Documentation for *Emissions of Greenhouse Gases in the United States 2006*

October 2008

Energy Information Administration
Office of Integrated Analysis and Forecasting
U.S. Department of Energy
Washington, D.C. 20585

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Introduction

The Energy Policy Act of 1992 requires the Energy Information Administration (EIA) to prepare an inventory of aggregate U.S. national emissions of greenhouse gases for the period 1987-1990, with annual updates thereafter. This report documents the methodology for the fifteenth annual inventory, covering national emissions over the period 1990-2006.

Most of the carbon dioxide emissions data are from EIA surveys, as are many of the data sources for the energy components of the non-CO_2 gases. However, because there are also non-energy sources related to CO_2 and the other gases, there are several data sources outside of EIA's survey structure.

EIA continually reviews its methods for estimating emissions of greenhouse gases. As better methods and information become available, EIA revises both current and historical emissions estimates. See the "Update Information" section for what is new for this documentation.

Scope and Organization

Publication of this document is supported by Public Law 93-275, Federal Energy Administration Act of 1974, Section 57(B) (1) (as amended by Public Law 94-385, Energy Conservation and Production Act), which states in part

...that adequate documentation for all statistical and forecast reports prepared...is made available to the public at the time of publication of such reports.

In particular, this report is designed to meet EIA's model documentation standards established in accordance with these laws. The box on page xx indicates the mapping from the main report to this documentation.

Update Information

The following section indicates the methodological changes between the 2005 and 2006 data reports. Unless indicated otherwise, the changes are applied to all years going back to 1990.

Carbon Dioxide

In keeping with international protocol, EIA has dropped the partial combustion factor from fossil fuel-related carbon dioxide emissions. This change is applied across time and means that coal and petroleum emissions are 1 percent higher and natural gas emissions are one half a percent higher. This change reflects the opinion among scientists that unless there is a conscious effort to sequester the carbon it will be oxidized over the next century.

Methane

Activity data for methane emissions from landfills include annual data on waste generated and landfilled for the period 1988 through 2000, 2002, and 2004 drawn from "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-2004). For 2001 and 2003 waste generation was interpolated. For 2005 onward, EIA used a regression equation that correlated changes in waste generation from 1988 to 2000 to changes in gross domestic product (GDP) over the same time period.

This was the first Emissions of Greenhouse Gases in the United States Inventory to directly incorporate estimates of methane emissions from industrial waste water treatment.

Methane emission factors from industrial sources were updated using The Intergovernmental Panel on Climate Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3, Industrial Processes and Product Use which was prepared by the National Greenhouse Gas Inventories Programme.

Nitrous Oxide

Nitrous Oxide emission factors from industrial sources were updated using The Intergovernmental Panel on Climate Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3, Industrial Processes and Product Use which was prepared by the National Greenhouse Gas Inventories Programme.

Other Gases: HFCs, PFCs, and SF_6

Electricity Transmission and Distribution. Changes in the calculations of emissions from electricity transmission and distribution resulted in an average annual increase in estimated SF6 emissions from electric power systems of 0.1 to 0.6 million metric tons carbon dioxide equivalent (MMTCO2e) for the 1990-2006 period.

Magnesium Production and Processing. Emissions estimates from the U.S. Environmental Protection Agency (EPA) have been revised to reflect more accurate data on emission factors for sand casting activities and updated historical secondary production data from the U.S. Geological Survey (USGS).

Substitution of Ozone-Depleting Substances. The EPA has updated assumptions for its Vintaging Model pertaining to trends in chemical substitutions, market size and growth rates, and amounts used.

Land-Use Issues

All of the sequestration and emissions estimates for Land Use, Land Use Change, and Forestry (LULUCF) contained in the Land Use chapter are obtained from the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Because the LULUCF data are obtained from the prior year's report they lag the other data sets by one year. The most recent year of data presented in EIA's inventory that this publication documents is 2005.

For the previous year's inventory (2004 data), EIA used the three EPA categories of forest land remaining forest land, croplands remaining croplands, and settlements remaining settlements. The 2005 EIA emissions inventory followed EPA's adoption of new IPCC guidance on LULUCF. The IPCC guidelines expanded the categories from three to the following six categories: 1) forest land remaining forest land, 2) cropland remaining cropland, 3) land converted to cropland, 4) grassland remaining grassland, 5) land converted to grassland, and 6) settlements remaining settlements. Despite the changes in the categories, the underlying methodology remains essentially the same.

Cross–Reference with Emissions of Greenhouse Gases in the U.S. 2006

The following table cross-references chapters in the report *Emissions of Greenhouse Gases in the United States 2006* with chapters in this report.

Emissions of Greenhouse Gases in the United States 2006	**Documentation for Emissions of Greenhouse Gases in the United States 2006 (This Report)**
Overview	Not applicable
Carbon Dioxide Emissions	Chapter 1. Carbon Dioxide Emissions
Methane Emissions	Chapter 2. Methane Emissions
Nitrous Oxide Emissions	Chapter 3. Nitrous Oxide Emissions
Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride	Chapter 4. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride
Land Use Issues	Chapter 5. Sequestration from Land Use Change and Forestry
Carbon Dioxide Emissions	Chapter 6. Carbon Coefficients
All non-CO2 gases	Chapter 7. Global Warming Potentials
All gases	Chapter 8. Uncertainty in Emission Estimates
All gases	Chapter 9. Emissions Excluded

Acronyms

AAMA	American Automobile Manufacturer Association
AER	Annual Energy Review
API	American Petroleum Institute
bcf	Billion cubic feet
BOD	Biochemical oxygen demand
Btu	British thermal units
CO_2	Carbon dioxide
CH_4	Methane
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EIA	Energy Information Administration
U.S. EPA	U.S. Environmental Protection Agency
FHWA	Federal Highway Administration
GTI	Gas Technology Institute
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
LPG	Liquefied petroleum gases
MMTCe	Million metric tons carbon equivalent
$MMTCO_2e$	Million metric tons carbon dioxide equivalent
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MT	Metric tons
MTBE	Methyl tertiary butyl ether
N_2O	Nitrous oxide
NASS	USDA National Agricultural Statistics Service
NMVOCs	Nonmethane volatile organic compounds
ODS	Ozone-depleting substances
PFCs	Perfluorocarbons
PSA	Petroleum Supply Annual
QBtu	Quadrillion Btu
RTECS	Residential Transportation Energy Consumption Survey
scf	Standard cubic foot
SEDR	State Energy Data Report
SF_6	Sulfur hexafluoride
st	Short ton
VMT	Vehicle miles traveled
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Part I

Estimation Methodologies

1. Carbon Dioxide Emissions

Most U.S. anthropogenic carbon dioxide emissions result from the consumption of fossil fuels. **Energy production** also contributes a small amount of carbon dioxide that results from the flaring of natural gas at oil and gas wells and the scrubbing of carbon dioxide from natural gas. In addition, a number of **industrial processes** emit carbon dioxide through non-combustion processes. The largest single source of emissions from these processes is the calcination of limestone in cement production. Other sources include lime manufacture, limestone and dolomite consumption, soda ash manufacture and consumption, industrial carbon dioxide manufacture, and aluminum production. Some small adjustments are made to reach the total for national emissions as stipulated by the United Nations Framework Convention on Climate Change. In addition, this chapter addresses carbon dioxide emissions from the combustion of **municipal solid waste**.

1.1 Energy Consumption

1.1.1 Carbon Dioxide Emissions from Fossil Fuel Combustion

Emissions Sources

Fossil fuel combustion comprises the single largest category of carbon dioxide emissions in the United States and worldwide. These emissions sources include the combustion of fossil fuels by electricity generators, which provide electric power to industrial, commercial, and residential electricity end-users. These energy end-use sectors, together with the transportation sector, also contribute carbon dioxide emissions from fossil fuel combustion.

Fossil fuels – petroleum, natural gas, and coal – provide approximately 85% of the energy consumed in the United States. Chemically, the main components of such fossil fuels are molecules containing hydrogen and carbon atoms. When these fuels are burned, atmospheric oxygen combines with the hydrogen atoms to create water vapor and with the carbon atoms to create carbon dioxide. In principle, if the amount of fuel burned and the amount of carbon in the fuel are known, the volume of carbon dioxide emitted into the atmosphere can be computed with a high degree of precision. In practice, however, a combination of real-world complexities, which are addressed in this document, can reduce the precision of the estimate. Nonetheless, energy-related carbon dioxide emissions can be estimated with greater reliability than any other greenhouse gas emissions source; the uncertainty of the estimate is probably in the 3 to 5 percent range. Documentation Part III, “Uncertainty in Emissions Estimates,” contains an extended discussion of the nature and sources of uncertainty in the estimates.

One real-world complexity in the process of estimating carbon dioxide emissions from fossil fuel combustion is that not all the carbon in fuel is perfectly combusted. Additionally, about 1.5 percent of the carbon in fossil fuels is emitted in the form of carbon monoxide, which swiftly decays into carbon dioxide in the atmosphere. Another 1 percent is emitted in the form of non-methane volatile organic compounds, which also eventually decay into carbon dioxide. The carbon dioxide emissions reported in Chapter 2 include all “potential” carbon dioxide emissions from the sources covered, including both carbon dioxide emitted directly and carbon emitted in other forms (such as carbon monoxide) that rapidly decay into carbon dioxide in the atmosphere.

Emissions Sources Excluded

Several emissions sources, specifically biofuel combustion, enhanced oil recovery, “off spec” gases, forest fires, unaccounted for natural gas, fermentation, and lead smelting, are excluded from the carbon dioxide emissions presented in this report. The emissions are excluded either because of the uncertainty of the estimates, or because they are based on biomass combustion, which is assumed to be consumed sustainably, that is, with a net flux of carbon dioxide to the atmosphere equal to zero. Should the energy use of biomass fuels result in a long-term decline in the total carbon embodied in standing biomass (e.g., forests), the net release of carbon would be treated as a land use issue (see Chapter 6). Documentation Part III, “Emissions Excluded,” further describes the rationale for excluding sources of carbon dioxide emissions.

Estimation Methodology

To estimate carbon dioxide emissions[1] from fossil fuel combustion, the Energy Information Administration (EIA) follows a bottom-up approach using consumption data disaggregated by fuel type and sector, as recommended by the *Good Practice Guidance* of the Intergovernmental Panel on Climate Change (IPCC).[2] This section describes the derivation of information on energy consumption, emission coefficients, and adjustments to the energy data. Carbon dioxide emissions from fossil fuel combustion are calculated by multiplying energy consumption for each fuel type (activity data) by an associated carbon emission coefficient. The result is then modified by subtracting carbon sequestered by nonfuel use. For submission to the United Nations Framework Convention on Climate Change, these emissions estimates are further adjusted by subtracting bunker fuel consumption and adding in estimates for emissions from U.S. Territories. Data required to complete the estimation process include:

- Fuel consumption data by fuel type and end use (also called activity data);
- Carbon content emissions factors for each fuel;
- Net calorific values for fuels by type;
- Value of carbon sequestered (stored) in products;
- Value of carbon in international bunker fuels;
- Estimates of emissions from U.S. Territories.

The current general estimation methodology is described in the following steps.

Step 1: Determine Fuel Consumption by Fuel Type and End Use

Fossil fuel activity data are disaggregated by fuel type (e.g., petroleum, natural gas, and coal) and secondary fuel type (e.g., petroleum coke, kerosene jet fuel), and then categorized by the

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[1] For reporting years 1990 through 2001, emissions were reported in units of carbon and carbon equivalents (i.e., MMTCe). For the first time in the 2002 report, and in the reports since then, emissions were reported in terms of carbon dioxide or carbon dioxide equivalent (i.e., MMTCO$_2$e).

[2] Intergovernmental Panel on Climate Change, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, published by the Institute for Global Environmental Strategies, Japan, ISBN 4-88788-000-6 (Montreal, May 2000), http://www.ipcc-nggip.iges.or.jp/public/gp/english/ (hereinafter *Good Practice Guidance*).

following energy-use sectors: residential, commercial, industrial, and transportation end-use sectors and the electric power energy-conversion sector (note, in Step 9, carbon dioxide emissions from fuel fossil consumption for the electric power sector are allocated among the four end-use sectors by their share of the final electric power demand). Fuel quantities are first collected in their natural units, and then converted to energy units.

Information about consumption of “other petroleum” is derived from unpublished EIA data. In recent years, these products have included crude oil, naphtha with a boiling temperature less than 401°F, petrochemical feedstocks with a boiling temperature greater than or equal to 401°F, motor gasoline blending components, miscellaneous products, pentanes plus, still gas, special naphthas, waxes, and unfinished oils. At one time petroleum coke was included in the “other petroleum” category, but the data for petroleum coke are now presented separately.

Step 2: Adjust Energy Consumption Data to Eliminate Double Counting

To eliminate double counting or miscounting of emissions, EIA makes several small adjustments to energy consumption statistics. Usually the adjustments amount to less than 0.1 percent of energy-related carbon dioxide emissions. They are performed as follows:

Ethanol. Because ethanol is a biofuel, the carbon it contains should not be counted as an emission. Hence, carbon from ethanol is subtracted from transportation gasoline consumption. Ethanol consumption is reported in various EIA publications. The emissions inventory uses the *Monthly Energy Review*.

Synthetic Gas from Coal. Small amounts of “supplemental gas,” particularly gas from the Great Plains Coal Gasification Plant in North Dakota, are manufactured from coal. The coal is counted in industrial energy consumption, and the gas is shipped into the pipeline system. EIA subtracts the carbon in synthetic gas from industrial coal emissions. The carbon in synthetic gas from coal is reported in the Natural Gas Annual.

Still Gas to Pipelines. Several refineries sell small volumes of “still gas” as supplemental gas to pipelines. EIA subtracts the carbon in still gas sales to pipelines from industrial “other petroleum” consumption. Still gas sales to pipelines are reported in the Natural Gas Annual.

Biogas. Small volumes of “supplemental gas” of biological origin (probably landfill gas) are incorporated in U.S. pipeline gas supplies. “Biomass gas” is typically landfill methane upgraded and sold to pipelines. In keeping with the accounting rule of excluding carbon of biological origin, these supplies are subtracted from U.S. natural gas consumption. Volumes of biogas are reported in the Natural Gas Annual.

Step 3: Determine Energy Consumption Data to Account for Fuel Consumption in U.S. Territories

EIA’s energy data for the United States cover only the 50 States and the District of Columbia. In contrast, energy data produced for the United States by the International Energy Agency cover the 50 States plus U.S. territories, including Puerto Rico, the U.S. Virgin Islands, and Guam. To include U.S. territories in the estimate of emissions of greenhouse gases in the United States, EIA must quantify U.S. territories primary energy consumption.

The U.S. territories data are compiled by the same EIA office that prepares the U.S. energy data (Office of Energy Markets and End Use), and published in the International Energy Annual. In addition, the source of some U.S. territories data is unpublished EIA data on “Other” countries in the Asia/Pacific region. These data are disaggregated by fuel type, but no attempt is made to allocate these data by end-use sectors. Data are shown in tables of “Apparent Consumption of Petroleum Products.”[3]

Step 4: Convert Physical Fuel Units to Energy Equivalents

Unit conversion factors are used to convert physical units to their energy equivalents (e.g., quadrillion British thermal units per thousand barrels). Definitions and heating values of the fossil fuels are documented in the appendices of EIA’s recurring reports: the *Annual Energy Review* (AER) and *State Energy Data Report* (SEDR), as well as the *Petroleum Supply Annual*, *Coal Industry Annual*, and *Natural Gas Annual*. This approach to estimating emissions enables EIA to provide detailed information about trends in sources of emissions.

Step 5: Identify Carbon Emission Coefficients and Calculate Total Carbon Content of Each Fuel Type

Carbon content is calculated from fossil fuels consumption in each end-use sector by multiplying the fossil fuel consumption activity data by fuel- and sector-specific carbon emission factors (carbon coefficients) in units of mass of carbon per energy unit of each fuel type (MMTC/QBtu). Energy consumption for U.S. territories is converted to carbon emissions using the same emission coefficients applied to U.S. energy data. These carbon values are converted to carbon dioxide by multiplying the values by 44/12. The carbon coefficients represent carbon at full combustion. The current thinking of scientists is that eventually all the carbon will be oxidized, whether or not it is fully combusted.

The amount of carbon released when a fossil fuel is burned depends on the density, carbon content, and gross heat of combustion of the fuel.[4] Most of the carbon coefficients for major fuels are assumed to be constant over time. However, for motor gasoline, LPG, jet fuel, and crude oil, EIA has developed annualized carbon emission coefficients to reflect changes in chemical composition or product mix over the years. Documentation Part II, Carbon Coefficients Used in This Report, contains a detailed discussion of the methods employed for developing the coefficients, including a table listing the emission factors that are used to estimate carbon dioxide emissions from combustion of crude oil, natural gas, and the complete slate of petroleum products.

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[3] Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, D.C., various years), http://www.eia.doe.gov/iea/. Energy Information Administration, unpublished preliminary data for most recent year.

[4] Combustion of hydrocarbons results in the production of carbon dioxide, water vapor, and heat. In the United States, the heat resulting from combustion is generally measured as the heat associated with production of water vapor and carbon dioxide. This is commonly referred to as the “higher” or “gross” heating value and is used in EIA statistics on thermal energy. The estimates in this report consistently employ coefficients that reflect the higher heating value assumption. Internationally, however, the “lower” heating value is used. If the lower heating value were used, the Btu content of the fuel would be 5 to 10 percent lower, and the coefficients would be 5 to 10 percent larger, but the carbon emissions estimate would be unchanged. This is sometimes a source of discrepancy. See Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm (hereinafter *Revised 1996 IPCC Guidelines*).

Step 6: Determine Value of Carbon Sequestered in Products

The carbon sequestered from nonfuel uses is estimated based on fossil fuels used as chemical feedstocks and other products. The methodology for estimating carbon stored in products from nonfuel use of fossil fuels is described in Section 1.3.

Step 7: Subtract Carbon in International Bunker Fuels

The Intergovernmental Panel on Climate Change *Good Practice Guidance* state that all emissions from international bunker fuels are to be excluded from national totals, and are to be reported separately.[5] The term "international bunker fuels" refers to fuels sold to and consumed by air or marine vessels engaging in international transport activities. By convention, trade statistics treat the sale of bunker fuels as a form of export by the selling country, because the purchaser promptly hauls the fuel outside national boundaries. This convention is followed by organizations that prepare international energy statistics, such as the United Nations and the International Energy Agency.

Bunker fuels, however, are an export without a corresponding import, because the purchasing vessel generally combusts the fuel during transport. EIA energy statistics, which are based on domestic sales of products, treat bunker fuels sales in the same manner as the sale of other fuels, i.e., as domestic energy consumption. Therefore, carbon emissions from bunker fuels are already incorporated in the domestic energy consumption statistics of the United States, primarily as transportation-related consumption of residual and distillate fuel oil by cargo and passenger vessels and kerosene-based jet fuel by commercial aircraft.

To quantify emissions of carbon dioxide from international bunker fuels, carbon coefficients are applied to annual consumption estimates for each of the relevant international bunker fuels, namely residual and distillate fuel oil to account for international marine bunkers, and kerosene-based jet fuel for international aviation bunkers. Consumption estimates for distillate and residual fuel oil are each taken as the sum of oil laden on American and foreign ocean-going vessels in the United States. Since the data available for jet fuel consumption by U.S. air carriers reflect total fuel consumed on international routes, EIA estimates assume that domestic fuel purchases for outgoing international flights are 50 percent of this total. Jet fuel consumption by foreign air carriers fueled in the United States is estimated based on the share of total expenses by these air carriers in U.S. ports that account for fuel and oil purchases, multiplied by the average annual price of jet fuel in U.S. ports. It is assumed that 99 percent of the fuel is combusted, in accordance with Intergovernmental Panel on Climate Change Guidelines for liquid fuels.[6]

Beginning with the 1999 data year, EIA has included estimates for military bunker fuels that make up about 10 percent of the total international bunker fuels category. Previous years' inventories included only bunker fuel estimates for the commercial fleets of aircraft and vessels.

The estimate of military bunker fuels is obtained from the U.S. Environmental Protection Agency (U.S. EPA) inventory of the previous year. Military bunker fuel emissions estimates are developed by the Department of Defense (DoD) based on bunker fuel consumption multiplied by appropriate emission factors. DoD developed estimates of the percentage of each of the Military Services' total fuel consumption that is considered to be international bunker fuels, as that term is

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[5] Intergovernmental Panel on Climate Change, *Good Practice Guidance*, (Montreal, May 2000), http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

[6] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.1.29, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

defined by decisions of the UNFCCC (i.e., fuel sold to a vessel, aircraft, or installation within the United States or its territories and used in international maritime or aviation transport). Military aviation bunkers include international operations (i.e., sorties that originate in the United States and terminate in a foreign country), 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 (e.g., anti-submarine warfare flights). For the Air Force, a bunker fuel weighted average was calculated based on flying hours by major command, which takes into account weighting factors for international flights and higher fuel use by some types of aircraft. The Naval aviation bunker fuel percentage of total fuel was developed by DoD using flying hour data and estimate of bunker fuel percent of flights provided by the fleet. For marine bunkers, fuels consumed while Navy ships were underway were assumed to be bunker fuels.[7]

Step 8: Calculate and Sum Emissions for All Fuel Types and End Uses

Carbon dioxide emissions from fossil fuel consumption for electricity generation are allocated among the other four end-use sectors by their share of the final electric power demand, based on retail sales to the end-use consuming sectors. The following equation summarizes the estimation methodology described above in steps 1 through 9 for carbon dioxide emissions from fossil fuel:

$$CO_2 = \sum \left[\mathrm{AD} \times \mathrm{EF} + (\mathrm{NFE}) \times \frac{44}{12} \right]$$

where,

CO_2 = Carbon dioxide emissions from fossil fuel combustion (million metric tons)

AD = Activity data, converted from physical to energy units, based on net fossil fuel consumption after nonfuel uses are subtracted

EF = Emission factor, equal to carbon coefficient times oxidation factor

NFE = Carbon emissions from nonfuel uses of fossil fuels, equal to carbon contained in fuels consumed in non-energy purposes minus carbon stored in products (see Section 1.3)

44/12 = Molecular weight of carbon dioxide to carbon

See discussion below for nonfuel calculations.

Data Sources

Data for carbon dioxide emissions from fossil fuel combustion include sectoral fuel consumption data by fuel type, unit conversion factors, and carbon emission coefficients. EIA collects a wide variety of information from primary suppliers on a frequent basis and from energy consumers less

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[7] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*, Annex H, EPA236-R-01-001 (Washington, D.C., April 2001), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2001.html.

often, but still in a timely manner. Thus, levels of energy consumption in the United States are fairly well known by end-use sector and detailed fuel type. Although some of EIA's detailed sectoral surveys are conducted only every four years on a sample basis, EIA collects information about apparent consumption of petroleum products (taken as "petroleum product supplied") in mandatory monthly surveys of primary suppliers (e.g., refiners, pipeline operators, importers/exporters, and bulk terminal operators).

To estimate carbon dioxide emissions, EIA obtains annual fuel data that are presorted by the four end-use sectors (residential, commercial, industrial, and transportation) for all the fossil fuels (coal, natural gas, and the full slate of petroleum products). The petroleum products include asphalt and road oil, aviation gasoline, distillate fuel, jet fuel, kerosene, liquefied petroleum gases (LPG), lubricants, motor gasoline, residential fuel, and other petroleum products. Original activity data are too numerous to report in this document format.

