140.3	1,306
1997	145.6	1,356
1998	145.2	1,352
1999	146.2	1,361

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.

The estimated methane emissions from wastewater treatment processes in the pulp and paper industry are based on an estimated proportion of the national BOD removal that occurs at facilities operating anaerobic processes. Identifying these facilities and the actual BOD removal that is accomplished in their treatment systems would result in a more accurate estimate of methane emissions from the industry.

Human Sewage

Sewage, after treatment in a septic system or wastewater treatment facility, is disposed on land or discharged into aquatic environments such as rivers and estuaries. Nitrous oxide (N_2O) may be generated during treatment and disposal through nitrification and denitrification of the nitrogen that is present in sewage.[9] Nitrification occurs aerobically and converts ammonium (NH_4^+) into nitrate (NO_3^-), while denitrification occurs anaerobically, and converts nitrate into dinitrogen gas (N_2). Nitrous oxide can be an intermediate product of both processes. In general, temperature, pH, biochemical oxygen demand (BOD), and nitrogen concentration affect N_2O generation from human sewage. The amount of protein consumed by humans determines the quantity of nitrogen contained in sewage.

Nitrous oxide emissions from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) with one exception. The IPCC methodology assumes that N_2O emissions associated with land disposal and sewage treatment are negligible and all sewage nitrogen is discharged directly into aquatic environments. In the United States, however, a certain amount of sewage nitrogen is applied to soils via sewage sludge applications, and therefore, not all sewage nitrogen enters aquatic environments.[10] The N_2O estimates presented here account for the amount of nitrogen in sewage sludge applied to soils.

Emissions of N_2O from sewage nitrogen discharged into aquatic environments were estimated to be 8.2 Tg CO_2 Eq. (26 Gg) in 1999. An increase in the U.S. population and the per capita protein intake resulted in an overall increase of 15 percent in N_2O emissions from human sewage between 1990 and 1999 (see Table 7-22).

Table 7-22: N_2O Emissions from Human Sewage

Year	Tg CO_2 Eq.	Gg
1990	7.1	23
1995	8.2	27
1996	7.8	25
1997	7.9	26
1998	8.1	26
1999	8.2	26

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[9] This section focuses on N_20 emissions from human sewage. Methane emissions due to the treatment of human sewage in wastewater treatment facilities are addressed in the previous section of this chapter, *Wastewater Treatment*.

[10] The IPCC methodology is based on the total amount of nitrogen in sewage, which is in turn based on human protein consumption and the fraction of nitrogen in protein (i.e., $Frac_{NPR}$). A portion of the total nitrogen in sewage in the United States is applied to soils in the form of sewage sludge each year. This amount is estimated as part of agricultural soil management (see Chapter 6) and is subtracted here from total nitrogen in human sewage to estimate sewage N_2O emissions.

Methodology

With the exception described above, N_2O emissions from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$N_2O(s) = \{[(\text{Protein})\times(\text{Frac}_{NPR})\times(\text{U.S. Population})] - N_{Soil}\} \times (\text{EF})\times ({}^{44}/_{28})$

where,

$N_2O(s)$ = N_2O emissions from human sewage

Protein = Annual, per capita protein consumption

Frac_{NPR} = Fraction of nitrogen in protein

N_{Soil} = Quantity of sewage sludge N applied to soils

EF = Emission factor (kg N_20-N/kg sewage-N produced)

$({}^{44}/_{28})$ = The molecular weight ratio of N_2O to N_2

Data Sources

U.S. population data were taken from the U.S. Census Bureau (2000). Data on annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 2000) (see Table 7-23). Because data on protein intake were unavailable for 1999, the value of per capita protein consumption for the previous year was used. An emission factor has not been specifically estimated for the United States, so 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).

Uncertainty

The U.S. population (NR people), per capita protein intake data (Protein), and fraction of nitrogen in protein (Frac_{NPR}) are believed to be fairly accurate. Significant uncertainty exists, however, in the emission factor (EF). This uncertainty is due to regional differences that would likely affect N_2O emissions but are not accounted for in the default IPCC factor. Moreover, the underlying methodological assumption that negligible N_2O emissions result from sewage treatment may be incorrect. Taken together, these uncertainties present significant difficulties in estimating N_2O emissions from human sewage.

Table 7-23: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year)

Year	Population	Protein
1990	249.4	39.1
1991	252.0	39.7
1992	254.9	39.9
1993	257.7	40.3
1994	260.2	41.4
1995	262.7	43.4
1996	265.2	41.0
1997	267.7	41.4
1998	270.2	42.0
1999	272.6	42.0

Waste Sources of Criteria Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of criteria air pollutant emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 1999 are provided in Table 7-24.

Methodology and Data Sources

These emission estimates were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1999* (EPA 2000). This EPA report provides emission estimates of these gases by sector, using a "top down" estimating procedure—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.

Table 7-24: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999
NO_x	**83**	**89**	**92**	**92**	**93**	**83**
Landfills	+	1	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+
Waste Combustion[a]	82	88	89	89	91	80
Miscellaneous[b]	+	1	1	1	1	1
CO	**979**	**1,075**	**1,012**	**1,024**	**1,035**	**3,439**
Landfills	1	2	5	5	5	5
Wastewater Treatment	+	+	+	+	+	+
Waste Combustion[a]	978	1,073	1,006	1,019	1,030	3,434
Miscellaneous[b]	+	1	+	+	+	+
NMVOCs	**895**	**968**	**378**	**382**	**388**	**532**
Landfills	58	68	32	32	33	33
Wastewater Treatment	57	61	61	62	63	64
Waste Combustion[a]	222	237	222	225	228	369
Miscellaneous[b]	558	602	64	64	65	65

[a] Includes waste incineration and open burning (EPA 2000)

[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

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 1997). 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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Iron and Steel Production: In iron and steel foundries, coking coal is used as a reducing agent during the production of the metal. Although a portion of the coal's carbon is combusted and released to the atmosphere as carbon dioxide, its role as a chemical reagent makes it an example of a non-energy use of fossil fuel.

Fertilizer: Natural gas is used in the production of ammonia, the key component of most nitrogenous fertilizers. Through catalytic steam reforming, natural gas is broken down into carbon dioxide, which is emitted to the atmosphere, and hydrogen, which is combined with nitrogen to make ammonia.

Scrap Tires: Tires are made from synthetic rubber and carbon black, both products of fossil fuels. Like plastics and synthetic fibers, storage of the carbon in tires is dependent upon the ultimate fate of the product.

Paint Resin: Paint resin is another example of a product derived from the non-energy use of fossil fuels. Petrochemical products with a myriad of formulations and uses are produced in the industrial sector, including lubricants, solvents, and waxes. Carbon is both stored by and emitted from these products.

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