The following EIA fossil fuel publications provide the sectoral consumption data for the carbon dioxide estimate:

- *Annual Energy Review* (AER);[8]
- *State Energy Data Report* (SEDR);[9] and
- *Monthly Energy Review* (MER).[10]

For the estimate of carbon dioxide emissions from fossil fuel combustion, the source of the consumption data for most fuel types is EIA's recurring report, the Monthly Energy Review (MER).

Detailed petroleum data are derived from unpublished MER data.

Because of the level of detail presented for some fuel categories, the State Energy Data Report (SEDR) is used where available. However, this data series often lags the other series by a year or two. International bunker fuel data are obtained from the U.S. Department of Commerce and the Air Transportation Association. Military bunker fuel data are developed by the U.S. Department of Defense and provided to the U.S. EPA for inclusion in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.[11] EIA obtains annual Military bunker fuel data from the most recent U.S. EPA inventory, and uses the previous year's value as a proxy for the most recent year.

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[8] U. S. Energy Information Administration, *Annual Energy Review 2002*, Table 5.12a Petroleum Consumption: Residential and Commercial Sectors, 1949-2002 (thousand barrels per day), DOE/EIA-0384(2002), (Washington, D.C., October 2003) p.150, http://tonto.eia.doe.gov/FTPROOT/multifuel/038402.pdf.

[9] U. S. Energy Information Administration, *State Energy Data Consumption Report*, DOE/EIA-0214, (Washington, D.C., various years), http://www.eia.doe.gov/emeu/states/_seds.html.

[10] U. S. Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(2004/12), http://www.eia.doe.gov/emeu/mer/contents.html.

[11] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: (various years)*, Annex 3.7, EPA 430-R-05-003 (Washington, D.C.). Submitted to the United Nations in April .http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Table 1-1. Data Sources for CO_2 Emissions from Fossil Fuel Combustion

Data Utilized	Citation
Fossil fuel consumption	Energy Information Administration, *State Energy Data Report*, DOE/EIA-0214 (Washington, D.C., various years), http://www.eia.doe.gov/emeu/states/_seds.html. Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384 (Washington, D.C., various years), http://www.eia.doe.gov/emeu/aer. Energy Information Administration, *Monthly Energy Review* DOE/EIA-0035 (Washington, D.C., various years and months), http://www.eia.doe.gov/emeu/mer/contents.html. Energy Information Administration, *Petroleum Supply Annual Volume 1*, DOE/EIA-0340 (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html.
Energy consumption data adjustments	Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/natural_gas_annual/nga.html. Energy Information Administration, *Petroleum Supply Monthly*, DOE/EIA-0109 (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_monthly/psm.html. Energy Information Administration, *Petroleum Supply Annual Volume 1*, DOE/EIA-0340 (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html. Energy Information Administration, *Monthly Energy Review* DOE/EIA-0035 (Washington, D.C., various years and months), http://www.eia.doe.gov/emeu/mer/contents.html. Energy Information Administration, *State Energy Data Report*, DOE/EIA-0214 (Washington, D.C., various years). http://www.eia.doe.gov/emeu/states/_seds.html
International bunker fuels	U.S. Department of Commerce, Bureau of Economic Analysis, unpublished BE-36 survey data (Washington, D.C., various years). U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division, "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries" (Washington, D.C., unpublished, various years). Air Transportation Association, Monthly Fuel Cost and Consumption (Washington, D.C., various years), http://www.airlines.org/econ/d.aspx?nid=5806. U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
U.S. territories data	Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, D.C., various years), http://www.eia.doe.gov/iea/. Energy Information Administration, Unpublished preliminary data (2004).

1.2 Carbon Dioxide Emissions and Sequestration from Non-Energy Use of Fossil Fuels

Portions of the fossil fuels consumed in the United States are not actually combusted (oxidized) but are used as chemical feedstocks, construction materials, lubricants, solvents, or reducing agents. Some of the carbon in these fuels is eventually sequestered, and is called stored carbon and subtracted from the total U.S. carbon dioxide emissions. The remaining carbon in these fuels is emitted. The fossil fuels that have non-energy (nonfuel) uses include:

Petroleum, including:

- Asphalt and road oil,
- Distillate and residual fuels,
- Liquefied petroleum gases,
- Lubricants,
- Miscellaneous petroleum products,
- Pentanes plus,
- Petrochemical feedstocks,
- Petroleum coke,
- Special naphtha,
- Still gas, and
- Waxes and polishes,
- Natural gas, and
- Coal.

For these fuels used for nonfuel purposes, EIA estimates the sequestered carbon (Chapter 2) based on the nonfuel use data and the rates of sequestration. Some but not all of the carbon is emitted to the atmosphere in the form of carbon dioxide. The principal nonfuel uses of fossil fuels, the methods of estimating nonfuel consumption for each applicable fossil fuel, and the fate of the carbon are described below for each fuel type.

1.2.1 Carbon Stored in Nonfuel Use of Asphalt and Road Oil

Carbon Storage

Carbon storage from nonfuel use of asphalt and road oil is estimated by multiplying the total carbon content of the asphalt and road oil used for non-energy uses by the carbon storage factor. EIA assumes that all carbon in asphalt and road oil is sequestered; none is emitted.

Estimation Methodology

Step 1: Quantify Consumption for Nonfuel Uses

The annual asphalt and road oil consumption is the value of U.S. products supplied, which EIA calculates as asphalt and road oil field production, plus refinery production, plus imports, plus unaccounted for crude oil, minus stock change, minus crude losses, minus refinery inputs, minus exports (in units of quadrillion Btu).[12] The asphalt and road oil annual consumption estimate can be obtained from Table 3 of the EIA *Petroleum Supply Monthly* (PSM), Table 2 of the EIA *Petroleum Supply Annual* (PSA), or the EIA *Annual Energy Review*. In addition, the EIA *State Energy Data Report* (SEDR) presents asphalt and road oil activity data in energy units. The physical to energy unit conversion factor is 6.636 million Btu per barrel, which is a constant value documented by EIA.

Step 2: Calculate Carbon Content

In Step 2, the carbon content is estimated by multiplying the U.S. consumption of asphalt and road oil (from Step 1) by the carbon content factor, which is 20.62 MMTC/quadrillion Btu. EIA assumes that asphalt and road oil use is nonfuel use by definition, and that all carbon in asphalt and road oil is permanently sequestered. Although carbon is not sequestered in the form of carbon dioxide, 44/12 is multiplied times the amount of carbon to convert to a carbon dioxide equivalent value.

Data Sources

Table 1-2. Data Sources for Carbon Stored from Nonfuel Use of Asphalt and Road Oil

Data Utilized	Citation
Asphalt and road oil consumption	Energy Information Administration, *Petroleum Supply Annual*, Volume 1, DOE/EIA-0340, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html.
	Energy Information Administration, *Petroleum Supply Monthly*, DOE/EIA-0109, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_monthly/psm.html.
	Energy Information Administration, *State Energy Data Report*, DOE/EIA-0214, (Washington, D.C., various years), http://www.eia.doe.gov/emeu/states/_seds.html.
Asphalt and road oil Btu content	Energy Information Administration, *State Energy Data Report*, Appendix B: Thermal Conversion Factor Source Documentation, DOE/EIA-0214(99), (Washington, D.C., various years), http://tonto.eia.doe.gov/FTPROOT/multifuel/021499.pdf.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines* for National Greenhouse Gas Inventories, Vol. 3 (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. (here in after *Revised 1996 IPCC Guidelines*).

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[12] U. S. Energy Information Administration, *Petroleum Supply Monthly*, DOE/EIA-0109 (Washington, D.C., various months and years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_monthly/psm.html.

1.2.2 Carbon Stored in and Emitted from Nonfuel Use of Distillate and Residual Fuels

Emissions Sources

Small amounts of distillate and residual fuels are stored in products from the chemical industry. The remainder of the carbon consumed in these nonfuel uses is assumed to be emitted and is combined with the emissions from the industrial sector.

Estimation Methodology

Carbon storage from nonfuel use of distillate and residual fuels is estimated by multiplying the total carbon content of these fuels used for non-energy uses by a carbon storage factor.

Step 1: Quantify Consumption for Nonfuel Uses

Chemical industry fuel product use is currently reported every four years in the Manufacturers Energy Consumption Survey (MECS), published by EIA. MECS is EIA's survey of energy consumption and usage patterns by U.S. manufacturers. The survey is administered and compiled by the U.S. Census Bureau. Surveys were conducted for calendar years 1988, 1991, 1994, 1998 and 2002. The MECS reports small volumes of distillate and residual oils used for nonfuel purposes in the chemical industry. For years prior to 2002, EIA applies linear interpolation to estimate values for years when MECS is not published. Values for years after 2002, for which MECS data are not available, are assumed to be constant and equal to 2002 values.

Step 2. Calculate Carbon Content

Based on EIA analysis, carbon content is calculated using a value of 19.95 and 21.49 MMTC per quadrillion Btu for distillate fuel and residual oils, respectively.

Step 3. Calculate Actual Carbon Stored and Emitted

Following the practice for gas oil petrochemical feedstocks, EIA assumes 50-percent sequestration. The remaining 50 percent is assumed to be emitted.[13] Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

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[13] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 1.28, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Data Sources

Table 1-3. Activity Data Sources for Carbon Stored and Emitted from Nonfuel Use of Distillate and Residual Fuels

Data Utilized	Citation
Distillate and residual fuel oil consumption for nonfuel use	Energy Information Administration, *Manufacturing Energy Consumption Survey*. Manufacturing Consumption of Energy 2002. http://www.eia.doe.gov/emeu/mecs/mecs2002/datatables/contents.html.
Distillate fuel and residual oil energy content value	Energy Information Administration, *State Energy Data Report 1999*, DOE/EIA-0214(99), (Washington, D.C., May 2001), http://tonto.eia.doe.gov/FTPROOT/multifuel/021499.pdf.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.3 Carbon Stored in and Emitted from Nonfuel Use of Liquefied Petroleum Gases

Liquefied petroleum gases (LPG), which include ethane, propane, and butane, are used by the chemical industry as a feedstock for plastics and other products. Most of the ethane, propane, and butane used by the chemical industry are used to manufacture ethylene, propylene, and butadiene, respectively, all of which are intermediate products for plastics. EIA assumes that 80 percent of the nonfuel use of LPG is sequestered in plastics, synthetic rubber, and related products.

Carbon Storage and Emissions Sources

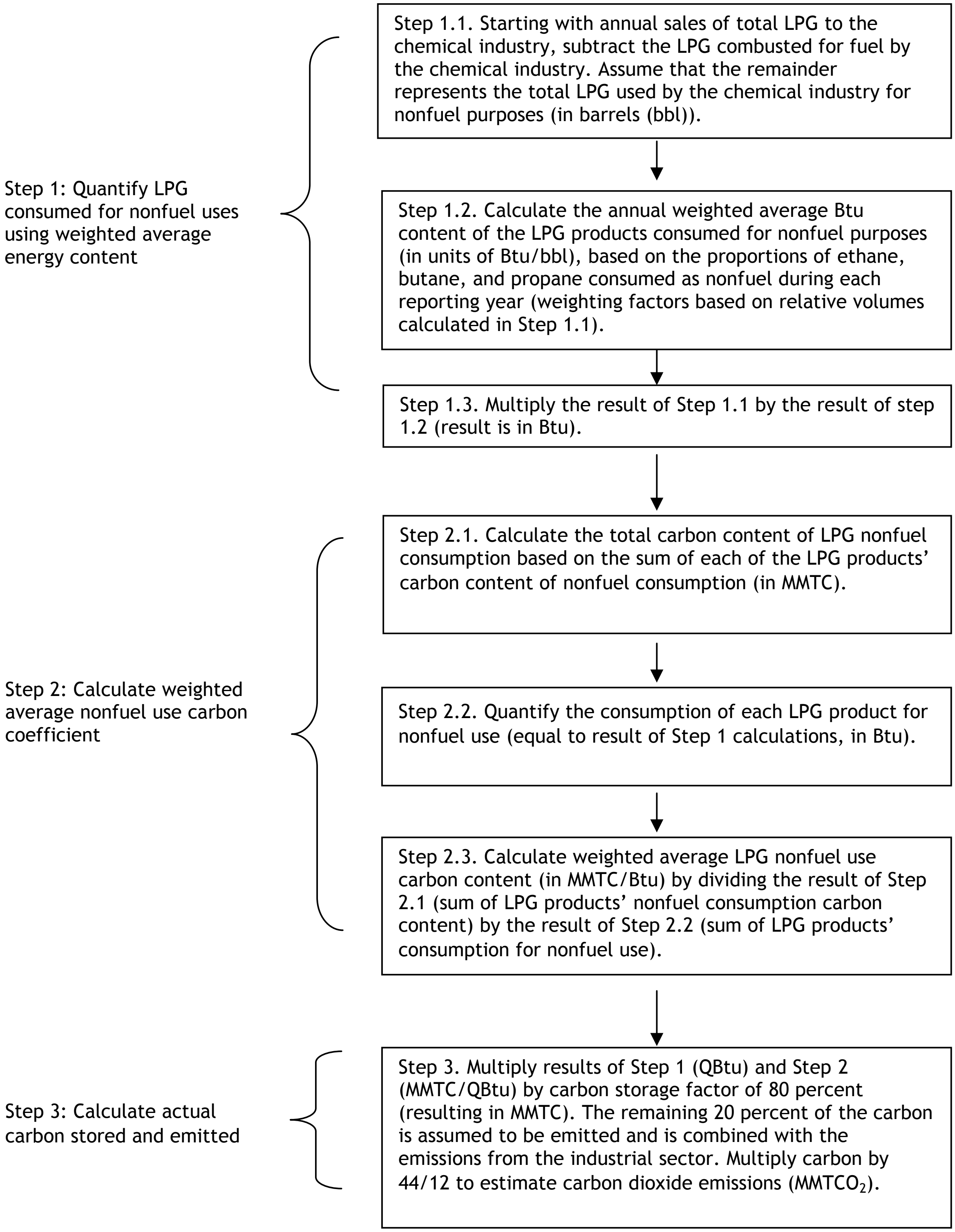
Portions of the LPG consumed in the United States are not actually combusted but are used in products and for other nonfuel purposes. Some of the carbon in the fuels used for products is eventually sequestered, and so is *subtracted* from the total U.S. carbon dioxide emissions calculation. The remainder of the carbon is assumed to be emitted and is combined with the carbon dioxide emissions from the industrial sector.

Estimation Methodology

The calculation for carbon stored from nonfuel use of LPG is relatively complex as LPG has both fuel and nonfuel uses and these uses straddle various sectors (i.e., industrial and transportation). There are several products in this category with differing energy content (e.g., Btu) values and they are not used equally as fuels and nonfuels.

The approach to estimating carbon stored from nonfuel use of LPG is to multiply the total estimated quantity of LPG consumed in nonfuel uses by a nonfuel use carbon coefficient for LPG, and multiply the result by the factor that represents the percent of nonfuel use that is sequestered in products. Figure 1-1 presents a process flow diagram that illustrates these steps.

Figure 1-1. Estimated Carbon Stored From Nonfuel Use of LPG



Step 1: Quantify LPG consumed for nonfuel uses using weighted average energy content

Step 1.1. Starting with annual sales of total LPG to the chemical industry, subtract the LPG combusted for fuel by the chemical industry. Assume that the remainder represents the total LPG used by the chemical industry for nonfuel purposes (in barrels (bbl)).

Step 1.2. Calculate the annual weighted average Btu content of the LPG products consumed for nonfuel purposes (in units of Btu/bbl), based on the proportions of ethane, butane, and propane consumed as nonfuel during each reporting year (weighting factors based on relative volumes calculated in Step 1.1).

Step 1.3. Multiply the result of Step 1.1 by the result of step 1.2 (result is in Btu).

Step 2: Calculate weighted average nonfuel use carbon coefficient

Step 2.1. Calculate the total carbon content of LPG nonfuel consumption based on the sum of each of the LPG products' carbon content of nonfuel consumption (in MMTC).

Step 2.2. Quantify the consumption of each LPG product for nonfuel use (equal to result of Step 1 calculations, in Btu).

Step 2.3. Calculate weighted average LPG nonfuel use carbon content (in MMTC/Btu) by dividing the result of Step 2.1 (sum of LPG products' nonfuel consumption carbon content) by the result of Step 2.2 (sum of LPG products' consumption for nonfuel use).

Step 3: Calculate actual carbon stored and emitted

Step 3. Multiply results of Step 1 (QBtu) and Step 2 (MMTC/QBtu) by carbon storage factor of 80 percent (resulting in MMTC). The remaining 20 percent of the carbon is assumed to be emitted and is combined with the emissions from the industrial sector. Multiply carbon by 44/12 to estimate carbon dioxide emissions ($MMTCO_2$).

Step 1: Quantify LPG Consumed for Nonfuel Uses Using Weighted Average Energy Content

To estimate LPG consumption for nonfuel uses, a weighted average energy content of the LPG products consumed in nonfuel uses (in quadrillion Btu/million barrels) is multiplied by the combined volume of the LPG products used by the chemical industry for nonfuel purposes (in million barrels).

The weighted average Btu content of the nonfuel use LPG is calculated to account for the varying proportions of ethane, propane, and butane that are consumed for nonfuel uses, and their different Btu values. To calculate the weighted average Btu content requires an estimate of the volumes of LPG products consumed for nonfuel uses. The volume of each fuel type consumed for nonfuel uses is based on the sales of LPG products to the chemical industry, from which chemical industry fuel use of LPG is subtracted; the remainder is assumed to be nonfuel uses.

The combined volume of the LPG products used by the chemical industry for nonfuel purposes (in million barrels) is estimated using the following equation:

$$LPG_{nonfuel} =$$

$$\left[\frac{\left(eth_{nonfuel}eth_{Btu}+pro_{nonfuel}pro_{Btu}+but_{nonfuel}but_{Btu}\right)}{eth_{nonfuel}+pro_{nonfuel}+but_{nonfuel}}\right]\left[\left(eth_{chem}+pro_{chem}+but_{chem}\right)-\left(eth_{fuel}+pro_{fuel}+but_{fuel}\right)\right]$$

where,

$LPG_{nonfuel}$ = LPG consumed for nonfuel uses (QBtu)

$Eth_{nonfuel}$ = Ethane consumed for nonfuel uses (10^6 bbl)

$Pro_{nonfuel}$ = Propane consumed for nonfuel uses (10^6 bbl)

$But_{nonfuel}$ = Butane consumed for nonfuel uses (10^6 bbl)

Eth_{Chem} = Total ethane delivered to chemical industry (10^6 bbl)

Pro_{Chem} = Total propane delivered to chemical industry (10^6 bbl)

But_{Chem} = Total butane delivered to chemical industry (10^6 bbl)

Eth_{Fuel} = Ethane consumed as fuel by chemical industry (10^6 bbl)

Pro_{Fuel} = Propane consumed as fuel by chemical industry (10^6 bbl)

But_{Fuel} = Butane consumed as fuel by chemical industry (10^6 bbl)

Eth_{Btu} = Ethane Btu content (QBtu/10^6 bbl)

Pro_{Btu} = Propane Btu content (QBtu/10^6 bbl)

But_{Btu} = Butane Btu content (QBtu/10^6 bbl)

The activity data used in Step 1 include sales of LPG products to the chemical industry, chemical industry fuel use of LPG, and LPG energy content. The American Petroleum Institute (API) reports sales of LPG products to the chemical industry before fuel uses are subtracted. API reported the sales of LPG products to the chemical industry in the API survey, *Sales of Natural Gas Liquids and Liquefied Refinery Gases.* The EIA publication, *PSA*, reports overall LPG consumption.

Chemical industry fuel use of LPG is currently reported every four years in the MECS. The MECS data are reported for 1988, 1991, 1994, 1998 and 2002. Values are linearly interpolated for years between the reporting years, and values for each year after 2002 are extrapolated.

The energy content, in million Btu per barrel, is a constant value for each of the fuel types as documented by EIA in the *State Energy Data Report (SEDR)*. These Btu values are presented in Table 1-4.

Table 1-4. LPG Btu Content (10^6 Btu/bbl)

Fuel Type	**Btu Content**
Propane	3.836
Ethane	3.082
Butane, normal	4.326
Isobutane	3.974

Source: Energy Information Administration, State Energy Data Report 1999, Appendix B: Thermal Conversion Factor Source Documentation, DOE/EIA-0214(99), (Washington, D.C., May 2001).

Step 2. Calculate Carbon Content

In Step 2, the carbon content is estimated using a weighted average nonfuel use carbon emission coefficient. This carbon content coefficient is calculated by dividing the combined carbon content of each LPG product’s nonfuel consumption by the total LPG used by the chemical industry for nonfuel purposes.

The carbon content of each of the fuel types is presented in Table 1-5. Documentation Part II, Variables Used in Emission Estimates, presents the background and methodology for estimating the carbon coefficients of fossil fuels used in the United States. The LPG weighted average nonfuel use carbon emission coefficient varies slightly over time, but is generally 16.8 or 16.9 MMTC/QBtu.

Table 1-5. Carbon Content of LPG Products Used as Nonfuel (MMTC/QBtu)

Fuel	**Carbon Content**
Ethane	16.25
Propane	17.20
Butane, normal	17.71
Isobutane	17.75

Source: See Documentation Part II, Variables Used in Emission Estimates.

Step 3. Calculate Actual Carbon Stored and Emitted

Following the recommendations provided in the *Revised 1996 IPCC Guidelines*, EIA assumes that 80 percent of the nonfuel use is sequestered in plastics, synthetic rubber, and related products.[14] In Step 3, the product of Step 1 and Step 2 are multiplied by the carbon storage factor of 0.80. The remaining 20 percent is combined with the emissions from the industrial sector. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-6. Data Sources for Carbon Stored and Emitted from Nonfuel Use of Liquefied Petroleum Gases

Data Utilized	Citation
Sales of LPG products to the chemical industry	American Petroleum Institute, Sales of Natural Gas Liquids and Liquefied Refinery Gases, various tables (Washington, DC, various years).
Industrial consumption of LPG products	Energy Information Administration, *Petroleum Supply Annual Volume 1,* DOE/EIA-0340, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/pet_data_publications.html.
Chemical industry fuel use of LPG	Energy Information Administration, *Manufacturer's Energy Consumption Survey,* 2002. http://www.eia.doe.gov/emeu/mecs/mecs2002/datatables/contents.html#fuel. Petroleum Supply Division, Form EIA-810, 'Monthly Refinery Report', (Washington, D.C.),
Btu content of ethane, propane, and butane	Energy Information Administration, *Annual Energy Review*, Appendix A, Table A1 Approximate Heat Content of Petroleum Products http://www.eia.doe.gov/emeu/aer/append_a.html
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.4 Carbon Stored and Emitted from Lubricants

Carbon Storage and Emissions Sources

The most common petroleum-based lubricant is motor oil, but the category "lubricants" also includes numerous other products such as industrial greases. The ultimate fate of lubricants is not easy to determine. For example, it is often the case that "recycling" motor oil means burning it as boiler fuel. The remainder of the carbon consumed in nonfuel uses that is not stored in products is assumed to be emitted and is combined with the emissions from the industrial sector.

Estimation Methodology

Step 1: Quantify Consumption for Nonfuel Uses

EIA publishes data on lubricant consumption by the industrial and transportation sectors in the *SEDR, MER, and AER*. All industrial and transportation consumption of lubricants is initially considered nonfuel use.

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[14] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 1.28, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 2: Calculate Carbon Content

The quantity of lubricants consumed for nonfuel use is multiplied by the carbon content value of 20.24 MMTC/QBtu. Chapter 6, Carbon Coefficients Used in This Report, presents the background and methodology for estimating the carbon coefficients of fossil fuels used in the United States.

Step 3: Calculate Actual Carbon Stored and Emitted

Following the Intergovernmental Panel on Climate Change, EIA assumes that 50 percent of the carbon in lubricants is sequestered. The remaining 50 percent is assumed to be released as emissions and is added to industrial emissions. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-7. Data Sources for Carbon Stored and Emitted from Nonfuel Use of Lubricants

Data Utilized	Citation
Industrial lubricant consumption	Energy Information Administration, State Energy Data Consumption Report, DOE/EIA-0214, (Washington, D.C., various years), http://www.eia.doe.gov/emeu/states/_use_multistate.html.
	Energy Information Administration, *Annual Energy Review*, (Washington, D.C., various years), http://www.eia.doe.gov/emeu/aer/contents.html.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.5 Carbon Stored from Nonfuel Use of Miscellaneous Petroleum Products

Carbon Storage

Miscellaneous products include all finished petroleum products not classified elsewhere (e.g., petrolatum, lube refining byproducts, aromatic extracts and tars, absorption oils, ram-jet fuel, petroleum rocket fuels, synthetic natural gas feedstocks, and specialty oils). Carbon stored from nonfuel use is calculated by multiplying the carbon content of miscellaneous products consumed by a 100-percent sequestration share.

Estimation Methodology

Step 1: Quantify Consumption for Nonfuel Uses

EIA assumes 100-percent nonfuel use for miscellaneous products consumption. Consumption estimates are obtained from EIA data publications, the *SEDR* (when available) and the *PSA*.

Step 2: Calculate Carbon Content

Carbon content is calculated by multiplying the annual consumption by a carbon content coefficient derived by EIA. .

Step 3: Calculate Actual Carbon Stored

EIA assumes 100 percent carbon sequestration for this category. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-8. Data Sources for Carbon Stored from Nonfuel Use of Miscellaneous Petroleum Products

Data Utilized	Citation
Miscellaneous petroleum product consumption	Energy Information Administration, *State Data System*, DOE/EIA-0214, (Washington, D.C., undated), http://www.eia.doe.gov/emeu/states/_use_multistate.html.
	Energy Information Administration, *Petroleum Supply Annual Volume 1*, DOE/EIA-0340, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/pet_data_publications.html.
Carbon content of miscellaneous petroleum products	Energy Information Administration estimates described in Chapter 6.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.6 Carbon Stored and Emitted from Nonfuel Use of Pentanes Plus

Emissions Sources

“Pentanes plus” are hydrocarbons heavier than butane that are extracted from natural gas at gas processing plants. Their principal uses are as contributors to the gasoline pool and as petrochemical feedstocks. The remainder of the carbon not stored is assumed to be emitted and is combined with the emissions from the industrial sector.

Estimation Methodology

Carbon storage from nonfuel use of pentanes plus is estimated by multiplying the total carbon content of pentanes plus used for non-energy uses by a pentanes plus carbon storage factor.

Step 1: Quantify Consumption for Nonfuel Uses

Nonfuel use of pentanes plus is estimated on the API annual survey of natural gas liquids and refinery gases sold to the chemical industry. For the most recent year of the inventory, which is estimated before API data become available, the consumption value is predicted based on the previous year’s API value scaled to EIA’s PSA value on industrial consumption of pentanes plus. The quantity of pentanes plus for nonfuel use is converted to energy units by multiplying by the energy content value published by EIA, which is 4.620 million Btu/bbl.[15]

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[15] U. S. Energy Information Administration. *State Energy Data Report 1999*. Appendix B: Thermal Conversion Factor Source Documentation. DOE/EIA-0214(99) (Washington, D.C., May 2001). http://www.eia.doe.gov/emeu/states/_use_multistate.html.

Step 2: Calculate Carbon Content

The carbon content is calculated by multiplying the consumption of pentanes plus for nonfuel use by the emission coefficient derived by EIA, which is 18.24 MMTC/quadrillion Btu. Documentation III, Carbon Coefficients Used in This Report, describes EIA's development of the emission factors.

Step 3: Calculate Actual Carbon Stored and Emitted

Following Intergovernmental Panel on Climate Change guidelines, EIA assumes that 80 percent of the carbon in pentanes plus used by the chemical industry is sequestered. The remaining 20 percent is added to the industrial emissions from consumption of pentanes plus. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-9. Data Sources for Carbon Stored and Emitted from Nonfuel Use of Pentanes Plus

Data Utilized	Citation
Sales of pentanes plus to the chemical industry	American Petroleum Institute, Sales of Natural Gas Liquids and Liquefied Refinery Gases, various tables (Washington, DC, various years).
Sales of pentanes plus to the chemical industry	Energy Information Administration, *Petroleum Supply Annual 2001. Volume 1,* DOE/EIA-0340/1, (Washington, D.C., June 2002), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/pet_data_publications.html .
Pentanes plus energy content value	Energy Information Administration, *State Energy Data Report 1999*, DOE/EIA-0214, (Washington, D.C., May 2001), http://tonto.eia.doe.gov/FTPROOT/multifuel/021499.pdf.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.7 Carbon Stored and Emitted from Petrochemical Feedstocks

Carbon Storages and Emissions Sources

EIA's petroleum surveys recognize two categories of products called "petrochemical feedstocks:" naphtha (synthetic) and gas oils. These products are presumably destined for ethylene crackers, and probably some mix of aromatic hydrocarbons (benzene, toluene, and xylene) and feedstocks used to make aromatic hydrocarbons. The remainder of the carbon not stored in products is assumed to be emitted and is combined with emissions from the industrial sector.

Estimation Methodology

Carbon storage from petrochemical feedstocks is estimated by multiplying the total carbon content of these fuels by a carbon storage factor.

Step 1: Quantify Consumption for Nonfuel Uses

All petrochemical feedstock supplies are included in nonfuel use by definition. EIA publishes petrochemical feedstock consumption values in various publications, including the *SEDR* in energy units and the *PSA* in barrels. Naphtha petrochemical feedstocks are converted to energy units by multiplying the consumption values in barrels by the EIA-derived thermal conversion value of 5.248 million Btu per barrel. The energy content of gas oil petrochemical feedstocks is calculated using an EIA thermal conversion factor of 5.825 million Btu per barrel.

Step 2: Calculate Carbon Content

The carbon content of petrochemical feedstocks is calculated using a carbon content value of 18.14 and 19.95 MMTC per quadrillion Btu for naphtha and gas oil feedstocks, respectively. Chapter 6, Carbon Coefficients Used in This Report, describes EIA's development of emission factors.

Step 3: Calculate Actual Carbon Stored and Emitted

Following the practice of the Intergovernmental Panel on Climate Change, EIA assumes that 75 percent of the carbon in synthetic feedstocks (naphtha) and 50 percent of the carbon in gas oil feedstock is sequestered in plastics, synthetic fibers, and related products. The difference between the total carbon and the fraction stored is assumed to be emitted and is added to industrial emissions. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-10. Data Sources for Carbon Stored and Emitted from Nonfuel Use of Petrochemical Feedstocks

Data Utilized	Citation
Naphtha and gas oil petrochemicals consumption	American Petroleum Institute, Sales of Natural Gas Liquids and Liquefied Refinery Gases, (various years). Energy Information Administration, *Petroleum Supply Annual, Volume 1,* DOE/EIA-0340/1, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/pet_data_publications.html.
Petrochemical feedstocks' energy content value	Energy Information Administration, *State Energy Data System*, DOE/EIA-0214, (Washington, D.C.), http://tonto.eia.doe.gov/FTPROOT/multifuel/021499.pdf.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.8 Carbon Stored and Emitted from Petroleum Coke

Carbon Storage and Emissions Sources

About 90 percent carbon by weight, petroleum coke is a coal-like solid created after intensive extraction of lighter hydrocarbons from petroleum feedstocks by oil refiners. Most petroleum coke is used in the refineries as fuel or as a catalyst. The remainder of the carbon consumed in nonfuel uses that is not stored in products is assumed to be emitted and is combined with the emissions from the industrial sector.

Estimation Methodology

Carbon storage from nonfuel use of petroleum coke is estimated by multiplying the total carbon content of petroleum coke used for non-energy uses by a carbon storage factor.

Step 1: Quantify Consumption for Nonfuel Uses

EIA estimates nonfuel use by taking the quantity of petroleum coke supplied, as reported in the *Petroleum Supply Annual (PSA)*, and deducting all known fuel uses (refinery use from the *PSA* and industrial uses (cement/lime uses) from the *MECS*).

Step 2: Calculate Carbon Content

The carbon content is calculated using a carbon content value of 27.85 MMTC per quadrillion Btu. Chapter 6, Carbon Coefficients Used in This Report, describes EIA's development of emission factors.

Step 3: Calculate Actual Carbon Stored and Emitted

EIA assumes that 50 percent of the carbon in petroleum coke for nonfuel use is sequestered, and the remaining fraction from nonfuel use of petroleum coke is added to industrial emissions. It should be noted, however, that it has been difficult to identify significant sequestering nonfuel uses of petroleum coke in the United States. In conjunction with the Environmental Protection Agency, this estimate is currently under evaluation and it may yield a downward estimation in the sequestering amounts allocated to petroleum coke. The principal identified nonfuel use is for sacrificial anodes in primary aluminum smelting, a non-sequestering use that EIA counts separately under process emissions. It appears that petroleum coke is also used in small quantities by many different industries as a reducing agent (a source of carbon monoxide that, in turn, can be used to scour oxygen from products such as lead oxide (to produce lead) or iron oxide (to produce iron). These are, however, non-sequestering uses. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-11. Data Sources for Carbon Stored and Emitted from Nonfuel Use of Petroleum Coke

Data Utilized	Citation
Petroleum coke supplied and refinery fuel consumption	Energy Information Administration, *Petroleum Supply Annual, Volume 1,* DOE/EIA-0340/1, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/pet_data_publications.html.
Petroleum coke industrial uses	Energy Information Administration, *Manufacturer's Energy Consumption Survey,* Energy Consumption Division, Form EIA-846, '2002 Manufacturing Energy Consumption Survey,' and Petroleum Supply Division, Form EIA-810, 'Monthly Refinery Report', (Washington, D.C.), http://www.eia.doe.gov/emeu/mecs/mecs2002/datatables/contents.html#fuel.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.9 Carbon Emissions from Nonfuel Use of Special Naphtha

Emissions Sources

"Special naphtha" is a catchall for an array of hydrocarbon-based solvents, such as hexane and the volatile oils used in petroleum-based paint. In general, solvents evaporate into the atmosphere as nonmethane volatile organic compounds (NMVOCs) after use and swiftly weather into atmospheric carbon dioxide. EIA assumes that 100 percent of the carbon in special naphtha is emitted.

Estimation Methodology

Carbon emissions from nonfuel use of special naphtha are estimated by multiplying the consumption activity data by an emission coefficient.

Step 1: Quantify Consumption for Nonfuel Use

EIA assumes that all special naphtha consumption is for nonfuel use. Special naphtha consumption data are obtained from the EIA *SEDR* or the *PSA*, depending on annual publication availability (EIA data publications are updated cyclically to maintain internal consistency). Data obtained from *PSA* are converted to energy units by multiplying the consumption values in barrels by the EIA-derived thermal conversion value of 5.248 million Btu per barrel.

Step 2: Calculate Carbon Content

Carbon content is calculated using a value of 19.86 MMTC per Quadrillion Btu. Chapter 6, Carbon Coefficients Used in This Report, describes EIA’s development of emission factors.

Step 3: Calculate Carbon Emissions

EIA assumes that no carbon in special naphtha is sequestered. Therefore, the total carbon content calculated in Step 2 is considered emissions converted to carbon dioxide using the carbon dioxide-to-carbon mass ratio of 44/12, and is added to industrial sector emissions.

Data Sources

Table 1-12. Data Sources for Carbon Dioxide Emitted from Nonfuel Use of Special Naphtha

Data Utilized	**Citation**
Special naphtha consumption for nonfuel use	Energy Information Administration, *State Energy Data System*, http://tonto.eia.doe.gov/FTPROOT/multifuel/021499.pdf.
	Energy Information Administration, *Petroleum Supply Annual, Volume 1*, DOE/EIA-0340/1, (Washington, D.C., various years) http://www.eia.doe.gov/oil_gas/petroleum/data_publications/pet_data_publications.html.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.10 Carbon Stored and Emitted from Still Gas

Carbon Storage and Emissions Sources

Still gas is the gas that floats to the top of distillation columns in oil refineries. Its chemical composition is a highly variable blend of free hydrogen, methane, carbon monoxide, and heavier hydrocarbons, depending on the refinery process, the feedstock, and process conditions. Still gas is used as a refinery fuel and a petrochemical feedstock. The remainder of the carbon consumed in nonfuel uses that is not stored in products is assumed to be emitted and is combined with the emissions from the industrial sector.

Estimation Methodology

Carbon storage from nonfuel use of still gas is estimated by multiplying the total carbon content of still gas consumed for non-energy use by a carbon storage factor.

Step 1: Quantify Consumption for Nonfuel Uses

EIA estimates nonfuel use by deducting all known fuel uses (refinery fuel use from the EIA *PSA* and pipeline gas supplies from the EIA *Natural Gas Annual*) from the products supplied value from the PSA. The remainder is assumed to be dispatched to chemical plants as a feedstock. If the calculated net value of still gas is less than zero, the value of zero is used instead. The data on pipeline gas supplies (supplemental gas-refinery gas) are converted to energy units by multiplying the volume in standard cubic feet by the annual thermal conversion factor and then converted to barrels. Once the nonfuel still gas consumption value is calculated in barrels, it is converted to energy units by dividing by the EIA-derived thermal conversion value of 6.000 million Btu per barrel.

Step 2: Calculate Carbon Content

The carbon content of still gas is calculated using a carbon content value of 17.51 MMTC per quadrillion Btu. Chapter 6, Carbon Coefficients Used in This Report, describes EIA's development of emission factors.

Step 3: Calculate Actual Carbon Stored and Emitted

Following the Intergovernmental Panel on Climate Change practice for LPG, EIA assumes that 80 percent of the carbon in still gas is sequestered. The remainder is assumed to be emitted and is added to the industrial sector emissions from still gas. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-13. Data Sources for Carbon Stored and Emitted from Nonfuel Use of Still Gas

Data Utilized	Citation
Product supplied and refinery fuel	Energy Information Administration, *Petroleum Supply Annual, Volume 1*, DOE/EIA-0340/1, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/pet_data_publications.html.
Supplemental gas-refinery gas	Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/natural_gas_annual/nga.html.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.11 Carbon Stored in Waxes and Polishes

Carbon Storage

The principal use of waxes is to make wax paper and food packaging materials, which usually end up in landfills. EIA assumes that no carbon is emitted from nonfuel uses of waxes and polishes.

Estimation Methodology

To quantify emissions and storage of carbon from waxes and polishes, EIA calculates the carbon content of waxes and polishes consumption, and multiplies by a 100 percent sequestration factor.

Step 1: Quantify Consumption for Nonfuel Uses

Following the Intergovernmental Panel on Climate Change, EIA attributes 100 percent of waxes and polishes consumption to nonfuel use. The waxes and polishes consumption data are obtained from the EIA *SEDR* (when data are available) or the EIA *PSA*. When using the *PSA* values in units of barrels, EIA applies the thermal conversion factor of 5.537 million Btu per barrel, a constant value documented by EIA in the *SEDR*.

Step 2: Calculate Carbon Content

The carbon content is calculated by multiplying the consumption by the emission coefficient derived by EIA, which is 19.81 MMTC per quadrillion Btu. Chapter 6, Carbon Coefficients Used in This Report, describes EIA’s development of emission factors.

Step 3: Calculate Actual Carbon Stored

Following the Intergovernmental Panel on Climate Change, EIA assumes that 100 percent of the carbon in waxes and polishes is sequestered. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-14. Data Sources for Carbon Stored from Nonfuel Use of Waxes and Polishes

Data Utilized	Citation
Waxes and polishes consumption	Energy Information Administration, *State Energy Data System*, http://tonto.eia.doe.gov/FTPROOT/multifuel/021499.pdf. Energy Information Administration, *Petroleum Supply Annual, Volume 1,* DOE/EIA-0340/1, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/pet_data_publications.html.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.12 Carbon Stored from Nonfuel Use of Natural Gas

Carbon Storage and Emissions

All nonfuel use of natural gas takes place in the industrial sector. Natural gas feedstocks are used to make nitrogenous fertilizers and for a range of chemical products other than ammonia, particularly methanol. Carbon storage from nonfuel use of natural gas is estimated by multiplying the total carbon content of natural gas used for non-energy uses by a carbon storage factor for natural gas.

Estimation Methodology

To estimate carbon stored, activity data on natural gas consumed for nonfuel purposes are multiplied by carbon content values.

Step 1: Quantify Natural Gas Consumed for Nonfuel Uses and Estimate Carbon Content

EIA MECS publishes natural gas consumption for nonfuel uses, divided into three categories:

Manufacture of nitrogenous fertilizers,

Other chemical use, and

All other nonfuel uses.

This data disaggregation of nitrogenous fertilizer consumption from other chemical uses of natural gas allows better estimation of the fate – whether sequestration or emission – of the natural gas because the fate differs by nonfuel use category. The most recent MECS publication provided data on 2002 consumption. For years when MECS data are unavailable, estimates are interpolated or extrapolated using chemical indices as scaling factors.

Once the natural gas for nonfuel uses is quantified, it is multiplied by the energy (Btu) content. The annual Btu content of natural gas is reported in EIA's *Natural Gas Annual*. The non-utility natural gas Btu value is used for the nonfuel use estimate. The associated carbon content is calculated by multiplying the combined quantity by the natural gas carbon content factor of 14.47 MMTC/Quadrillion Btu.

Step 2: Determine Actual Carbon Stored and Emitted

The carbon stored from nonfuel use of natural gas is determined for each of the three non-fuel use categories. The use of natural gas feedstocks to make nitrogenous fertilizers is considered a non-sequestering use, because the underlying chemical in nitrogenous fertilizers is ammonia (NH_3), which is manufactured by steam reforming of natural gas and reacting the synthesis gas with atmospheric nitrogen, literally leaving the carbon in the feedstock "up in the air." In many cases, the carbon dioxide is recovered to make urea or for other industrial use. However, carbon in urea and industrial carbon dioxide are generally only temporarily delayed before eventual release into the atmosphere.

Although the methanol used to make methyl tertiary butyl ether (MTBE) winds up in the gasoline pool and is combusted, EIA already counts the carbon in MTBE in gasoline emissions, and does not count it again in the feedstock so as to avoid double counting. Future research on the fate of the carbon in feedstocks for other chemical industry uses will probably gradually reduce the 100-percent sequestration share currently assumed. In addition, EIA assumes that other nonfuel uses of natural gas in the chemical industry result in 100 percent carbon sequestration. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-15. Data Sources for Carbon Stored and Emitted from Nonfuel Use of Natural Gas

Data Utilized	Citation
Manufacture of nitrogenous fertilizers; other chemical use of natural gas; and all other nonfuel uses of natural gas	Energy Information Administration, *Manufacturer's Energy Consumption Survey*, Energy Consumption Division, Form EIA-846, '2002 Manufacturing Energy Consumption Survey,' and Petroleum Supply Division, Form EIA-810, 'Monthly Refinery Report', (Washington, D.C., Various years), http://www.eia.doe.gov/emeu/mecs/mecs2002/datatables/contents.html#fuel
Ammonia production data	U.S. Department of Commerce, *DOC Current Industrial Reports. Fertilizer Materials and Related Products*, (Washington, D.C., Various years), http://www.census.gov/cir/www/325/mq325b.html.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.13 Carbon Stored and Emitted from Nonfuel Use of Coal

Carbon Storage and Emissions Sources

The manufacture of coke is the largest nonfuel use of coal. By EIA convention, however, coke manufacture is treated as a fuel use. This is not unreasonable, because coke is almost always ultimately combusted. Coke is manufactured by "cooking" high-grade coal in huge ovens in the absence of oxygen. Volatile materials, moisture, and certain categories of impurities are driven off, leaving behind a high-carbon material suitable for metallurgical use. Among the byproducts of the process are "coal tars" or "coal liquids," which typically are rich in aromatic hydrocarbons, such as benzene. Coal tars generally are used as feedstocks in the chemical industry. "Nonfuel use" of coal, as defined for this report, consists of the coal tars driven off during the manufacture of coke. The remainder of the coal tar carbon consumed in nonfuel uses that is not stored in products is assumed to be emitted and is combined with the emissions from the industrial sector.

Estimation Methodology

Step 1: Quantify Consumption for Nonfuel Uses

Coal tar production data were obtained, for years prior to 1995, from the International Trade Commission's *Synthetic Organic Chemicals*, a data series that was discontinued in 1995. This data series reported in units of thousand liters for data years 1990 through 1991 and thousand kilograms for data years 1992 through 1994. Since 1995, production has been estimated on the basis of the ratio of EIA's estimate of 1994 coke production, reported in the *Quarterly Coal Report*, to the legacy International Trade Commission data series for coal tar production.

Step 2: Calculate Carbon Content

Carbon content is calculated by multiplying the annual consumption by a coefficient derived by EIA.

Step 3: Calculate Actual Carbon Stored and Emitted

Following the Intergovernmental Panel on Climate Change guidelines, EIA assumes that 75 percent of the carbon in coal tars is sequestered. Finally the value is converted to carbon dioxide equivalent by multiplying times 44/12.

Data Sources

Table 1-16. Data Sources for Carbon Stored and Emitted from Nonfuel Use of Coal

Data Utilized	**Citation**
Coal tar production data	International Trade Commission. *Synthetic Organic Chemicals.* (discontinued after 1995)
Coke production	Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384, (Washington, D.C., various years), http://www.eia.doe.gov/emeu/aer/.
Carbon content	Energy Information Administration estimates described in chapter 6.
Carbon storage factor	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

1.2.14 Carbon Dioxide Emissions from Natural Gas Flaring

Other carbon dioxide emissions include emissions from energy production and industrial emissions that are not caused by the combustion or feedstock use of commercial fossil fuels. These emissions typically are created either by the combustion of waste products containing fossil carbon (such as natural gas flaring) or by chemical reactions with carbon-containing minerals.

Emissions Sources

U.S. energy production also generates small volumes of carbon dioxide emissions. The two principal sources are the flaring of natural gas and the venting of carbon dioxide produced in conjunction with natural gas.[16] When a field is developed for petroleum extraction, any natural gas associated with that field may be flared if its use is not economically justifiable. This is typically the case for remote sites or when the gas is of poor quality or minimal volume. During natural gas production, flaring may be used for disposal of waste products (e.g., hydrogen sulfide), capacity testing, or as a result of process upsets.

Emissions from the second source, carbon dioxide produced in conjunction with natural gas, occur during production activities. Natural gas is actually a mixture of several different gases including carbon dioxide. If the carbon dioxide content of natural gas is large enough to reduce the heating value of the gas below the specification for pipeline gas (870 Btu per standard cubic foot), the carbon dioxide is typically extracted by amine scrubbing. The extracted carbon dioxide generally is released to the atmosphere.

Estimation Methodology

The method for estimating emissions from natural gas flaring is based on the volume of vented and flared gas reported to EIA (assuming that all gas is flared). To calculate carbon dioxide emissions, the figures are aggregated, converted into Btu, and then multiplied by an emission

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[16] See discussion of carbon dioxide manufacture for the treatment of vented carbon dioxide.

coefficient of 14.92 MMTC per quadrillion Btu. The value is converted to carbon dioxide equivalent by multiplying times 44/12.

There is greater uncertainty associated with this estimate, given that operators in the field are not required to meter gas that is vented or flared.

The following information is used to estimate carbon dioxide emissions from flared natural gas:

Annual volume of flared natural gas;

Energy content of a cubic foot of natural gas;

The fraction of gas combusted; and

The emission factor for carbon dioxide emissions from flared natural gas.

The following two steps are taken to derive the CO_2 emissions from natural gas flaring.

Step 1: Determine flared gas volume

EIA publishes the amount of natural gas flared and vented in its *Natural Gas Monthly* and *Natural Gas Annual* reports. EIA assumes 100 percent of all identified gas to be flared as the amount is so small and many states mandate its flaring.

Step 2: Calculate the emissions from carbon in flared natural gas

Calculation of the carbon dioxide emissions from flared gas is based on volume and energy content of flared natural gas, multiplied by an emission factor for carbon dioxide emissions from flared natural gas. Most of the variables are assumed to remain constant, as provided in the following equation:

$$CO_{2\ FNG} = F_{FNG} \text{ x } E_{FNG} \text{ x } EF_{FNG} \text{ x } Frac_{COMB} \text{ x } 10^{-6} \text{ x } 44/12$$

where,

$CO_{2\ FNG}$ = Carbon dioxide emissions from flared natural gas (million metric tons)

F_{FNG} = Volume of fuel (natural gas) flared (billion cubic feet)

E_{FNG} = Energy content per standard cubic foot (scf) of natural gas (assumed constant at 1,106 Btu)

EF_{FNG} = Emission factor from flared natural gas (14.92 metric ton C per quadrillion Btu)

$Frac_{COMB}$ = Fraction of gas combusted (assumed to be 100 percent)

44/12 = Molecular weight of carbon dioxide to carbon

The Btu content of marketed natural gas (likely the closest to flared gas) has tended to vary from 1,105 to 1,110 Btu/scf since 1990, with most towards the lower end. The carbon coefficient for flared gas is assumed to be 14.92 MMTC per quadrillion Btu, which is slightly more than pipeline gas as it contains some additional liquids. EIA has documented the carbon coefficients for pipeline quality gas in its *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573 (Washington, D.C., November, 1994) Appendix A.

Data Sources

EIA obtains total U.S. natural gas production data from the *Natural Gas Annual* and *Natural Gas Monthly*. Since the *Natural Gas Annual* is not released prior to the annual publishing date for *Emissions of Greenhouse Gases in the United States*, EIA uses instead the *Natural Gas Monthly* Table 1, Summary of Natural Gas Production in the U.S., p. 3, for the most recent year. The *Natural Gas Monthly* data point is a placeholder until the *Natural Gas Annual* is published with the non-estimated data and revisions to prior years.

Table 1-17. Data Sources for Carbon Dioxide Emissions from Natural Gas Flaring

Data Utilized	Citation
Natural gas flaring volume earlier years	Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/natural_gas_annual/nga.html.
Natural gas flaring volume, most recent year's preliminary estimate	Energy Information Administration, *Natural Gas Monthly*, DOE/EIA-0130, (Washington, D.C., various years), Table 1, http://www.eia.doe.gov/natural_gas/data_publications/natural_gas_monthly/ngm.html.
Energy content of gas	Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035, (Washington, D.C., various issues), Table 1.3, http://www.eia.doe.gov/emeu/mer/contents.html.
Emission factor for CO_2 emissions from flared natural gas	Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, Appendix A, DOE/EIA 0573. (Washington, D.C., November, 1994), http://www.eia.doe.gov/oiaf/1605/87-92rpt/appa.html.

1.3 Other Carbon Dioxide Emissions from Industrial Processes

In addition to energy-related emissions, carbon dioxide is also produced during certain industrial processes. The primary source of industrial emissions is the calcination of limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$) to create lime (CaO). Both compounds are basic materials in a variety of manufacturing processes, particularly cement, iron, steel, and glass. Other sources of industrial emissions include the production and use of soda ash (Na_2CO_3), the manufacture of carbon dioxide, and aluminum production.

For this source category, emissions estimates are based on the compound used in the industrial process. By multiplying the amount of production or consumption of the compound by a carbon coefficient (the relative amount of carbon in that compound), a process-specific estimate is derived. Each industrial process, emissions source, and estimation method is discussed below.

1.3.1 Carbon Dioxide Emissions from Cement Manufacture

Emissions Sources

More than 60% of the carbon dioxide emissions from industrial sources originate from cement manufacturing. Four basic materials are required to make cement: calcium, silicon, aluminum, and iron. Substrates of these materials are ground into a powder and heated in a kiln. While in the kiln, limestone (the predominant source of calcium) is broken down into carbon dioxide and lime. The carbon dioxide is driven off into the atmosphere. After the kilning process has been completed, cement clinker is left.

Estimation Methodology

One mole of calcinated limestone produces one mole of carbon dioxide and one mole of lime. Since virtually all of the lime produced is absorbed into the clinker, the lime content of clinker is assumed to be representative of the amount of carbon dioxide emitted. EIA calculates the carbon dioxide emissions from three types of production – clinker, masonry cement, and cement kiln dust – to derive the total emissions from cement manufacture.

A carbon coefficient must be calculated for both clinker and masonry cement. In addition, during clinker production, some of the clinker materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust. EIA follows the procedures set forth in the *Revised 1996 IPCC Guidelines* in a four-step methodology:

1) Determine clinker and masonry cement volumes;

2) calculate the emissions from carbon in cement manufacture;

3) Calculate the emissions from cement kiln dust; and

4) Sum the emissions from clinker, cement, and kiln dust.

The four steps taken to derive the CO_2 emissions from cement manufacture are described below.

Step 1: Determine Clinker and Masonry Cement Volumes

U.S. Geological Survey (USGS) publishes two reports that provide annual estimates of clinker production in the U.S. and Puerto Rico, including “Cement,” a two-page *Mineral Commodity Summary* released on the web at the end of each year[17] and the December issue of *Mineral Industry Surveys*.[18]

At times, USGS has delayed publication of its *Mineral Industry Surveys* until April. If Puerto Rico clinker production is not available at the time of EIA report preparation, EIA uses the growth rate of U.S. clinker to estimate the change in Puerto Rican production.

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[17] U.S. Geological Survey, “Cement,” a two-page *Mineral Commodity Summary* (December annual), http://minerals.usgs.gov/minerals/pubs/mcs. U.S. clinker production (excluding Puerto Rico) is listed in the second row in the first table and U.S. masonry cement is provided in the first sentence under the heading “Domestic Production and Use.”

[18] U.S. Geological Survey, *Mineral Industry Surveys* (March annual). December data are released on the internet in March. Table 4, “Clinker Production by Producing Districts for December,” provides year-to-date production of clinker for Puerto Rico (in South Atlantic district) in metric tons.

Step 2: Calculate the emissions from carbon in cement manufacture

Calculation of the CO_2 emissions from clinker and masonry cement manufacture employs the same equation, with different production data and carbon emission coefficients, which are assumed constant for each product. The equation follows:

$$CO_{2(IND)Cx} = M_{Cx} \times Frac_{LIME} \times CF_{C/CaO} \times 10^{-3} \times 44/12$$

where,

$CO_{2(IND)Cx}$ = carbon dioxide emissions from clinker and cement production (million metric tons)

Cx = masonry cement (CEM) or clinker (CLK) as applicable

M_{Cx} = mass of clinker or masonry cement production (thousand metric tons)

$Frac_{LIME}$ = Percent lime based on molecular weight (assumed constant at 64.6% for clinker and 3% for masonry cement)

$CF_{C/CaO}$ = Conversion factor (12 g C/56.08 g CaO)

44/12 = Molecular weight of carbon dioxide to carbon

EIA uses the average lime fraction of 64.6% lime in clinker, as published by Intergovernmental Panel on Climate Change.[19] The lime fraction for masonry cement is the amount of lime not accounted for as clinker, which is assumed to be 3 percent.[20] Its calculation is based on the 5 percent gain in weight to cement by non-plasticizer additives, of which lime represents 60 percent (0.05 x 0.6 = 0.03). The conversion factor is the ratio of carbon produced to lime produced, which is the same for both clinker and masonry cement (12/56.08).

Step 3: Calculate the emissions from cement kiln dust

The carbon dioxide emissions attributable to the calcinated portion of cement kiln dust are not accounted for by the clinker production emission factor. EIA adopted the Intergovernmental Panel on Climate Change *Good Practice Guidance* rule, which estimates that an additional increment of CO_2 emissions from clinker production equal to 2 percent of direct emissions from clinker production are attributable to cement kiln dust.[21] The equation used is:

$$CO_{2(IND)CKD} = CO_{2(IND)CLK} \times Frac_{CKD}$$

where,

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[19] Intergovernmental Panel on Climate Change, *Good Practice Guidance* (Montreal, May 2000) p. 3.12, http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

[20] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, (Washington, D.C., April 2003), p. 84, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[21] Intergovernmental Panel on Climate Change, *Good Practice Guidance* (Montreal, May 2000) p. 3.12, http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

$CO_{2\ (IND)CKD}$ = carbon dioxide emissions from cement kiln dust (million metric tons)

$CO_{2\ (IND)CLK}$ = carbon dioxide emissions from clinker production (million metric tons)

$Frac_{CKD}$ = Percent additional lime in cement kiln dust not accounted for elsewhere (assumed constant at 2 percent)

Step 4: Sum emissions from clinker, cement, and kiln dust

The final step involves simply summing the carbon dioxide emissions (million metric tons) for the three sources of U.S. clinker, masonry cement, and cement kiln dust operations

Data Sources

The current year is always considered preliminary in "Cement," the two-page *Mineral Commodity Summary* released on the web at the end of each year at http://minerals.usgs.gov/minerals/pubs/mcs. U.S. clinker production (excluding Puerto Rico) is the second row in the first table and U.S. masonry cement is written in the first sentence under the heading "Domestic Production and Use."

EIA obtains year-to-date production of clinker for Puerto Rico (in South Atlantic district) in metric tons from the December issue of the USGS *Mineral Industry Surveys*, released on the web each March. Table 4, "Clinker Production by Producing Districts for December," provides current year data. Prior year clinker production can be checked in Table 4A.

Table 1-18. Data Sources for CO_2 Emissions from Cement Manufacture

Data Utilized	Citation
U.S. clinker and masonry cement production	U.S. Geological Survey, "Cement," *Mineral Commodity Summary* at http://minerals.usgs.gov/minerals/pubs/mcs, select CEMENT, select MINERAL COMMODITY SUMMARIES and most recent year.
Puerto Rico clinker production	U.S. Geological Survey, Mineral Industry Surveys, select CEMENT, select MINERAL INDUSTRY SURVEYS and DEC of most recent year (released in March) Tables 4 and 4A, http://minerals.usgs.gov/minerals/pubs/mcs.
Carbon emission coefficients	Intergovernmental Panel on Climate Change, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, published by the Institute for Global Environmental Strategies, (Japan), ISBN 4-88788-000-6, p. 3.12, http://www.ipcc-nggip.iges.or.jp/public/gp/english/. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

1.3.2 Carbon Dioxide Emissions from Limestone Consumption

Emissions Sources

The primary source of CO_2 emissions from limestone consumption is the calcination of limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$) to create lime (CaO). These compounds are basic raw materials used by a wide variety of industries, including construction, agriculture, chemicals, metallurgy, glass manufacture, and environmental pollution control. Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished. Demand from the transportation sector for crushed stone continues to drive growth in limestone and dolomite use.

Lime is an important chemical with a variety of industrial, chemical, and environmental applications. For U.S. operations, the term "lime" actually refers to a variety of chemical compounds, including calcium oxide or high-calcium quicklime, calcium hydroxide or hydrated lime, dolomitic quicklime, and dolomitic hydrate.

Limestone (including dolomite) can be used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization systems in utility and industrial plants, as a raw material in glass manufacturing, or as an input for the production of dead-burned dolomite. Limestone is heated during these processes, generating carbon dioxide as a byproduct.

Lime production involves three main stages: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone is roasted at high temperatures, just as it is released during clinker production. The carbon dioxide is driven off as a gas and normally exits the system with the stack gas.

Estimation Methodology

Based on the ratio of the molecular weight of carbon dioxide to the weight of calcium carbonate, EIA calculates an emission factor that is applied to the annual levels of manufacturing processes that consume the lime, limestone, or dolomite.

> Limestone has a carbon content of 12 percent and yields 120 metric tons of carbon for every 1,000 metric tons of sorbent consumed in the iron smelting, steelmaking, and glass manufacture industries, and in flue gas desulfurization systems.
>
> Dolomite has a carbon content of 13.2 percent and yields 132 metric tons of carbon for every 1,000 tons of dolomite consumed (when dolomite is distinguished in the data).
>
> Lime has a carbon content of 21.4 percent and releases 214 metric tons of carbon for every 1,000 metric tons of lime produced

In the case of limestone (including dolomite) used in flue gas desulfurization units, the estimate of carbon emitted is adjusted based on the application of a capacity utilization rate from the calcination process of sorbents used. Likewise, carbon emitted from limestone consumed in copper refining is adjusted.

EIA does not account for the instances in which the carbon dioxide is recovered or reabsorbed. Representatives of the National Lime Association believe that 10 to 20 percent of the carbon dioxide emitted in lime manufacture is recovered for industrial use or reabsorbed from the atmosphere by chemical reactions induced by the use of lime.

Eight steps are taken to derive the CO_2 emissions from limestone consumption:

> Step 1: Determine lime production volumes
>
> Step 2: Estimate limestone consumed in iron smelting
>
> Step 3: Estimate limestone consumed in steelmaking

Step 4: Estimate limestone consumed in copper refining

Step 5: Estimate limestone consumed in glass manufacturing

Step 6: Estimate limestone consumed in flue gas desulfurization

Step 7: Estimate limestone consumed in dolomite manufacturing

Step 8: Calculate the emissions from carbon in limestone consumption and lime and dolomite manufacture

Step 1: Determine Lime Production Volumes

USGS publishes an annual *Mineral Commodity Summary*, entitled “Lime,” that provides recent history and current estimate of U.S. production of quicklime and hydrated lime (in thousand metric tons).

Step 2: Estimate Limestone Consumed in Iron Smelting

In 1994, USGS published the last issue of a series that provided annual short tons of limestone consumed in iron smelting. EIA continues this time series by using the changes in pig iron production to extrapolate the growth rate of limestone consumption since 1994. These data are converted to metric tons by applying the factor 0.9071847 metric tons per short ton.

Step 3: Estimate Limestone Consumed in Steelmaking

The American Iron and Steel Institute publishes an *Annual Statistical Report* that includes consumption (in thousand short tons) of limestone, lime, and other fluxes in Table 30 of the report. EIA converts this data to metric tons by applying the factor 0.9071847 metric tons per short ton.

Step 4: Estimate Limestone Consumed in Copper Refining

EIA uses the U.S. Geological Survey’s *Mineral Commodity Summary* on “Copper” to obtain production data on primary copper refining in thousand of metric tons. The current year is always preliminary, and thus is regularly updated in each subsequent year.

Step 5: Estimate Limestone Consumed in Glass Manufacturing

From 1998 to 2000, the USGS withheld limestone consumption in glass manufacturing to avoid disclosure of specific producers in Table 14, “Crushed Limestone and Dolomite Sold or Used by Producers in the U.S.,” of the chapter on “Stone, Crushed” in its annual *Mineral Commodities Yearbook*. In 2001, USGS reported data, which EIA used to perform more recent estimates.

Step 6: Estimate Limestone Consumed in Flue Gas Desulfurization

EIA obtains unpublished data on sorbent use (in thousand short tons) by flue gas desulfurization (FGD) units. EIA converts these data to metric tons by applying the factor 0.9071847 metric tons per short ton. EIA includes the amount of limestone used, as identified by power plant. In addition, EIA assumes that half of the sorbent used in one plant that identified its sorbents as “Limestone and Alkaline Fly Ash,” is limestone. EIA sums the two to obtain the total limestone estimated to be used in FGD units. The data lags by one year; as a result, the most recent year is used as a proxy for the current year.

Step 7: Estimate Limestone Consumed in Dolomite Manufacturing

EIA employs Table 13, “Crushed Stone Sold or Used by Producers in the U.S.,” of the chapter on “Stone, Crushed” from the USGS annual *Mineral Commodities Yearbook* to identify dead-burned dolomite use. The data lags by one year; as a result, EIA uses the most recent year as a proxy for the current year. From 1992 and 1997, when the USGS withheld limestone consumption in dolomite manufacturing to avoid disclosure of specific producers, EIA averaged the reported use of the two closest years with available data.

Step 8: Calculate the Emissions from Carbon in Limestone Consumption and Lime and Dolomite Manufacture

The calculation of the CO_2 emissions involves multiplying annual production and consumption data for each source by a calcinations fraction, if appropriate, and a carbon conversion factor, which is assumed constant, using the following equation:

$$CO_{2(IND)Lx} = M_{Lx} \times Frac_{Lx} \times CF_{Lx} \times 10^{-3} \times 44/12$$

where,

$CO_{2\,(IND)Lx}$ = carbon dioxide emissions from lime production and limestone consumption (million metric tons)

Lx = lime (LIM), limestone (LST), or dolomite (DOL) as applicable

M_{Lx} = mass of lime production or limestone consumption (thousand metric tons)

$Frac_{Lx}$ = Percent utilization rate of limestone through calcination process (assumed constant at 35 percent for flue gas desulfurization, 20 percent for copper refining, and 100 percent for all other sources)

CF_{Lx} = Conversion factor (see Table 1-19)

44/12 = The molecular weight of carbon dioxide to carbon

The carbon conversion factor for lime applies to the equation for lime production only. The carbon conversion factor for limestone consumption is derived from the ratio of carbon produced to limestone consumed and is used in the equations for iron making, steelmaking, glass manufacture, copper refining, and flue gas desulfurization. The dolomite manufacture equation uses the dolomite conversion factor (see Table 1-19). Flue gas desulfurization and copper refining do not completely use up the limestone consumed; their equations require fractions defined below. According to information obtained from the USGS regarding the characterization of limestone consumed in fluidized-bed combustion systems and flue gas desulfurization units, the utilization rate of calcium obtained from the calcination process ranges from approximately 30 to 40 percent.

Table 1-19. Emission Coefficients for CO_2 from Limestone Consumption

Material	Conversion factor	Fraction
Lime	12 g C/56.08 g CaO	1.0
Limestone Consumption		
Iron Smelting	12 g C/100.09 g $CaCO_3$	1.0
Steelmaking	12 g C/100.09 g $CaCO_3$	1.0
Glass Manufacturing	12 g C/100.09 g $CaCO_3$	1.0
Copper Refining	12 g C/100.09 g $CaCO_3$	0.2
Flue Gas Desulfurization	12 g C/100.09 g $CaCO_3$	0.35
Dolomite	48.4 g C/368 g $CaCO_3MgCO_3$	0.132

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks (various years),* (Washington, D.C., April of each year) http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html.

Data Sources

The current year is always considered preliminary in all *Mineral Commodity Summary* reports released on the web at the end of each year at http://minerals.usgs.gov/minerals/pubs/mcs. Table 1-20 presents the data sources employed by EIA.

Table 1-20. Data Sources for CO_2 Emissions from Lime Manufacture

Data Utilized	Citation
U.S. lime production	U.S. Geological Survey, "Lime," *Mineral Commodity Summary*, (Washington, D.C., various years), http://minerals.usgs.gov/minerals/pubs/mcs, select LIME, select most recent year.
U.S. pig iron production	U.S. Geological Survey, "Iron and Steel," *Mineral Commodity Summary*, (Washington, D.C., various years) http://minerals.usgs.gov/minerals/pubs/mcs, select IRON & STEEL, select most recent year.
U.S. limestone consumed in steelmaking	American Iron and Steel Institute, *Annual Statistical Report*, (Washington, D.C., various years).
U.S. copper refining	U.S. Geological Survey, "Copper," *Mineral Commodity Summary*, (Washington, D.C., various years) http://minerals.usgs.gov/minerals/pubs/mcs, select COPPER, select most recent year.
U.S. limestone consumed in glass manufacturing, Dead-burned dolomite	U.S. Geological Survey, "Stone, Crushed," *Mineral Commodities Yearbook* (Washington, D.C., various years) http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#myb, select most recent year.
U.S. limestone consumed in flue gas desulfurization	Energy Information Administration, unpublished data on Sorbents Used by FGD Units, form EIA-767.
Carbon emission coefficients	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: (various years)*, (Washington, D.C., April of each year), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html.

1.3.3 Carbon Dioxide Emissions from Soda Ash Manufacture and Consumption

Emissions Sources

Commercial soda ash (sodium carbonate) is used in many familiar consumer products, such as glass, soap and detergents, paper, textiles, and food. Two methods are used to manufacture natural soda ash in the United States. The majority of production comes from Wyoming, where soda ash is manufactured by calcination of trona ore in the form of naturally occurring sodium sesquicarbonate. For every mole of soda ash created in this reaction, one mole of carbon dioxide is also produced and vented to the atmosphere. The other process used to manufacture soda ash is carbonation of brines; however, the carbon dioxide created in this process is captured and reused.

Once manufactured, most soda ash is consumed in glass and chemical production. Other uses include water treatment, flue gas desulfurization, soap and detergent production, and pulp and paper production. As soda ash is processed for these purposes, additional carbon dioxide may be emitted if the carbon is oxidized. Because of the limited availability of specific information about such emissions, only certain uses of soda ash are considered in this report. Sodium silicate ($Na_2CO_3+SiO_2$) and sodium tripolyphosphate ($Na_5P_3O_{10}$) are included as inorganic chemicals manufactured from soda ash and components of detergents. In detergents, the silica in sodium silicate prevents the redeposition of soils on clothing. In clay processing, the silica helps keep the clay dispersed using substantially less water. Sodium tripolyphosphate is a complex compound that softens water, suspends soil, serves as an anti-spotting agent, and promotes protein-water binding in ham, chicken tenders, and pet food.

Estimation Methodology

In order to ensure that carbon dioxide from the carbonation of brines is not included in emissions estimates for soda ash manufacture, the calculations in this report are derived solely from trona ore production figures. Approximately 1.8 metric tons of trona ore are required to yield 1 metric ton of soda ash. This amounts to 97 metric tons of carbon dioxide for every 1,000 metric tons of trona ore produced annually. For soda ash consumption, EIA applies a factor of 113 metric tons of carbon for every 1,000 metric tons of soda ash consumed in glass manufacturing or in flue gas desulfurization.

Six steps are taken to derive the CO_2 emissions from soda ash production and consumption:

Step 1: Determine trona production volumes

Step 2: Calculate soda ash production from trona

Step 3: Estimate soda ash consumed in glass manufacturing

Step 4: Estimate soda ash consumed in flue gas desulfurization

Step 5: Estimate sodium silicate and sodium tripolyphosphate production

Step 6: Calculate the emissions from carbon in the manufacture and consumption of soda ash, sodium silicate, and sodium tripolyphosphate

The steps are described below.

Step 1: Determine Trona Production Volumes

USGS reports the most recent annual production of Wyoming trona in thousand metric tons in Table 1, "Salient Soda Ash Statistics," of the December issue of the *Mineral Industry Survey* entitled "Soda Ash." Revisions to prior year production levels are updated using "Table 1, Salient Soda Ash Statistics," of the chapter on "Soda Ash" in USGS's annual *Mineral Commodities Yearbook*.

Step 2: Calculate Soda Ash Production from Trona

Approximately 1.8 metric tons of trona ore are required to yield 1 metric ton of soda ash. EIA multiplies this conversion factor, equivalent to 0.556, by the trona production data to calculate the thousand metric tons of soda ash produced.

Step 3: Estimate Soda Ash Consumed in Glass Manufacturing

USGS reports soda ash consumption by Total Glass in metric tons in Table 3, "Reported Consumption of Soda Ash in the U.S., By End Use, By Quarter," in the chapter on "Soda Ash" in USGS's *Mineral Commodities Yearbook*. The data lags by one year; as a result, EIA uses the most recent year as a proxy for the current year.

Step 4: Estimate Soda Ash Consumed in Flue Gas Desulfurization

EIA obtains unpublished data on sorbent use (in thousand short tons) by flue gas desulfurization units. EIA converts this data to metric tons by applying the factor 0.9071847 metric tons per short ton. EIA sums the amount of soda ash and sodium carbonate used. The data lags by one year; as a result, EIA uses the most recent year as a proxy for the current year.

Step 5: Estimate Sodium Silicate and Sodium Tripolyphosphate Production

The annual Census Bureau document *Current Industrial Report* (CIR) on Inorganic Chemicals is published too late for data to be included in EIA's *Emissions of Greenhouse Gases in the United States*. Instead, EIA uses the quarterly CIR on Inorganic Chemicals, in particular the quarterly production quantities in short tons from the product codes 325188A181 and 325188A174. In the event data are withheld, EIA simply estimates the missing quarter's data with an average of the three or two other quarters, depending on how much is withheld. Data are often withheld for sodium tripolyphosphate; for example, the 1991 production level was used as a proxy for 1992-1997 and 1999 production was used as a proxy for 2000-2002.

Step 6: Calculate the Emissions from Carbon in the Manufacture and Consumption of Soda Ash, Sodium Silicate, and Sodium Tripolyphosphate

Calculation of the CO_2 emissions is performed by multiplying annual production data by a carbon conversion factor, which is assumed constant, as follows:

$$CO_{2(IND)Sx} = M_{Sx} \times CF_{Sx} \times 10^{-3} \times 44/12$$

where,

$CO_{2(IND)Sx}$ = Carbon dioxide emissions from production and consumption of soda ash, sodium silicate, and sodium tripolyphosphate (million metric tons)

Sx = Soda ash (SA), sodium silicate (SS), or sodium tripolyphosphate (STP) as applicable.

M_{Sx} = Mass of soda ash production or consumption by various sources (thousand metric tons)

CF_{Sx} = Conversion factor (see Table 1-21)

44/12 = The molecular weight of carbon dioxide to carbon

The carbon conversion factor for soda ash applies to the equation for soda ash production and consumption in glass manufacture and flue gas desulfurization. The carbon conversion factor for sodium silicate applies to the equation for sodium silicate production. The sodium tripolyphosphate equation uses the sodium tripolyphosphate conversion factor (see Table 1-21).

Table 1-21. Emissions Conversion Factors for CO_2 Related to Soda Ash

Material	Conversion Factor
Soda Ash	12.01 g C / 106 g Na_2CO_3
Sodium Silicate	12.01 g C / 188 Na_2O SiO_2
Sodium Tripolyphosphate	(12 x 2.5) g C / 368 $Na_5P_3O_{10}$

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: (various years)*, (Washington, D.C., April of each year), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html.

Data Sources

Table 1-22. Activity Data Sources for CO_2 Emissions from the Manufacture and Consumption Soda Ash, Sodium Silicate, and Sodium Tripolyphosphate

Data Utilized	Citation
U.S. trona production	U.S. Geological Survey, "Soda Ash," monthly Mineral Industry Survey, (Washington, D.C., various years), http://minerals.usgs.gov/minerals/pubs/mcs
U.S. soda ash consumed in glass manufacturing, revisions to historic soda ash production	Dennis Kostick, "Soda Ash," U.S. Geological Survey, Mineral Commodities Yearbook (Washington, D.C., various years), http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#myb,
U.S. soda ash consumed in flue gas desulfurization	Energy Information Administration, unpublished data on Sorbents Used by FGD Units, form EIA-767.
U.S. sodium silicate and sodium tripolyphosphate production	1997-Current Data: U.S Census Bureau, "Inorganic Chemicals," quarterly Current Industrial Report, MQ325A (yr)-qtr, (Washington, D.C., various years/quarters) http://www.census.gov/cir/www/325/mq325a.html, 1980-1996 Data: Chemical Manufacturers Association, U.S. Chemical Industry Statistical Handbook 1998, (Washington, D.C., September 1998), pp. 37-38.
Carbon emission coefficients	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: (various years), (Washington, D.C., April of each year), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

1.3.4 Carbon Dioxide Emissions from Carbon Dioxide Manufacture

Over the years, carbon dioxide emissions have also been calculated from shale oil production and carbon dioxide production, itself. Estimates for shale oil have not been prepared since 1990.

Emissions Sources

Carbon dioxide is produced from a small number of natural wells and as a byproduct of chemical (i.e., ammonia) manufacturing. The Freedonia Group has determined that there is an 80-to-20 percent split between carbon dioxide produced as a byproduct and carbon dioxide produced from wells in the United States.[22] Emissions of byproduct carbon dioxide are incorporated into the natural gas energy consumption estimates as non-fuel, non-sequestered carbon and, therefore, are not included here to avoid double counting. Most carbon dioxide produced from wells is injected back into the ground for enhanced oil recovery. This process sequesters the carbon dioxide, at least in the short run. Conceptually, only carbon dioxide produced from wells and diverted to industrial use is emitted to the atmosphere.

Estimation Methodology

The Freedonia Group estimates that non-sequestering industrial use of carbon dioxide resulted in emissions of 1.3 million metric tons of carbon in 1993.[23] If 20 percent of this industrial use is supplied by wells, emissions can be estimated at 0.26 million metric tons of carbon dioxide. Based on the Freedonia reports, for which actual 1990 and 1993 data were available, carbon dioxide production increased by 4.2 percent annually. This annual growth factor was used to estimate the amount of carbon dioxide emissions for all years since 1993.

Calculation of CO_2 emissions from this source is performed by multiplying the emissions level in 1993 by the annual growth rate of 4.2 percent, which is derived from actual data in 1990 and 1993, using the following equation:

$$\mathrm{CO}_{2(\mathrm{IND})\mathrm{CO2}(y)} = \mathrm{CO}_{2(\mathrm{IND})\mathrm{CO2}(93)} \times \mathrm{Frac}_{\mathrm{CO2}}$$

where,

$\mathrm{CO}_{2(\mathrm{IND})\mathrm{CO2}(y)}$ = carbon dioxide emissions from carbon dioxide manufacture in year (current or 1993 in million metric tons)

$\mathrm{Frac}_{\mathrm{CO2}}$ = Annual rate of growth (assumed constant at 4.2 percent)

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[22] The Freedonia Group, Inc., *Carbon Dioxide, Business Research Report* B286 (Cleveland, OH, November 1991), p. 46.

[23] The Freedonia Group, Inc., *Carbon Dioxide, Industry Study* 564 (Cleveland, OH, February 1994), p. 37.

Data Sources

Table 1-23. Activity Data Sources for CO_2 Emissions from Carbon Dioxide Manufacture

Data Utilized	Citation
U.S. CO_2 production and growth rates	Freedonia Group, Inc., *Carbon Dioxide, Business Research Report* B286 (Cleveland, OH, November 1991), and *Carbon Dioxide, Industry Study* 564 (Cleveland, OH, February 1994).

1.3.5 Carbon Dioxide Emissions from Aluminum Manufacture

Carbon dioxide from aluminum manufacture is the most significant source of miscellaneous industrial process emissions. Aluminum is an element used in alloys. Because it is light in weight, malleable, and not readily corroded or tarnished, it is used as a principal material for kitchen utensils, aircraft, some automobiles, bicycles, and other manufactured products. The United States is a major producer of aluminum and also an importer, depending on market conditions.

Emissions Sources

As part of the primary aluminum smelting process, alumina (aluminum oxide, Al_2O_3) is vaporized by a powerful electric current. Emissions from generation of the electrical current are included with emissions from industrial electricity consumption and are not counted separately. The current also vaporizes a carbon “sacrificial anode,” typically manufactured from petroleum coke. This is a non-sequestering non-fuel use of a fossil fuel. To avoid double counting, 50 percent of non-fuel use of petroleum coke is carried as “sequestering.” Thus, process emissions from aluminum smelting can be treated as a deduction from the sequestering portion of non-fuel use of petroleum coke.

Estimation Methodology

The MECS indicated that non-fuel use of fuels by aluminum smelters totaled 40 trillion Btu in 1994.[24] The composition of these fuels by fuel type has been withheld for confidentiality purposes, but it is probable that most of the 40 trillion Btu consists of petroleum coke, which would imply an emission factor of about 0.338 metric tons of carbon per metric ton of aluminum smelted (0.04 quadrillion Btu of coke multiplied by 27.85 million metric tons of carbon per quadrillion Btu, divided by 3.295 million metric tons of aluminum smelted in 1994). EIA now uses an emission factor of 0.4 metric tons carbon per metric ton of aluminum smelted, which equals the mass balance for a “typical” aluminum smelter from another supporting source.[25] Pending further research, EIA has continued to use this factor based on the earlier MECS data.

Step 1: Determine Aluminum Production Volumes

USGS publishes an annual *Mineral Commodity Summary*, entitled “Aluminum,” that provides recent history and current estimate of U.S. production of aluminum (in thousand metric tons).

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[24] Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, D.C., December 1997), Table A3, p. 49.

[25] Drexel University Project Team, *Energy Analysis of 108 Industrial Processes* (Lilburn, GA: The Fairmont Press, 1996), p. 282.

Step 2: Calculate the Emissions from Carbon in Aluminum Manufacture

Calculation of the CO_2 emissions from aluminum manufacture employs an equation that multiplies production data by a carbon conversion factor, which is assumed constant. The equation follows:

$$CO_{2(IND)Al} = M_{Al} \times CF_{C/Al} \times 10^{-3} \times 44/12$$

where,

$CO_{2(IND)Al}$ = carbon dioxide emissions from aluminum production (million metric tons)

M_{Al} = mass of aluminum production (thousand metric tons)

$CF_{C/Al}$ = Conversion factor

44/12 = Molecular weight of carbon dioxide to carbon

Data Sources

Table 1-24. Data Sources for CO_2 Emissions from Aluminum Manufacture

Data Utilized	Citation
U.S. aluminum production	U.S. Geological Survey, "Aluminum," *Mineral Commodity Summary,* (Washington, D.C., various years), http://minerals.usgs.gov/minerals/pubs/mcs.
Carbon emission coefficient for aluminum	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: (Washington, D.C., various years) http://epa.gov/climatechange/emissions/usinventoryreport.html

1.3.6 Carbon Dioxide "Scrubbed" from Natural Gas

Pipeline quality natural gas is limited in the amount of carbon dioxide it can contain to 1 percent. When natural gas is processed, the excess carbon dioxide between the pipeline quality gas and the produced natural gas is vented into the atmosphere. By estimating the average percentage amount of carbon dioxide in produced natural gas and subtracting 1 percent from that amount one can estimate the amount of carbon dioxide vented to the atmosphere. Detailed estimates on carbon dioxide from various basins in the United States were produced from 1990 to 1998. Since 1998 the amount of emissions from scrubbed natural gas has been moved by the value of dry natural gas produced.

Data Sources

Table 1-25. Data Sources for CO_2 Emissions from "Scrubbed" Natural Gas

Data Utilized	Citation
Dry Natural Gas Production	Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131, (Washington, D.C., various years), Natural Gas Navigator, Table 1 Summary Statistics, http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/natural_gas_annual/nga.html.

1.4 Carbon Dioxide Emissions from "Renewables"

Most renewable energy forms produce no direct emissions of carbon dioxide. Exceptions include municipal solid waste and geothermal energy. These emissions are estimated and added to emissions from fossil fuel combustion where appropriate.

The combustion of municipal solid waste (MSW) generates carbon dioxide from the combustion of plastics, synthetic rubber, and synthetic fibers, as well as from synthetic rubber and carbon black in tires. Almost all combustion of MSW in the United States occurs at waste-to-energy facilities where energy is recovered. Combustion is used to manage about 7 to17 percent of the MSW generated in the United States.[26] Combustion of MSW also results in emissions of methane and nitrous oxide, which are addressed elsewhere in this report. It should be noted that EIA has recently re-classified nonbiogenic MSW as non-renewable.

Emissions Sources

While most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), some components—plastics, synthetic rubber, and synthetic fibers—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as 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 MSW combustion estimate, though waste disposal practices for tires differ from the rest of MSW.[27]

Estimation Methodology

Combustion of MSW results in conversion of the organic inputs to carbon dioxide. According to the *Revised 1996 IPCC Guidelines*,[28] when the carbon dioxide emitted is of fossil origin it is counted as a net anthropogenic emission of carbon dioxide to the atmosphere. Thus, the emissions from waste combustion are calculated by estimating the quantity of waste combusted and the fraction of the waste that is carbon derived from fossil sources. EIA uses the methodologies employed by U.S. EPA to estimate the carbon dioxide emissions from the four main MSW stream: plastics, rubber tires, synthetic rubber and leather, and synthetic fibers in textiles.

The composition of the waste stream is estimated annually by U.S. EPA using multiple sources but primarily U.S. EPA's Office of Solid Waste publication *Characterization of Municipal Solid Waste in the United States* and trade association data. None of these sources provides data on the portion of discards going to landfills versus the portion combusted so the U.S. EPA apportions the discards of specific MSW streams to landfilling and combustion based on a gross U.S. estimate. Further, waste composition data are only available periodically so U.S. EPA interpolates data for missing years. Because EIA publishes the report documented here prior to obtaining the latest U.S. EPA data, last year's published data values are carried over for the data year

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[26] U.S. Environmental Protection Agency, Office of Solid Waste, *Characterization of Municipal Solid Waste in the United States: 2001 Update*. Report No. EPA530-R-03-011 (Washington, D.C., October 2003).

[27] U.S. Environmental Protection Agency, Office of Solid Waste, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, USEPA #430-R-03-004 (Washington, D.C., April 2003), p. 62, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[28] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

documented by this report. EIA adjusts the U.S. EPA MSW data in order to avoid double-counting carbon dioxide emissions already reported in its documentation on electric power sector energy consumption. Unpublished annual data from the Office of Coal, Nuclear, Electricity and Alternate Fuels (CNEAF) details waste combusted for electricity generation and/or steam production by utilities, independent power producers, and commercial and industrial facilities. The carbon dioxide emissions from this combustion are deducted from the U.S. EPA estimates each year to provide “Other Emissions from Waste Combustion.”

Carbon Dioxide in Geothermal Steam

Both the “flash” geothermal technology and dry steam from the Geysers, when used to generate electricity, result in the release of carbon dioxide. EIA estimates that an average of 56.7 pounds of carbon dioxide is released for each megawatt-hour of electricity generated from geothermal energy. About 14 to 15 billion kWh are generated each year from geothermal sources yielding about 400 thousand metric tons of carbon dioxide per year. These emissions are added to emissions from fuel combustion in the electric power sector.

Data Sources

Table 1-26. Activity Data Sources for CO_2 Emissions from Waste Combustion

Data Utilized	Citation
Calculation methodology	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: (Washington, D.C., various years) http://epa.gov/climatechange/emissions/usinventoryreport.html; and Personal communication with Leif Hockstad, U.S. Environmental Protection Agency GHG Inventory Program, April 11, 2003 and June 4, 2003.
Plastics data	U.S. Environmental Protection Agency, Office of Solid Waste, *Characterization of Municipal Solid Waste in the United States: 2001 Update*, Report No. U.S. EPA530-R-03-011, (Washington, D.C., October 2003).
Synthetic rubber and carbon black in tires data	Rubber Manufacturers Association, *Scrap Tire Use/Disposal Study 1998/1999 Update*, Executive Summary, September 15, 1999, downloaded from web site [www.rma.org/excsumn.html] on July 26, 2000, but not currently available online.
Synthetic fiber data	Personal communication between Joe Casola of ICF Consulting and Diane DeZan of Fiber Economics Bureau, August 4, 2000.
Waste-to-energy data	Unpublished annual data from Energy Information Administration, Office of Coal, Nuclear, Electricity, and Alternative Fuel on MSW combustion for electricity, cogeneration, and steam production by utilities, independent power producers, commercial, and industrial plants larger than 1 MW.

2. Methane Emissions

This chapter describes methods for estimating emissions of methane from **sources of energy**, such as coal mining and petroleum and natural gas systems; **mobile and stationary combustion** sources; **agricultural emissions** including the cultivation of rice, crop residue burning, and enteric fermentation in domesticated animals; and **emissions from waste**, including methane produced in landfills and domestic and commercial wastewater treatment. The primary sources of methane from **industrial processes**—chemicals and iron and steel—are also addressed.

2.1 Energy Sources

2.1.1 Methane Emissions from Coal Mining

Emissions Sources

As coal is formed from organic material by natural chemical and physical processes, methane is also produced. The methane is stored in the pores (open spaces) of the coal itself and in cracks and fractures within the coalbed. As coal is mined, the pressure surrounding the stored methane decreases, allowing much of it to be released into the operating coal mine (in the case of an underground mine) or into the atmosphere (in the case of a surface mine). The methane remaining in the coal pores is emitted when the coal is transported and pulverized for combustion. There are five avenues for methane emissions from coal mines: (1) ventilation systems in underground mines; (2) degasification systems in underground mines; (3) surface mines; (4) post-mining emissions; and (5) methane recovery for energy. Each is described in the sections that follow.

Methane emissions from abandoned coal mines are not included in the estimates presented in this report. Please refer to Chapter 8, *Emissions Excluded*, below.

Methodology for Total Methane Emissions from Coal Mining

EIA calculates the total amount of methane released as a result of coal mining activities by aggregating emissions from underground mining (ventilation and degasification systems), surface mining, and post-mining activities. In addition, the quantity of methane that is recovered and used as fuel (that would have otherwise been released to the atmosphere) is subtracted from the total amount of methane emitted.

$$CH_{4(CM)} = \left(CH_{4(V)} + CH_{4(D)} + CH_{4(S)} + CH_{4(P)}\right) - CH_{4(R)}$$

where,

$CH_{4(CM)}$ = Total methane emissions from coal mining (million metric tons)

$CH_{4(V)}$ = Total methane from ventilation systems in underground mines (million metric tons)

$CH_{4(D)}$ = Total methane from degasification systems in underground mines (million metric tons)

$CH_{4(S)}$ = Total methane from surface mining (million metric tons)

$CH_{4(P)}$ = Total methane from post-mining activities (million metric tons)

$CH_{4(R)}$ = Total methane recovered for energy (million metric tons)

Estimation Methodology for Methane Emissions from Ventilation Systems in Underground Mines

Methane in concentrations over 5 percent is explosive and presents a mortal danger to coal miners. To meet safety standards set by the Mine Safety and Health Administration (MSHA) requiring levels of methane concentration to be maintained well below the 5 percent threshold, mine operators use large fans to provide a steady airflow across the mine face and ventilate the mine shaft. Typically, these ventilation systems release substantial quantities of methane in the fan exhaust.

Emissions from ventilation systems in underground mines are segregated into two classes: emissions from “gassy” mines and emissions from “nongassy” mines.[29] Because methane concentrations and airflows in gassy mines are carefully monitored by MSHA, a fairly reliable set of data can be derived for emissions from ventilation systems in gassy mines. Prior to 1993, however, MSHA data are available for only a sub-sample of years (1980, 1985, 1988, and 1990). Thus, EIA developed a methodology that uses available MSHA data in conjunction with coal production data to develop emission factors per ton of coal mined on a basin-by-basin level for those years.[30] Emission factors for non-sample years are interpolated. MSHA data are available for all years from 1993 and estimates of emissions from ventilation systems are based on a compilation of MSHA data by the U.S. EPA Office of Air and Radiation.

Emissions from nongassy mines make up less than 2 percent of all emissions from underground mines.[31] Basin-level emission factors for nongassy mines were established by dividing 2 percent of each basin’s estimated emissions from nongassy mines for 1988 by that year’s production levels. The resulting emission factors are applied to annual production data for the period through 1992. For 1993 onward, emissions from nongassy mines are based on calculations from the U.S. EPA.

The following steps are utilized in estimating methane emissions from underground mine ventilation systems:

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[29] Gassy mines are defined as those underground coal mines with measured emissions from ventilation exhaust in excess of 100,000 cubic feet of methane per day.

[30] For purposes of this report, the U.S. has five distinct coal basins: Northern Appalachia includes Pennsylvania, Northern West Virginia, Maryland, and Ohio; Central Appalachia includes Eastern Kentucky, Virginia, Southern West Virginia, and Tennessee; the Warrior basin includes Alabama; the Illinois basin includes Illinois, Indiana, Western Kentucky, Iowa, and Oklahoma; and the Western basin includes Colorado, New Mexico, Utah, and Wyoming.

[31] M.A. Trevits, G.L. Finfinger, and J.C. LaScola, “Evaluation of U.S. Coal Mine Emissions,” in Society for Mining, Metallurgy and Exploration, *Proceedings of the Fifth U.S. Mine Ventilation Symposium* (Littlejohn Co., 1991), p. 2.

Step 1: Estimate Daily CH_4 Emissions from Ventilation Systems

EIA's estimates of emissions from ventilation systems are based on a compilation of MSHA data by the U.S. EPA Office of Air and Radiation. MSHA estimates average daily methane emissions at all underground mines with detectable emissions based on four quarterly measurements.

For the period 1990-1999, average daily methane emissions were multiplied by 365 to determine the annual emissions for each individual mine, as in the following formula:

$$CH_{4(V)} = \frac{\mathrm{CH}_{4(\mathrm{V})(\mathrm{D})} \times 365}{\mathrm{CF}_{\mathrm{SCF/MT}}}$$

where,

$CH_{4(V)}$ = Total annual methane emissions from ventilation systems in underground mines (million metric tons)

$CH_{4(V)(D)}$ = Daily production of CH_4 from ventilation systems in underground mines (million cubic feet)

$CF_{SCF/MT}$ = Conversion factor (52,145.2 scf CH_4 per metric ton CH_4)

From 2000 onward, MSHA provided emissions estimates on a quarterly basis. In this instance, average daily methane emissions were multiplied by the number of days corresponding to the number of quarters the mine vent was operating. For example, if the mine vent was operational in one out of the four quarters, the average daily methane emissions were multiplied by 92 days.

$$CH_{4(V)} = \frac{\mathrm{CH}_{4(\mathrm{V})(\mathrm{D})} \times D}{\mathrm{CF}_{\mathrm{SCF/MT}}}$$

where,

$CH_{4(V)}$ = Total annual methane emissions from ventilation systems in underground mines (million metric tons)

$CH_{4(V)(D)}$ = Daily production of CH_4 from ventilation systems in underground mines (million cubic feet)

D = Number of days in operation (92 days)

$CF_{SCF/MT}$ = Conversion factor (52,145.2 scf CH_4 per metric ton CH_4)

Step 2: Calculate Annual CH_4 Emissions from Ventilation Systems

Total ventilation emissions for each year are estimated by summing emissions from individual mines.[32]

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[32] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001)*, Annex F (Washington, D.C., April 2003), page F-1, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Data Sources

Activity data for methane emissions from ventilation systems in underground mines include an emissions figure received from the U.S. EPA Office of Air and Radiation (Table 2-1). Coal mine ventilation data for the gassiest U.S. mines were drawn from a database prepared by the Department of the Interior's Bureau of Mines for the years 1980, 1985, 1988, 1990, and 1993. Ventilation data for 1994 and later were obtained from the U.S. U.S. EPA, Climate Protection Partnerships Division, Coalbed Methane Outreach Program. Coal production data for years prior to 1998 are reported to EIA on Form EIA-7A, "Coal Production Report." Coal production data for 1998 are based on Form 7000-2, "Quarterly Mine Employment and Coal Report," collected by the Mine Safety and Health Administration. Basin-level emissions for non-gassy mines in 1988 were calculated by the U.S. EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, D.C., April 1993), pp. 3-19–3-24.

Table 2-1. Data Sources for CH_4 Emissions from Ventilation Systems in Underground Mines

Data Utilized	Citation
Emission factors, methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001,* Annex F, (Washington, D.C., April 2003), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Ventilation data for the years 1980, 1985, 1988, 1990, and 1993	Department of the Interior's Bureau of Mines, (Washington, D.C.).
Ventilation data for 1994- present	U.S. Environmental Protection Agency, Climate Protection Partnerships Division, Coalbed Methane Outreach Program (Washington, D.C.), http://www.epa.gov/coalbed/.
Coal production data for years prior to 1998	Energy Information Administration, Form EIA-7A, "Coal Production Report," (Washington, D.C., various years).
Coal production data for 1998 and onward	Mine Safety and Health Administration, Form 7000-2, "Quarterly Mine Employment and Coal Report," (Washington, D.C., various years).
Basin-level emissions for non-gassy mines in 1988	U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, (Washington, D.C., April 1993), pp. 3-19-3-24.

Estimation Methodology for Degasification Systems in Underground Mines

When the volume of gas in underground mines is too high to be practically reduced to safe levels by standard ventilation techniques, degasification systems are employed. Degasification may take place before mining or may take the form of gob-wells or in-mine horizontal boreholes. Methane captured by degasification systems may be vented, flared, or recovered for energy.

Degasification emissions are not monitored by any regulatory agency. Where degasification does occur, the method of disposition may not be tabulated. Estimated emissions from degasification systems during the period 1993 onward are based on data collected by the U.S. EPA's Office of Air and Radiation, Coalbed Methane Outreach Program. For years prior to 1993, emissions from degasification systems are estimated by multiplying annual production in mines known to have degasification systems in place by a per-ton emission factor.

Many coalmines that utilize degasification systems provide U.S. EPA with information regarding methane liberated from their degasification systems. For these mines, this reported information was used as the estimate. In other cases in which mines sell methane recovered from degasification systems to a pipeline, gas sales were used to estimate methane liberated from degasification systems. Finally, for those mines that do not sell methane to a pipeline and have not provided information to U.S. EPA, methane liberated from degasification systems was estimated based on the type of system employed. For example, for coalmines employing gob wells and horizontal boreholes, the methodology assumes that degasification emissions account for 40 percent of total methane liberated from the mine.[33]

Data Sources

Emission factors data for methane emissions from degasification systems in underground mines include an emissions figure received from the U.S. EPA Office of Air and Radiation (Table 2-2). Data on drainage from degasification systems from 1993 onward are from the U.S. EPA's Office of Air and Radiation, Climate Protection Partnerships Division, Coalbed Methane Outreach Program. Emission factors for this source are derived from estimates of 1988 emissions from degasification systems prepared by the U.S. EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, D.C., April 1993), pp. 3-19B–3-24. Annual production figures for years prior to 1998 are reported to EIA on Form EIA-7A, "Coal Production Report." Coal production data for 1998 are based on Form 7000-2, "Quarterly Mine Employment and Coal Report," collected by the Mine Safety and Health Administration.

Table 2-2. Data Sources for CH_4 Emissions from Degasification Systems in Underground Mines

Data Utilized	Citation
Emission Factors, methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: (various years)*, Annex F, (Washington, D.C.), page F-2, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Data on drainage from 1993 - present	U.S. Environmental Protection Agency, Office of Air and Radiation, Climate Protection Partnerships Division, Coalbed Methane Outreach Program, (Washington, D.C.), http://www.epa.gov/coalbed/.
Emission factors	U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, (Washington, D.C., April 1993), pp. 3-19B to 3-24.
Coal production data - for years prior to 1998	Energy Information Administration, Form EIA-7A, "Coal Production Report," (Washington, D.C., various years).
Coal production data - for years 1998 and onward	Mine Safety and Health Administration, Form 7000-2, "Quarterly Mine Employment and Coal Report," (Washington, D.C., various years).

Estimation Methodology for Surface Mines

Because coal mined from the surface has formed at lower temperatures and pressures than coal from underground mines, its methane content is lower. Further, because the coal is located near the surface, methane has had ample opportunity to migrate to the atmosphere before mining.

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[33] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, Annex F, (Washington, D.C., April 2003), page F-2, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Thus, while methane emissions from surface mines are heterogeneous in nature, they are systematically less than emissions from underground mines.

Emissions from U.S. surface mines have not been systematically measured. However, Intergovernmental Panel on Climate Change studies on surface coal mines in the United States, England, France, and Canada suggest a range of 0.3 to 2.0 cubic meters per metric ton of coal mined.[34] This report uses that range and adopts the "Global Average Method" -- a Tier 1 approach in accordance with IPCC *Good Practice Guidance*.

Step 1: Determine High and Low Yield Emissions Estimates

As previously mentioned, EIA has adopted the Intergovernmental Panel on Climate Change's range of 0.3 to 2.0 cubic meters of CH_4 per metric ton of coal mined to estimate total U.S. methane emissions from surface mining. For example, to estimate low-yield emissions from surface mining the low CH_4 emission factor (0.3 m^3/ton) is multiplied by EIA's figure for surface coal production.

$$CH_{4(S,LY)} = \mathrm{CP}_{(\mathrm{S})} \times EF_{(LY)}$$

where,

$CH_{4(S, LY)}$ = Total annual low-yield methane emissions from surface mining (million metric tons)

$CP_{(S)}$ = Surface coal production figure (metric tons)

$EF_{(LY)}$ = Intergovernmental Panel on Climate Change's emission factor for low-yield emissions from surface mining (m^3 of CH_4/metric ton)

Step 2: Calculate an Average Emissions Estimate

Total annual CH_4 emissions from surface mines are calculated by summing the low- and high-yield emissions estimates, then dividing by 2 to find an average emissions estimate.

$$CH_4 = \frac{\mathrm{CH}_{4(\mathrm{S,LY})} + \mathrm{CH}_{4(\mathrm{S,\,HY})}}{2}$$

where,

CH_4 = Total methane emissions for surface mining (million metric tons)

$CH_{4(S,LY)}$ = Low-yield methane emissions estimate from surface mining (million metric tons)

$CH_{4(S,HY)}$ = High-yield methane emissions estimate from surface mining (million metric tons)

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[34] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), pp. 1.98-1.112, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Data Sources

Emission factors for methane emissions from surface mining are found in IPCC, *Revised 1996 IPCC Guidelines*, Vol. 3 (Paris, France, 1997). Coal production data for years prior to 1998 are reported to EIA on Form EIA-7A, "Coal Production Report." Coal production data for 1998 and onward are based on Form 7000-2, "Quarterly Mine Employment and Coal Report," collected by the Mine Safety and Health Administration (Table 2-3).

Table 2-3. Data Sources for CH_4 Emissions from Surface Mines

Data Utilized	Citation
Emission factors, methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Coal production data - For years prior to 1998	Energy Information Administration, Form EIA-7A, "Coal Production Report," (Washington, D.C., various years).
Coal production data - For years 1998 and onward	Mine Safety and Health Administration, Form 7000-2, "Quarterly Mine Employment and Coal Report," (Washington, D.C., various years).

Estimation Methodology for Post-Mining Emissions

Methane that remains in coal pores after either underground or surface mining will desorb slowly as the coal is transported (typically by train) to the end user. Because coal that is consumed in large industrial or utility boilers is pulverized before combustion, any methane remaining in the coal pores after transport will be released prior to combustion.

Like emissions from surface mines, post-mining emissions are not measured systematically. Thus, global average emission factors must be applied. Post-mining emissions for coal mined from the surface are estimated to be very low, between 0.0 and 0.2 cubic meters per metric ton of coal mined. In contrast, post-mining emissions from underground coal are estimated to be more significant, between 0.9 and 4.0 cubic meters of methane per metric ton of coal mined.[35]

Step 1: Determine High- and Low-Yield Emissions Estimates for both Underground and Surface Mining Activities

To estimate methane emissions from post-mining activities, EIA utilizes the Intergovernmental Panel on Climate Change's "Global Average Method." Resembling the methodology for finding high- and low-yield emissions estimates for surface mining, the Intergovernmental Panel on Climate Change recommends a range of high- and low-yield emission factors to estimate total U.S. methane emissions from post-mining activities. For example, to estimate high-yield emissions from post-mining activities, the Intergovernmental Panel on Climate Change's high methane emission factors for both underground and surface-mined coals (4.0 m^3 of CH_4/metric ton and 0.2 m^3 of CH_4/metric ton, respectively) are multiplied by EIA figures for underground and surface coal production.

$$CH_{4(P,HY)} = \sum\left[\left(CP_{(PS)} \times EF_{(PS,HY)}\right) + \left(CP_{(PU)} \times EF_{(PU,HY)}\right)\right]$$

where,

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[35] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), pp. 1.98-1.112, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

$CH_{4(P,\,HY)}$ = Total annual high-yield methane emissions from post-mining activities (million metric tons)

$CP_{(PS)}$ = Surface coal production figures (million metric tons)

$CP_{(PU)}$ = Underground coal production figures (million metric tons)

$EF_{(PS)}$ = Intergovernmental Panel on Climate Change emission factors for high-yield post-mining emissions from surface-mined coal (m^3 of CH_4/metric ton)

$EF_{(PU,\,HY)}$ = Intergovernmental Panel on Climate Change emission factors for high-yield post-mining emissions from underground mined coal (m^3 of CH_4/metric ton)

Step 2: Calculate an Average Emissions Estimate

Total annual CH_4 emissions from post-mining activities are calculated by summing the low- and high-yield emissions estimates for both underground and surface-mined coal and dividing by 2 to find an average emissions estimate for each. These two average emissions estimates are then summed together to produce a total methane emissions figure, as shown in the following equation:

$$CH_{4(PMA)} = \left(\frac{\mathrm{CH}_{4(\mathrm{PS,LY})} + \mathrm{CH}_{4(\mathrm{PS,\,HY})}}{2}\right) + \left(\frac{\mathrm{CH}_{4(\mathrm{PU,LY})} + \mathrm{CH}_{4(\mathrm{PU,\,HY})}}{2}\right)$$

where,

$CH_{4(PMA)}$ = Total methane emissions for post-mining activities (million metric tons)

$CH_{4(PS,LY)}$ = Low-yield post-mining methane emissions estimate from surface mining (million metric tons)

$CH_{4(PS,HY)}$ = High-yield post-mining methane emissions estimate from surface mining (million metric tons)

$CH_{4(PU,LY)}$ = Low-yield post-mining methane emissions estimate from underground mining (million metric tons)

$CH_{4(PU,HY)}$ = High-yield post-mining methane emissions estimate from underground mining (million metric tons)

Data Sources

Emission factors for methane emissions from surface mining are found in the IPCC *Revised 1996 IPCC Guidelines*, Vol. 3 (Paris, France, 1997). Coal production data for years prior to 1998 are reported to EIA on Form EIA-7A, “Coal Production Report.” Coal production data for 1998 and onward are based on Form 7000-2, “Quarterly Mine Employment and Coal Report,” collected by the Mine Safety and Health Administration (Table 2-4.)

Table 2-4. Data Sources for Post-Mining CH_4 Emissions	
Data Utilized	**Citation**
Emission factors, methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Coal production data – For years prior to 1998	Energy Information Administration, Form EIA-7A, "Coal Production Report," (Washington, D.C., various years).
Coal production data – For years 1998 and onward	Mine Safety and Health Administration, Form 7000-2, "Quarterly Mine Employment and Coal Report," (Washington, D.C., various years).

Estimation Methodology for Mine Methane Recovery for Energy

In some cases (for example, in some mining degasification systems), methane is emitted from coal mines in sufficiently high volumes and concentrations to justify commercial recovery of the gas as either pipeline gas, power generation fuel, or for mine site uses. Because coal mine methane recovered commercially is combusted (destroyed), the quantities recovered are subtracted from estimates of total coal mine methane emissions. EIA adopts a time series of methane recovery prepared by the U.S. EPA Coalbed Methane Outreach Program for all years.

According to U.S. EPA, methane recovery for energy is restricted to a small sample of mines that typically meter their gas sales. Thus, total methane recovery can be estimated from the volume and heat content of sales. The estimation methodology for recovered methane from pipeline sales, for example, requires information regarding the amount of gas recovered and the number of years in advance of mining that a well is drilled. Several state agencies, as well as coal mine operators, provide gas sales data and/or the number of years in advance of mining which were then used to estimate emissions avoided for these mines. For instance, if a coal mine recovers and sells methane using a vertical well drilled five years in advance of mining, the emissions avoided associated with those gas sales (cumulative production) are attributed to the well up to the time it was mined through (e.g., five years of gas production).

According to U.S. EPA, when individual well data are not available, approximate percentages of the operator's annual gas sales within the field around the coal mine are attributed to emissions avoidance. In some instances, various individual well data points from coal mine operators and state agencies are used to allocate gas sales in order to calculate the appropriate amount of emissions avoided for that year.[36]

Data Sources

Methane recovery estimates are obtained from the U.S. EPA's Office of Air and Radiation, Climate Protection Division, Coalbed Methane Outreach Program (Table 2-5).

Table 2-5. Data Sources for CH_4 Emissions from Mine Methane Recovery for Energy	
Data Utilized	**Citation**
Methane recovery estimates	U.S. Environmental Protection Agency, Office of Air and Radiation, Climate Protection Division, Coalbed Methane Outreach Program, (Washington, D.C.), http://www.epa.gov/coalbed/.

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[36] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, Annex F (Washington, D.C., April 2003), page F-2, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

2.1.2 Methane Emissions from Natural Gas Production, Processing, and Distribution

Emissions Sources

Because methane is the principal constituent of natural gas (representing about 95 percent of the mixture), releases of natural gas result in methane emissions. Methane emissions can be grouped into three categories: (1) fugitive or unintentional leaks emitted from sealed surfaces such as pipelines, gaskets, and flanges; (2) vented or intentional releases from process vents, maintenance blowdowns, and pneumatic devices; and (3) releases from incomplete combustion in compressor engines, burners, and flares.[37]

The natural gas industry can be divided into four source segments:

Gas Production. This segment consists of gas and oil wells, surface equipment to produce gas, and gathering pipeline. Leakage occurs from valves, meters, and flanges. Pneumatic valves release gas when they are reset. Gathering pipeline may be emptied for maintenance or may have fugitive emissions.

Gas Processing. When gas is processed, liquefied petroleum gases and natural gasoline are removed for sale or further refining. Water is also removed, and gas is conformed to commercial pipeline quality and heat content. Methane is released during maintenance, via leaks, and during system upsets when sudden increases in pressure require a gas release or result in a system rupture.

Transmission and Storage. High-pressure transmission pipelines transport natural gas from production fields and gas processing facilities to distribution pipelines. Natural gas may escape through leaky pipes and valves. Methane may be emitted as part of compressor exhaust. Gas is often stored near consumption centers to meet peak demand during periods of high consumption. These storage facilities emit methane in compressor exhaust and from dehydrators.

Distribution. The pressure of natural gas received from the transmission system is lowered at the gate station before the natural gas is forwarded to distribution pipeline for delivery to residential, commercial, and industrial consumers. Leaks may occur at gate stations, through leaky pipes, and at customer meters.

Estimation Methodology

Step 1: Calculate Base-year Emissions Estimates and Emission Factors

EIA utilizes 1992 base-year emissions estimates that were developed in a study sponsored jointly by the U.S. EPA and the Gas Technology Institute (GTI), formerly known as the Gas Research Institute.[38] The U.S. EPA/GTI study provides activity data and disaggregated emission factors for 86 separate gas industry process components. In an effort to take advantage of this level of detail,

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[37] National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996), p. 19.

[38] National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996), p. 19.

this report estimates the number of each process components for the years 1990 to present. The derived activity data are then applied to the component emission factor from the U.S. EPA/GTI report. The activity data are multiplied by emission factors, as shown in the following equation:

$$CH_{4(PC)} = AL_{(PC)} \times EF_{(PC)}$$

where,

$CH_{4(PC)}$ = Total methane emissions from each process component (1,000 scf)

$AL_{(PC)}$ = Activity level of each process component

$EF_{(PC)}$ = Emission factor for each process component

Step 2: Scale Emissions Estimates to Activity Data

Estimates of emissions from the natural gas system are scaled to commonly available activity data such as number of wells in operation, miles of gathering pipeline, gas throughput, gas volumes processed, miles of transmission pipeline, and miles of distribution pipeline that are most related to the process activity. Table 2-6 below provides an example of data used to calculate emissions from natural gas systems.

Step 3: Identify Natural Gas STAR Reductions Below-the-Line

The U.S. EPA, based on annual submissions by companies participating in the Natural Gas STAR Program, estimates reductions of more than 1.0 million metric tons methane from the natural gas system in recent years. These reductions are not included in EIA’s net estimates of emissions from this source because of difficulty in documenting the reductions and any interactions they may have with the method for otherwise estimating emissions for natural gas systems. Thus, EIA reports these reductions “below the line” and excludes them from emission totals.

Table 2-6. Natural Gas Industry Methane Emission Factors for Vented and Flared Emissions

Emissions Source	Emission Factor	Methane Emissions Units
Drilling and Well Completion		
Completion Flaring	751	Scf/comp
Normal Operations		
Pneumatic Device Vents	126,027.2	Scf/device
Chemical Inj. Pumps	90,538.25	Scf/pump
Kimray Pumps	992	Scf/MMScf
Dehydrator Vents	275.57	Scf/MMScf
Compressor Exhaust Vented		
Gas Engines	0.24	Scf/Hphr
Routine Maintenance		
Well Workovers		
Gas Wells	2,454	Scf/WO
Well Clean Ups (LPG Wells)	49,570	Scf/LPG well
Blowdowns		
Vessel BD	78	Scf/vessel
Pipeline BD	309	Scf/mile
Compressor BD	3,774	Scf/compressor
Compressor Starts	8,443	Scf/compressor
Upsets		
Pressure Relief Valves	34	Scf/PRV
ESD	256,888	Scf/platform
Mishaps (Dig-Ins)	669	Scf/mile

Sources: Emission factors from U.S. Environmental Protection Agency, Gas Technology Institute, National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GTI-94/0257.1 and U.S. EPA-600-R-96-08 (Research Triangle Park, NC, June 1996). Activity data from Energy Information Administration, *Natural Gas Annual* (Washington, D.C., various years), *Natural Gas Monthly* (Washington, D.C., various years), and *Monthly Energy Review*, (Washington, D.C., various years).

Step 3: Calculate Emissions for Each Process and Year

Emissions for all years are estimated by multiplying activity levels by emission factors for each separate gas industry process component, then summing the results of each of the four source segments.

$$CH_{4(NGPD)} = \frac{\left((CH_{4(PROD)} + CH_{4(PROC)} + CH_{4(TS)} + CH_{4(D)}\right)}{CF_{SCF/MT}} \times 10^{-3}$$

where,

$CH_{4(NGPD)}$ = Total methane emissions from natural gas production, processing, and distribution (million metric tons)

$CH_{4(PROD)}$ = Total methane emissions from natural gas production (1,000 scf)

$CH_{4(PROC)}$ = Total methane from natural gas processing (1,000 scf)

$CH_{4(TS)}$ = Total methane from natural gas transmission and storage (1,000 scf)

$CH_{4(D)}$ = Total methane from natural gas distribution (1,000 scf)

$CF_{SCF/MT}$ = Conversion factor (52,145.2 scf CH_4 per metric ton CH_4)

Data Sources

Data for methane emissions from natural gas production, processing, and distribution include emission factors and activity levels for 1992 from the joint U.S. EPA/GTI study: National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GTI-94/0257.1 and U.S. EPA-600-R-96-08 (Research Triangle Park, NC, June 1996). Activity data for all other years are scaled to data from the following sources: gas wellheads, gross gas withdrawals, gas processing and gas removed from storage can be found in EIA's *Natural Gas Annual* (Washington, D.C., various years), *Natural Gas Monthly* (Washington, D.C., various years), and *Monthly Energy Review* (Washington, D.C., various years). Transmission and distribution pipeline mileage are published annually by the American Gas Association in *Gas Facts*; numbers of gas processing plants are published in the *Oil & Gas Journal*, special issue for "Worldwide Gas Production" (various years); numbers of oil wells are published in the *World Oil Magazine* (February issue, various years); crude oil production is published in the *Petroleum Supply Annual and Petroleum Supply Monthly* (Table 2-7).

Table 2-7. Data Sources for CH_4 Emissions from Natural Gas Production, Processing, and Distribution

Data Utilized	Citation
Emission factors and activity data for 1992	U.S. Environmental Protection Agency and Gas Technology Institute, National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GTI-94/0257.1 and U.S. EPA-600-R-96-08 (Research Triangle Park, NC, June 1996).
Activity data for gas wellheads, gross gas withdrawals, gas processing and gas removed from storage	Energy Information Administration, *Natural Gas Annual* (Washington, D.C., various years), *Natural Gas Monthly* (Washington, D.C., various years), and *Monthly Energy Review*, (Washington, D.C., various years).
Activity data for transmission and distribution pipeline mileage	American Gas Association, *Gas Facts,* (various years).
Activity data for gas processing plants	*Oil & Gas Journal*, issue for "Worldwide Gas Production," (various years).
Activity data for oil wells	World Oil Magazine, (various years).
Activity data for crude oil production	Energy Information Administration, *Petroleum Supply Annual,* (Washington, D.C., various years); *Petroleum Supply Monthly* (Washington, D.C., various years).

2.1.3 Methane Emissions from Petroleum Systems

Emissions Sources

Methane emissions from petroleum systems involve technology and processes similar to those of the natural gas industry. The vast preponderance of methane emissions from petroleum systems occur during crude oil exploration and production. Much smaller emissions occur during crude transportation and crude refining. The largest single source of methane emissions from petroleum systems is venting at crude oil storage tanks. Emissions from petroleum systems can be divided into four types: (1) vented emissions; (2) fugitive emissions; (3) combustion emissions; and (4) upset emissions:

1) Vented emissions are intentional releases to the atmosphere by facility design or operational practice.

2) Fugitive emissions are accidental and often ongoing releases associated with a leak source within the system.

3) Combustion emissions are the result of fuel use to drive compressors or flares.

4) Upset emissions are typically the result of safety measures such as emergency pressure releases or oil platform shutdowns.[39]

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[39] U.S. Environmental Protection Agency, Office of Air and Radiation, *Estimates of Methane Emissions from the U.S. Oil Industry*, Draft Report, (Washington, D.C., 1999).

Estimation Methodology

Step 1: Determine Emission Factors for all Activities

Estimates of emissions from petroleum systems are derived by multiplying emission factors for approximately 90 separate components of the petroleum system by an estimate of the total number of components on the national system. Emission factors are taken from U.S. EPA's *Estimates of Methane Emissions from the U. S. Oil Industry*.

Step 2: Determine Activity Levels for Each Year

To produce a time-series of estimates, the number of components for 1990 onward is scaled to readily available industry activity data such as number of oil wells, refinery input, and crude transported by pipeline, marine vessel or truck. Because activity levels change from year to year, a decision is made on a case-by-case basis as to which measure of petroleum industry data best reflects the change in annual activity levels. Table 2-8 provides further examples of activity level units.

Step 3: Estimate Total Emissions from Each Petroleum System Process

Total methane emissions from each process component are estimated using the following formula.

$$CH_{4(PC)} = AL_{(PC)} \times EF_{(PC)}$$

where,

$CH_{4(PC)}$ = Total methane emissions from each process component (1,000 scf)

$AL_{(PC)}$ = Activity level of each process component

$EF_{(PC)}$ = Emission factor for each process component

Table 2-8. Oil Exploration & Production Methane Emission Factors for Vented Emissions

Emissions Source	Emission Factor	Methane Emissions Units
Vented Emissions		
Oil Tanks	18	scf of CH_4/bbl crude
Pneumatic Devices, High Bleed	345	scfd CH_4/device
Pneumatic Devices, Low Bleed	35	scfd CH_4/device
Chemical Injection Pumps	248	scfd CH_4/pump
Vessel Blowdowns	78	scfy CH_4/vessel
Compressor Blowdowns	3,775	scf/yr CH_4/compressor
Compressor Starts	8,443	scf/yr. CH_4/compressor
Stripper wells	2,345	scf/yr CH_4/stripper well
Well Completion Venting	733	scf CH_4/completion
Well Workovers	96	scf CH_4/workover
Pipeline Pigging	2. 40	scfd of CH_4/pig station
Offshore Platforms, Gulf of Mex.	1,283	scfd CH_4/platform
Offshore Platforms, Other U.S.	1,283	scfd CH_4/platform

Sources: Emission factors from U.S. Environmental Protection Agency, Office of Air and Radiation, *Estimates of Methane Emissions from the U. S. Oil Industry* (Final Draft Report), (Washington, D.C., 1999). Activity data from Energy Information Administration, *Monthly Energy Review* (Washington, D.C., various years), *Petroleum Supply Annual* (Washington, D.C., various years); Oil and Gas Journal, *Worldwide Refining Issue*, (December 2004) and *Pipeline Economics Issue*, (August 2004).

Step 4: Calculate Methane Emissions for Each Source for Each Year

Annual methane emissions for a particular source are calculated by multiplying the appropriate emission factor by the corresponding activity level. Emissions for each individual source are then summed to estimate the total amount of methane emissions for that year.

$$CH_{4(NGPD)} = CH_{4(CR)} + CH_{4(CT)} + CH_{4(CEP)}$$

where,

$CH_{4(CR)}$ = Total methane emissions from crude refining (million metric tons)

$CH_{4(CT)}$ = Total methane from crude transportation

$CH_{4(CEP)}$ = Total methane from crude oil exploration and production

Step 5: Identify Natural Gas STAR Reductions Below-the-Line

The U.S. EPA, based on annual submissions by companies participating in the Natural Gas STAR Program, estimates methane emissions from petroleum systems annually. These reductions are not subtracted from EIA's net estimates of emissions from this source because of difficulty in documenting the reductions and any interactions they may have with the method for otherwise estimating emissions for natural gas systems. Thus, EIA reports these reductions "below the line."

Data Sources

Emission factors are taken from the U.S. EPA, Office of Air and Radiation, *Estimates of Methane Emissions from the U. S. Oil Industry* (Final Draft Report). Activity data are from EIA's *Monthly Energy Review*, EIA's *Petroleum Supply Annual*, and Oil and Gas Journal's *Worldwide Refining Issue and Pipeline Economics Issue* (Table 2-9).

Table 2-9. Data Sources for CH_4 Emissions from Petroleum Systems

Data Utilized	Citation
Emission factors	U.S. Environmental Protection Agency, Office of Air and Radiation, *Estimates of Methane Emissions from the U. S. Oil Industry* (Final Draft Report), (Washington, D.C., 1999).
Activity data for crude oil supply and disposition; petroleum imports and exports	Energy Information Administration, *Monthly Energy Review,* (Washington, D.C., various years).
Activity data for crude oil production	Energy Information Administration, *Petroleum Supply Annual,* (Washington, D.C., various years).
Activity data for crude refining, transportation, exploration and production.	*Worldwide Refining Issue,* Oil and Gas Journal (December 20, 2004) and *Pipeline Economics Issue,* Oil and Gas Journal (August, 23, 2004).

2.1.4 Methane Emissions from Stationary Combustion

Emissions Sources

The principal products of fuel combustion are carbon dioxide and water vapor. When fuel combustion is incomplete, methane may also be released. The volume of methane released varies according to the efficiency and temperature of the combustion process. Most stationary sources are large, comparatively efficient boilers, such as those found in the industrial and utility sectors, and thus have low levels of methane emissions. However, a significant amount of wood is consumed in residential woodstoves and fireplaces, which are typically inefficient combustion chambers. Wood combustion in these devices produces most of the U.S. methane emissions from stationary sources.

Estimation Methodology

Step 1: Determine Emission factors Based on Each Fuel and Sector Type

Emission factors for fossil fuels are from the IPCC *Revised 1996 Guidelines*. Table 2-10 below provides a list of the emission factors for fossil fuels used. The emission factor used for wood combustion is 30.0 pounds per ton combusted in the residential sector and 0.1 pounds per ton wood combusted in all other sectors.

Table 2-10. CH_4 Emission factors by Fuel and Sector Type (G/GJ)

Sector and Fuel Type	Emission Factor
Residential	
Distillate	1.780
Natural Gas	2.700
LPG	0.245
Commercial	
Coal	0.030
Residual	0.475
Distillate	0.216
Natural Gas	2.700
LPG	0.245
Industrial	
Coal	0.030
Residual	1.000
Distillate	0.052
Natural Gas (lb/10^6 scf)	3.000
LPG (lb/10^3 gal)	0.275
Electric Utilities	
Coal	0.030
Residual	0.280
Natural Gas	0.300

Source: Intergovernmental Panel on Climate Change, *Revised 1996 Guidelines*, (Paris, France, 1997), Tables 1-7, 1-8, 1-10, and 1-11, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 2: Determine Energy Consumption by Fuel and Sector Type

Consumption data for each fuel and sector type are obtained from numerous EIA publications that are listed in the table below.

Step 3: Calculate Total Methane Emitted for each Fuel and Sector Type

Annual methane emissions from stationary combustion are calculated by multiplying consumption data for each fuel and sector type by the corresponding emission factor. Emissions for each individual source are then summed to estimate the total amount of methane emissions for that year.

$$CH_{4(S,F)} = CD_{(S,F)} \times EF_{(S,F)}$$

where,

$CH_{4(S,F)}$ = Total methane emissions for each sector and fuel type

$CD_{(S,F)}$ = Consumption data for each sector and fuel type

$EF_{(S,F)}$ = Emission factor for each sector and fuel type

Data Sources

Emission factors for wood combustion were obtained from the U.S. EPA's Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors, AP-42*, and emission factors for fossil fuel consumption from the IPCC, *Revised 1996 IPCC Guidelines* (Table 2-11). Fuel consumption data were drawn from the Energy Information Administration, *State Energy Data Report*, DOE/EIA-0214 (Washington, D.C., various years) for 1990-1997; and *Monthly Energy Review*, DOE/EIA-0035 (Washington, D.C., various years) for 1998 onward. Residential wood fuel consumption data were derived from EIA's *Annual Energy Review* DOE/EIA-0384 (Washington, D.C., various years).

Table 2-11. Data Sources for CH_4 Emissions from Stationary Combustion

Data Utilized	Citation
Emission factors	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Fuel consumption data	For 1980-1997: Energy Information Administration, *State Energy Data Report*, DOE/EIA-0214, (Washington, D.C., various years). For 1998-present: Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035, (Washington, D.C., various years).
Residential wood fuel consumption data	Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384, (Washington, D.C., various years), http://www.eia.doe.gov/emeu/aer/.
Fuel consumption data for recreational boats	Oak Ridge National Laboratory, Center for Transportation Analysis, *Transportation Energy Data Book*, (Oak Ridge, TN, various years), http://www-cta.ornl.gov/publications/tedb.html.

2.1.5 Methane Emissions from Mobile Combustion

Emissions Sources

Methane emissions from mobile combustion are, like those from stationary combustion, the result of incomplete fuel combustion. In automobiles, methane emissions result when oxygen levels in the combustion chamber drop below levels sufficient for complete combustion. This condition occurs especially in low-speed and idle-engine situations. The effects of incomplete combustion in automobiles may be moderated somewhat by post-combustion emissions controls, such as catalytic converters. Methane emissions are also generated by fuel combustion in other modes of transport, including aircraft, ships and locomotives, farm and construction equipment. There is, however, some evidence that jet airplane engines may consume ambient methane during flight, thereby reducing their net emissions. Due to improvements in technology and increasing stringency of environmental regulations, motor vehicle methane emissions have generally declined over time.

The data sources and methodologies used to estimate methane emissions from mobile sources since 1990 have changed, resulting in revised emissions estimates. EIA now utilizes internal estimates from its Office of Integrated Analysis and Forecasting for vehicle use data based on the most recent Polk[40] data on vehicle stocks. The data sources replace those taken historically from subscription publications such as *Wards Automotive Yearbook*. These changes also apply to nitrous oxide emissions.

Estimation Methodology

Research indicates that emissions rates differ among motor vehicles by vehicle type and by type of catalytic converter (associated with the vintage of the motor vehicle) for light-duty vehicles. Consequently, EIA partitions vehicle use data by vehicle type (i.e. by passenger cars, light-duty trucks, buses, motorcycles, and heavy-duty trucks), as well as by motor vehicle vintage (model year) for passenger cars and light-duty trucks.

> Step 1: Partition Vehicle Use Data by Vehicle Type, as well as by Vehicle Vintage for Passenger Cars and Light-Duty Trucks

Historically, EIA compartmentalized vehicle use data by utilizing annual statistics from a variety of sources, including the American Automobile Manufacturer Association's *AAMA Vehicle Facts and Figures*, and Ward's *Automotive Yearbook* and *Automotive Report*, for the U.S. fleet of cars and trucks by model year. As mentioned above, EIA now utilizes internal estimates from its Office of Integrated Analysis and Forecasting for vehicle use data based on the most recent Polk data on vehicle stocks.

> Step 2: Determine Total Distance Traveled by Each Vehicle Vintage for Passenger Cars and Light-Duty Trucks

For motor vehicles, it is necessary to know how many miles are traveled by various vehicle types and models. Data used to calculate vehicle miles traveled (VMT) for light-duty vehicles (passenger cars and light-duty trucks) during the years 1990-2000 are now based on the most recent Polk data on vehicle stocks, with VMT modified by the Oak Ridge National Laboratory

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[40] R. L. Polk & Co, http://usa.polk.com/.

(ORNL). The data for 1996-2000 are further adjusted to incorporate fleet-vehicle data, and the methodology adjusts for the aging population of vehicles by applying survival curves. For the years 2001 onward, methane emissions from mobile sources are estimated using data from fleet vehicles and econometrically modeled VMT, while also adjusting for the aging population of vehicles.

Step 3: Determine Total Distance Traveled by Non-Household Vehicles, Motorcycles, Buses, and Heavy-Duty Trucks.

Vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks are obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics*. EIA's Office of Integrated analysis and Forecasting provides preliminary data to calculate current year estimates of VMT.

Step 4: Determine Emission Factors for Methane Emissions for Highway Vehicles

To develop estimates of mobile source methane emissions, this report uses emission factors published by the U.S. EPA (passenger cars and light trucks) and the Intergovernmental Panel on Climate Change (all other vehicles), expressed in grams of methane per kilometer traveled. To use these coefficients, information is required on the types of fuels consumed, the combustion technologies used, and the extent to which emission control measures are employed. Because the vintage of each vehicle is associated with the type of catalytic converter it employs, emission factors have been broken down by a vehicle's emissions technology type (see Tables 2-12 and 2-13).

Table 2-12. Methane Emission Factors for Passenger Cars & Light Trucks (gram CH_4 per km traveled)

	Passenger Cars	Light Trucks
Uncontrolled	0.135	0.135
Non-Catalyst Control	0.120	0.14
Oxidation Catalyst	0.070	0.09
Three-way Catalyst	0.040	0.07
Three-way Catalyst Control	0.030	0.035
Low-emission Vehicle Technology	0.025	0.03

Source: U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 -2003, Annex 3, *Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Mobile Combustion*, (Washington, D.C., April 2005)
http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2005.html

Step 4: Calculate Total Methane Emissions for Highway Vehicles Based on Vehicle Use and Miles Traveled Activity Data

Methane emissions from highway vehicles are estimated by applying the above emission factors (grams of CH_4 per vehicle kilometer traveled) to vehicle use data.

$$\mathrm{CH}_{4(\mathrm{HV})} = \mathrm{MVMT}_{\mathrm{HV}} \times R_{KM/M} \times \mathrm{EF}_{\mathrm{HV}}$$

where,

$CH_{4(HV)}$ = Total annual methane emissions for each vehicle (thousand metric tons)

$MVMT_{HV}$ = VMT per vehicle (million miles)

$R_{KM/M}$ = Ratio of kilometers to miles (1.609344)

EF_{HV} = emission factor for each highway vehicle (g of CH_4/km)

Table 2-13. Methane Emission Factors for Motorcycles, Buses and Heavy-Duty Trucks

Motorcycles	0.26
Buses	0.10
Heavy-Duty Trucks	0.05

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 5: Determine Annual Methane Emissions from Aircraft, Ships, Locomotives, Recreational Boats, and Farm and Construction Equipment

In accordance with the Intergovernmental Panel on Climate Change *Good Practice Guidance*, U.S.-specific emission coefficients (Table 2-14) are applied directly to annual fuel consumption data to calculate methane emissions from non-highway mobile sources, as shown in the formula below:

$$\text{KMTCH}_{4(\text{NHV})} = \text{FC}_{\text{T}} \times \text{R}_{\text{J/BTU}} \times \text{EF}_{\text{T}}$$

where,

$CH_{4(NHV)}$ = Total annual methane emissions from each non-highway mobile source type (thousand metric tons)

FC_T = Annual fuel consumption data for each source type (trillion Btu)

$R_{J/Btu}$ = Ratio of joules to Btu (1055.1)

EF_T = Intergovernmental Panel on Climate Change emission factor for each source type (grams/MJ)

Table 2-14. Methane Emission Factors for Non-Highway Mobile Sources (grams/MJ)	
Recreational Boats	0.005
Locomotives	0.006
Farm Equipment	0.011
Construction	0.004
Domestic Trade Ships	0.006
Jet Aircraft	0.0005
Aviation Gas	0.06

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 6: Calculate Total Methane Emissions from All Mobile Sources

To calculate the total amount of methane emitted from all mobile sources, the aggregate sum of each vehicle type is computed, as follows:

$$\mathrm{KMTCH}_4 = \mathrm{KMTCH}_{4\mathrm{HV}} + \mathrm{KMTCH}_{4(\mathrm{NHV})}$$

where,

KMTCH_4 = Total annual methane emissions from all mobile sources (thousand metric tons)

$\mathrm{KMTCH}_{4\mathrm{HV}}$ = Total annual methane emissions from the aggregate sum of each highway vehicle type (thousand metric tons)

$\mathrm{KMTCH}_{4(\mathrm{NHV})}$ = Total annual methane emissions from the aggregate sum of each non-highway vehicle type (thousand metric tons)

Data Sources

Emission factors for all vehicles are provided in the IPCC *Revised 1996 IPCC Guidelines*, Vol. 3 (Paris, France, 1997) and the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, Annex 3 – Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Mobile Combustion, Table 3-18.

Vehicle miles traveled (VMT) for light-duty vehicles (passenger cars and light-duty trucks) during the years 1990-2000 are based on the most recent Polk[41] data on vehicle stocks, with VMT modified by the Oak Ridge National Laboratory (ORNL). The data for 1996-2000 are further adjusted to incorporate fleet-vehicle data. For the years 2001 onward, econometrically modeled VMT are used. Vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks were obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics* (Washington, D.C., various years).

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[41] R. L. Polk & Co, http://usa.polk.com/.

Fuel consumption for ships, locomotives, and farm and construction equipment is based on data from EIA's *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, D.C., various years). Jet and piston-powered aircraft fuel consumption data are contained in the Energy Information Administration's *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, D.C., various years). Data on fuel consumption by recreational boats are taken from Oak Ridge National Laboratory, Center for Transportation Analysis, *Transportation Energy Data Book* (Oak Ridge, TN, various years). (See Table 2-15 below.)

Data Sources

Table 2-15. Data Sources for Estimating Methane Emissions from Mobile Combustion

Data Utilized	Citation
Emission factors, calculation methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factors	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002,* Annex 3 – Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Mobile Combustion, (Washington, D.C., April 2004), Table 3-18, pg.111. http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html
Activity data for miles traveled in personal transportation vehicles (cars and light-duty trucks)	Internal estimates from Energy Information Administration's Office of Integrated Analysis and Forecasting based on Polk company (R. L. Polk & Co, http://usa.polk.com/) data.
Activity data for U.S. fleet of cars and trucks by model year	Internal estimates from Energy Information Administration's Office of Integrated Analysis and Forecasting based on Polk company (R. L. Polk & Co, http://usa.polk.com/) data.
Activity data for vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks	U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics*, (Washington, D.C., various years), www.fhwa.dot.gov/ohim/ohimstat.htm.
Fuel consumption data for ships, locomotives, farm and construction equipment	Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/fuel_oil_and_kerosene_sales/foks.html.
Fuel consumption data for jet and piston-powered aircraft	Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340, (Washington, D.C., various years), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html.
Fuel consumption data for recreational boats	Oak Ridge National Laboratory, Center for Transportation Analysis, *Transportation Energy Data Book*, (Oak Ridge, TN, various years), http://www-cta.ornl.gov/publications/tedb.html.

2.2 Waste Management

2.2.1 Methane Emissions from Landfills

Emissions Sources

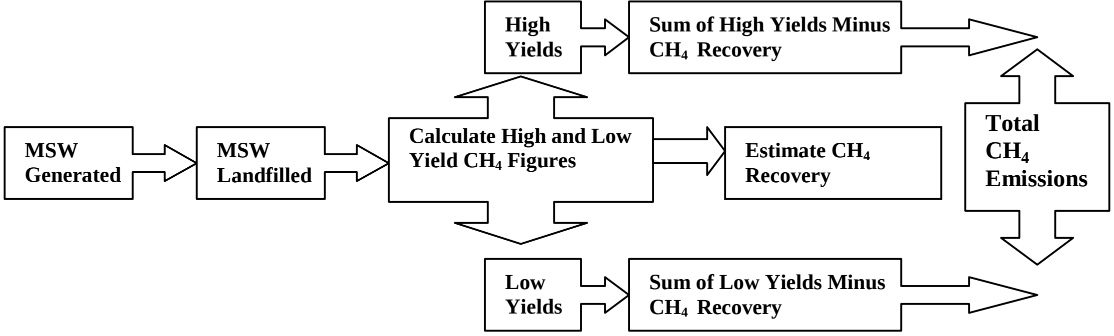
After organic wastes (e.g., food, paper, yard waste) are placed in landfills, they begin to decompose. Aerobic bacteria, consuming oxygen, convert organic material to carbon dioxide, heat, and water. When available oxygen is depleted, anaerobic bacteria, including methanogens, begin digesting the waste and producing methane. Methanogenic anaerobes are highly sensitive to temperature, pH, and moisture levels. Because U.S. sanitary landfills are essentially closed systems designed to minimize entry and exit of moisture, conditions within a landfill are largely a product of the composition of the waste it contains. Thus, methane is likely to be produced at different rates and volumes both across different landfills and within a single landfill.

The biogas produced in a landfill is typically between 40 and 60 percent methane. When emitted, biogas mixing with air can result in methane concentrations within the explosive range of 5 to 15 percent. Often, landfill operators put methane control systems in place to prevent migration of high methane concentrations to nearby buildings. Methane captured by control systems may be vented to the atmosphere or flared, but it is also a potentially valuable energy resource. Where landfills produce steady, large volumes of methane and landfill gas-to-energy prices are competitive with other energy alternatives, recovered gas may be used as an energy resource. In most cases, the gas is combusted to generate electricity and used for on-site energy needs or sold to local utilities. In some cases, the gas is transported via pipeline to a local end user.

Estimation Methodology

Data on methane emissions from landfills are limited to those landfills with methane recovery systems in place. For more than 100 U.S. landfills with gas recovery systems in place, Thorneloe, *et al*, measured or estimated methane emissions at 2.1 million metric tons for 1992.[42] Methane emissions from landfills without gas recovery systems have not been measured, and even the number of landfills is subject to considerable uncertainty.

The methodology for estimating methane emissions from landfills is described in more detail below.



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[42] S.A. Thorneloe, M.R.J. Doorn, L.A. Stefanski, M.A. Barlaz, R.L. Peer, and D.L. Epperson, *Estimate of Methane Emissions From U.S. Landfills*, Prepared for U.S. Environmental Protection Agency, Office of Research and Development (April 1994), p. 1087.

Step 1: Determine Total Amount of Municipal Solid Waste Generated

From 1988 onward, the figures for total waste generated have been derived from *Biocycle*'s "Nationwide Survey: The State of Garbage in America" (Before 1988, these data were not collected by *Biocycle*). In 2002, *Biocycle* developed a new survey methodology which substantially reduced the total estimate of municipal solid waste generated by more effectively excluding construction and demolition waste. To ensure a consistent time series of municipal solid waste generation data, EIA adjusted the prior and subsequent estimates of waste generation by scaling previous estimates of waste generation provided by *Biocycle* to the ratio of *Biocycle*'s new estimate for 2002 to its prior estimates for 2002. In order to account for categories of waste other than MSW going to landfills between 1960 and 1987, an average ratio of waste generation estimated by *Biocycle* and waste generation estimated by Franklin Associates for 1988 through 1997 was calculated. The annual average ratio during this period was 1.47 to 1. Thus, all Franklin estimates for 1960 through 1987 were multiplied by 1.47 to estimate overall waste generation and landfilling for those years. To further extend waste generation estimates back to 1940, a regression equation relating waste generation to gross domestic product (GDP) and population was developed. Waste generation data were not available from *Biocycle* for 2003 and years after 2005, so EIA interpolated the 2003 value and used a regression equation that correlated changes in waste generation reported by *Biocycle* since 1988 to GDP over the same time period to derive waste generation estimates from 2005.

Step 2: Determine Total Amount of Municipal Solid Waste Landfilled

Emissions from a given landfill are largely the product of the composition of the waste it contains and an array of site-specific factors. Waste composition data on a landfill-specific basis are nonexistent; however, national-level waste flow and waste composition data are available, and their reliability has improved over time. Thus, for this report, all waste not disposed of in a landfill with measured emissions is treated as if it has flowed to one very large national landfill.

EIA estimates the annual amount of waste landfilled using a function of total waste generated multiplied by a percentage landfilled factor obtained from *Biocycle*'s "Nationwide Survey: The State of Garbage in America." The volume of waste recycled or combusted rather than landfilled was assumed to have remained stable at 34.4 percent in recent years.

Step 3: Calculate High and Low Yields for Methane Generated at Municipal Solid Waste Landfills for Each Year

To estimate methane emissions from all waste not disposed of in a landfill with measured emissions, waste volumes are subjected to a modified version of the EMCON Methane Generation Model.[43] This model divides the waste into three categories—readily decomposable, moderately decomposable, and slowly decomposable—each with its own set of emissions characteristics. The EMCON model provides both a high methane yield scenario and a low methane yield scenario. For each category of decomposable waste, a time lag until methane generation begins is estimated, as well as a time constant during which the methane yield of the waste is realized. The methane yield represents the total amount of methane that a given amount of waste will produce over its lifetime. For example, under a low methane yield scenario, slowly

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[43] D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environment Change* (December 1992), pp. 311-328.

decomposing waste will begin producing methane after a 5-year lag and will continue emitting over a 40-year period. Table 2-16 below shows the EMCON methane generation model parameters.

Table 2-16. EMCON Methane Generation Model Parameters

Waste Category	Decomposable Portion (Percent by Dry Weight)	Methane Yield (Cubic Feet CH4 per Pound MSW)	Lag Time (Years)	Time Constant
High Yield (Default)				
Readily Decomposable	4. 0	4. 5	0. 2	3
Moderately Decomposable	45. 0	3. 6	1. 5	10
Slowly Decomposable	5. 2	0. 5	5. 0	20
Low Yield (Default)				
Readily Decomposable	4. 0	2. 8	0. 3	4
Moderately Decomposable	45. 0	2. 0	2. 0	20
Slowly Decomposable	5. 2	0. 3	5. 0	40
High Yield (Modified)				
Readily Decomposable	4. 0	8. 8	0. 0	3
Moderately Decomposable	45. 0	7. 0	2. 0	10
Slowly Decomposable	5. 2	1. 0	5. 0	20
Low Yield (Modified)				
Readily Decomposable	4. 0	5. 4	0. 0	4
Moderately Decomposable	45. 0	3. 8	2. 0	20
Slowly Decomposable	5. 2	0. 6	5. 0	40

Source: D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," Global Environmental Change (December 1992), pp. 311-328.

Waste flows were estimated from 1940 onward. Waste in place in the nation's landfills was assumed to represent the waste stream for all previous years plus the current year's additions. The landfills examined by Thorneloe, *et al*, contained 9.2 percent of the waste estimated to be in place in the Nation's landfills during 1992. This report assumes that the share of waste in these landfills and the share in all other landfills remained constant over time. Thus, the EMCON model was applied to 90.8 percent of the waste generated each year.

To estimate emissions from those landfills with measured data for 1992 but no data for other years, the EMCON model was recalibrated to produce the 2.1 million metric tons of measured emissions in 1992. The recalibrated model, with methane yields almost twice as large as the original, was then applied to 9.2 percent of the waste stream for all years. These much higher yields are not unexpected, as gas recovery systems are most economically employed in high-emitting landfills. Total methane emissions for each year under each yield scenario are calculated using the following formula:

$$\mathrm{CH}_{4(\mathrm{YR})} = \frac{\left(MSW_{TL} \times \mathrm{D}_{\mathrm{RMS}} \times \mathrm{CH4}_{(\mathrm{RATE})}\right)}{CF_{CF/MT}}$$

where,

$CH_{4(YR)}$ = Total methane emissions under each yield scenario for a given year

MSW_{TL} = Total amount of waste landfilled for each yield scenario (lbs)

D_{RMS} = Percentage of waste apportioned to the three decomposition scenarios (Readily, Moderately, Slowly)

CH_{4RATE} = Methane yield rate for each decomposition scenario (cubic feet per lb)

$CF_{CF/MT}$ = Conversion factor (52,145.2 cubic feet of CH_4 per metric ton of CH_4)

Step 4: Estimate Methane Generated at Industrial Landfills for Each Year

The U.S. Environmental Protection Agency assumes that industrial landfills emit methane equal to seven percent of emissions levels from municipal solid waste landfills annually. EIA adopts that convention for this report.[44]

Step 5: Estimate Methane Emissions Avoided

The EIA estimate of methane emissions avoided is based on estimates of methane recovery for energy and methane recovered and flared prepared by the U.S. Environmental Protection Agency.

Step 5a: Estimate Methane Emissions Avoided through Flaring

According to U.S. EPA, the quantity of methane flared is based on data collected from the EIA's Voluntary Reporting of Greenhouse Gas Emissions and Reductions Program and a database developed by the EPA's Landfill Methane Outreach Program cross referenced with information from flaring equipment vendors, including information on the quantity of flares, landfill gas flow rates, and year of installation. The total amount of methane recovered through flaring was estimated by summing the estimates of methane recovered by each flare for each year.[45]

Step 5b: Estimate Methane Emissions Avoided through Landfill Gas-to-Energy Recovery.

Estimates of methane emissions avoided through landfill gas-to-energy (LFGTE) projects were provided by the U.S. Environmental Protection Agency, Landfill Methane Outreach Program who also used a combination of data collected by EPA and data from EIA's Voluntary Reporting of Greenhouse Gas Emissions and Reductions Program. Using data on landfill gas flow and energy

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[44] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*, Annex 3.14, Methodology for Estimating Methane Emissions from Landfills, page 233, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[45] U. S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*, Annex 3.14, Methodology for Estimating Methane Emissions from Landfills, page 234, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

generation (i.e. MW capacity), the total amount of methane emissions avoided as a result of the recovery and use of methane were estimated.[46]

Step 5: Calculate Total Methane Emitted

EIA calculates the total amount of methane emitted from landfills by applying the average of the high and low yields produced by the EMCON generation model, adding emissions from industrial landfills and subtracting estimates of methane recovered.

Data Sources

Activity data for methane emissions from landfills include annual data on waste generated and landfilled for the period 1988 through 2000, 2002, and 2004 drawn from "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-2004). For 2001and 2003 waste generation was interpolated. For 2005 onward, EIA used a regression equation that correlated changes in waste generation from 1988 to 2000 to changes in gross domestic product (GDP) over the same time period. These data were not collected by *Biocycle* before 1988. Waste generated and landfilled for the period 1960 through 1987 was estimated from data produced by Franklin Associates. On behalf of the U.S. EPA's Office of Solid Waste and Emergency Response, Franklin Associates have estimated municipal solid waste generated and landfilled for the years 1960 through 1997. See Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States*, Worksheets, 1992 update, prepared for the U.S. EPA, Municipal Solid and Industrial Solid Waste Division (July 1992), and U.S. EPA, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1998 Update*, U.S. EPA-530-S-99-021 (Washington, D.C., July 1999). In contrast to the *Biocycle* data for the period 1988 through 2001, which include all waste going to landfills, including construction and demolition (C&D) waste and sludge, the Franklin data include only MSW going to landfills. The data for 2002 and 2004 have been adjusted by Biocycle to better exclude construction and demolition waste. Thus, EIA adjusted Biocycle data for 1988 through 2001, and 2003 based on the relationship between previously reported Biocycle estimates for 2002 and the downward revision published by Biocycle in 2004. Annual methane recovery for energy data are from the U.S. EPA's Landfill Methane Outreach Program database.[47] (See Table 2-17).

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[46] U. S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*, Annex 3.14, Methodology for Estimating Methane Emissions from Landfills, page 233, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[47] U.S. Environmental Protection Agency Landfill Methane Outreach Program, www.epa.gov/lmop.

Table 2-17. Data Sources for CH_4 Emissions from Landfills

Data Utilized	Citation
Waste generation data	"Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-2002).
Calculation methodology	Thorneloe, S.A., *et al*, "Estimate of Methane Emissions from U.S. Landfills," Prepared for the U.S. Environmental Protection Agency, Office of Research and Development, a departmental review (April 1994).
Calculation methodology	Augenstein, D., "The Greenhouse Effect and U.S. Landfill Methane," *Global Environmental Change* (December 1992), pp. 311-328.
Waste generated and landfilled for the period 1960 through 1987	Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States*, Worksheets, 1992 update, Prepared for the U.S. Environmental Protection Agency, Municipal Solid and Industrial Solid Waste Division (July 1992).
Waste generated and landfilled for the period 1960 through 1987	U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1998 Update*, U.S. EPA-530-S-99-021 (Washington, D.C., July 1999).
Annual methane recovery data	U.S. Environmental Protection Agency, Landfill Methane Outreach Program database, (Washington, D.C.) http://www.epa.gov/lmop.
Annual methane flare data	U.S. Environmental Protection Agency, Landfill Methane Outreach Program database, (Washington, D.C.) http://www.epa.gov/lmop.
U.S. GDP data (for calculation of later year waste generation estimates)	Bureau of Economic Analysis, *Real Gross Domestic Product and Related Measures*, http://www.bea.gov/bea/dn/home/gdp.htm.

2.2.2 Methane Emissions from Domestic and Commercial Wastewater Treatment

Emissions of methane from the treatment of wastewater occur when liquid waste streams containing high concentrations of organic materials are treated anaerobically (in the absence of oxygen). Treatment processes used in the United States are anaerobic and aerobic digestion, and facultative (combining aerobic and anaerobic processes) stabilization lagoons, septic tanks, and cesspools.[48]

Emissions Sources

Treatment of wastewater solids using anaerobic digestion is the most obvious potential source of methane emissions; however, emission of significant quantities of methane from this process requires that the digester gas be vented rather than recovered or flared. Anaerobic and facultative lagoons involve retention of wastewater in impoundments, where the organic materials in the wastewater undergo bacterial decomposition. The growth of algae, which absorb carbon dioxide and release oxygen as a result of photosynthesis, sustains aerobic conditions at least near the surface of the lagoon. Bacteria deplete oxygen at the bottom of the lagoon, producing conditions suitable for methanogenic bacteria. The extent of the resulting anaerobic zone and the associated methane generation depend on such factors as organic loadings and lagoon depth. In facultative lagoons, unlike anaerobic lagoons, a significant aerobic zone persists.

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[48] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *International Anthropogenic Methane Emissions: Estimates for 1990*, EPA-230-R-93-010 (Washington, D.C., January 1994), p. 10-9.

Nearly 75 percent of U.S. households are served by sewers that deliver domestic wastewater to central treatment plants. Septic tanks or cesspools treat domestic wastewater from most of the remaining households.[49] Anaerobic digestion is frequently used to treat sludge solids at U.S. municipal wastewater treatment plants; however, anecdotal evidence suggests that neither recovery nor flaring of digester gas is common in the United States and that equipment for recovery and flaring of digester gas is poorly designed or maintained, allowing most of the methane produced to be released to the atmosphere. [50]

Methane emissions from industrial wastewater treatment are not included in the estimates presented in this report. Please refer to Chapter 8, *Emissions Excluded*, below.

Estimation Methodology

Insufficient information is available to develop separate estimates of methane emissions from each of the sources discussed above. Information on the type of treatment used by the thousands of municipal and industrial treatment facilities is not available. For instance, no reliable statistics were found for the use of anaerobic digestion at municipal treatment facilities. Knowledge regarding the emissions of methane from lagoons, septic systems, and cesspools is likewise limited. Another difficulty is the overlap between municipal and industrial treatment systems. Many industrial concerns discharge wastewater, which may or may not have been treated, into municipal systems.

Step 1: Estimate Annual Total of U.S. Biochemical Oxygen Demand (BOD)

EIA bases its current estimate of methane emissions from wastewater treatment on the approach recommended by the Intergovernmental Panel on Climate Change,[51] which assumes that each person in a developed nation contributes 0.065 kilogram of 5-day biochemical oxygen demand (BOD_5) to domestic wastewater annually.[52] Using the Intergovernmental Panel on Climate Change BOD factor and U.S. Census data, an annual total of U.S. BOD is determined by multiplying population data by the Intergovernmental Panel on Climate Change's BOD figure, as follows:

$$BOD_{US} = POP_{US} \times BOD_{PC}$$

where,

$BOD_{(US)}$ = Annual total of U.S. Biological Oxygen Demand (kilograms of BOD)

$POP_{(US)}$ = Census data U.S. population (millions)

$BOD_{(PC)}$ = Per capita daily BOD.

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[49] U.S. Census, 1980, 1990, 2000.

[50] William Hahn, Science Applications International Corporation, personal communication (May 23, 1996).

[51] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 6.23, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[52] Biochemical oxygen demand (BOD) represents the oxygen consumed by bacteria to decompose organic matter contained in a wastewater stream. It provides a measure of the organic loading of wastewater, which is the primary determinant of its potential to produce methane. BOD_5 is a standardized measurement of BOD that measures the oxygen consumed over a 5-day period.

Step 2: Determine Amount of CH_4 Generated

The amount of CH_4 generated can then be calculated by multiplying the annual BOD by the Intergovernmental Panel on Climate Change's emission factors for anaerobically treated wastewater (16.25 percent), and the amount of methane per kilogram of BOD_5 in the wastewater (0.6 kg). EIA assumes that recovery of methane at municipal wastewater treatment facilities is negligible. This calculation is shown in the following equation:

$$CH_{4(WW)} = BOD_{US} \times EF_{ATW} \times EF_{BOD} - CH_{4(R)}$$

where,

$CH_{4(WW)}$ =Annual total methane emitted from wastewater treatment (million metric tons)

$BOD_{(US)}$ = Annual total of U.S. biochemical oxygen demand (kilograms of BOD)

EF_{ATW} = Emission factor for anaerobically treated wastewater (16.25 percent)

EF_{BOD} = Emission factor for amount of methane per kilogram of BOD in wastewater (0.6 kg)

$CH_{4(R)}$ = Amount of methane recovered.

Data Sources

Activity data for Methane Emissions from Domestic and Commercial Wastewater Treatment include statistics for U.S. population data, as well as Intergovernmental Panel on Climate Change emission factors including a measurement for biochemical oxygen demand (BOD) and a calculation for the annual percentage of anaerobically treated wastewater in developed countries. (See Table 2-18).

Table 2-18. Data Sources for CH_4 Emissions from Domestic and Commercial Wastewater Treatment

Data Utilized	Citation
Emission factors, methodology.	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Census data	U.S. Census Bureau, U.S. Population, July Estimate (Washington, D.C., various years), http://www.census.gov.

2.2.3 Methane Emissions from Industrial Wastewater Treatment

As with domestic and commercial wastewater treatment, emissions of methane from the treatment of industrial wastewater occur when liquid waste streams containing high concentrations of organic materials are treated anaerobically. Treatment processes used in the United States that have the potential to emit methane include anaerobic and anaerobic lagoons.

Emissions Sources

The organic matter in the wastewater undergoes bacterial decomposition in industrial wastewater treatment lagoons. The carbon dioxide and nutrients released by this process promotes the growth of algae, which release oxygen as a product of photosynthesis and sustain aerobic conditions at least near the surface of the lagoon. Bacteria deplete oxygen at the bottom of the lagoon, creating an anaerobic zone conducive to the growth of methanogenic bacteria. The extent of the resulting methane-producing anaerobic zone depends on such factors as organic loadings and lagoon depth. In aerobic facultative lagoons, aeration results in the persistence of a significant aerobic zone.

The major sources of methane from industrial wastewater treatment are those industries that produce large volumes of wastewater with high organic loadings, including pulp and paper manufacturing, meat and poultry processing, and vegetables, fruits, and juices processing.[53]

Estimation Methodology

The estimates of methane emissions from industrial wastewater treatment were developed using the IPCC's method,[54] as applied by EPA in its greenhouse gas emission inventory.[55] Annual methane emissions were estimated for each source using the following equation:

$$CH_4 \text{ Emissions} = P * W * (COD) * TA * B_0 * MCF$$

CH_4 Emissions = CH_4 emissions in inventory year, kg CH_4/yr
P = industry output (metric tons/year)
W = volume of wastewater generated (m3/metric ton of output)
COD = organics loading in wastewater (kg/m^3)
TA = percent of wastewater treated anaerobically on site
B_0 = maximum CH_4 producing potential of wastewater
MCF = CH_4 correction factor indicating the extent to which organic content degrades anaerobically

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[53] U.S. Environmental Protection Agency, Office of Atmospheric Programs, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2005*, EPA 430-R-07-002, (Washington, DC, April 15, 2007), p. 8-10.

[54] The Intergovernmental Panel on Climate Change (IPCC), *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5, Waste*. Prepared by the National Greenhouse Gas Inventories Programme (Japan, 2006) pp. 6.18-6.24.

[55] 55 U.S. Environmental Protection Agency, Office of Atmospheric Programs, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2005*, EPA 430-R-07-002, (Washington, DC, April 15, 2007), p. 8-10–8.11.

Data Sources

The sources of industry output data are summarized in Table 2-19.

Table 2-19 Sources of Industrial Output Data for Industrial Wastewater Emission Sources

Industrial Wastewater Emission Source	Units	Source of Industry Output Data
Pulp and Paper Manufacturing	Tg/yr	Personal communication with Melissa Weitz (EPA) by Dick Richards, 09/17/07.
Meat and Poultry Packing		
Meat		
Beef	tons	Calculated from number of animal slaughtered and average live weight per animal for cattle and calves.
Cattle slaughtered (Commercial)	1000s	USDA/NASS, Agricultural Statistics, 2007 (Table 7-13 for 1997-2006), 2000 (Table 7-13 for 1990-1996)
Avg. live weight	lbs	USDA/NASS, Agricultural Statistics, 2007 (Table 7-15 for 1997-2006), 2000 (Table 7-15 for 1990-1996)
Calves slaughtered (Commercial)	1000s	USDA/NASS, Agricultural Statistics, 2007 (Table 7-13 for 1997-2006), 2000 (Table 7-13 for 1990-1996)
Avg. live weight	lbs	USDA/NASS, Agricultural Statistics, 2007 (Table 7-15 for 1997-2006), 2000 (Table 7-15 for 1990-1996)
Hogs	tons	Calculated from number of animal slaughtered and average live weight per animal
No. slaughtered (Commercial)	1000s	USDA/NASS, Agricultural Statistics, 2007 (Table 7-30 for 1997-2006), 2000 (Table 7-30 for 1990-1996)
Avg. live weight (Fed. Inspected)	lbs	USDA/NASS, Agricultural Statistics, 2007 (Table 7-37 for 1997-2006), 2000 (Table 7-36 for 1990-1996)
Sheep and lambs	tons	Calculated from number of animal slaughtered and average live weight per animal
No. slaughtered (Commercial)	1000s	USDA/NASS, Agricultural Statistics, 2007 (Table 7-51 for 1997-2006), 2000 (Table 7-51 for 1990-1996)
Avg. live weight	lbs	USDA/NASS, Agricultural Statistics, 2007 (Table 7-52 for 1997-2006), 2000 (Table 7-52 for 1990-1996)
Poultry		
Mature chickens (live weight)	1000 lbs	USDA/NASS, Poultry Slaughter, 2006 Annual Summary, Feb. 2007 (p. 1 for 2006); Agricultural Statistics, 2007 (Table 8-48 for 1996-2005), 2000 (Table 8-46 for 1990-1996)
Broilers	1000 lbs	USDA/NASS, Poultry Slaughter, 2006 Annual Summary, Feb. 2007 (p. 1 for 2006); Agricultural Statistics, 2007 (Table 8-49 for 1996-2005), 2000 (Table 8-45 for 1990-1996)

Table 2-19 Sources of Industrial Output Data for Industrial Wastewater Emission Sources

Industrial Wastewater Emission Source	Units	Source of Industry Output Data
Turkeys	1000 lbs	USDA/NASS, Poultry Slaughter, 2006 Annual Summary, Feb. 2007 (p. 2 for 2006); Agricultural Statistics, 2007 (Table 8-60 for 1996-2005), 2000 (Table 8-54 for 1990-1996)
Vegetables, Fruits and Juices Processing		
Potatoes	1000 cwt	USDA/NASS, Agricultural Statistics, 2007 (Table 4-50 for 1997-2006), 1999 (Table 4-44 for 1990-1996)[1]
Total Vegetables	tons	USDA/NASS, Agricultural Statistics, 2007 (Table 4-1 for 1996-2005), 2000 (Table 4-1 for 1990-1995)
Apples	Tg/yr	Quantity of apples processed calculated by subtracting quantity of fresh apples from utilized production.
Apples - utilized production	10^6 lbs	USDA/NASS, Agricultural Statistics, 2007 (Table 5-6 for 1997-2006), 2000 (Table 5-6 for 1990-1996)
Apples - fresh	10^6 lbs	USDA/NASS, Agricultural Statistics, 2007 (Table 5-6 for 1997-2006), 2000 (Table 5-6 for 1990-1996)[2]
Citrus	Tg/yr	Quantity of citrus process calculated from volume and packing density data.
Citrus Volumes	1000 boxes	USDA/NASS, Agricultural Statistics, 2007 (Table 5-28 for 1997-2006), 2000 (Table 5-28 for 1990-1996)
Citrus Packing Density	lbs/box	USDA/NASS, Agricultural Statistics, 2007 (Table 5-29 for 2004-2005 and 2005-2006), 2000 (Table 5-29 for 1997-1998 and 1998-1999)
Non-citrus (total)	1000 tons	USDA/NASS, Agricultural Statistics, 2007 (Table 5-75 for 1997-2006), 2000 (Table 5-73 for 1990-1996)[3]
Grapes for wine	tons	USDA/NASS, Agricultural Statistics, 2007 (Table 5-43 for 1997-2006), 2000 (Table 5-41 for 1990-1996)

EPA = U.S. Environmental Protection Agency; USDA/NASS = U.S. Department of Agriculture, National Agricultural Statistics Service

[1] 2006 value unavailable. Proxy estimated as average of values for previous 5 years (2001-2005).

[2] 2006 value unavailable. Proxy estimated by applying 5-year average of ratio of fresh apples to utilized production to 2006 value for utilized production.

[3] 2006 values for non-citrus subcategories unavailable. Proxies estimated by applying 5-year average of ratio of production for each non-citrus subcategory and total non-citrus production to 2006 value for total non-citrus production.

The sources for the parameters used to estimate methane emissions from wastewater treatment in the pulp and paper industry are summarized in Table 2-20.

Table 2-20. Parameters for Estimating Methane Emissions from Wastewater Treatment from Pulp and Paper Industry

Parameter	Value	Source
Volume of wastewater generated (W)	85.00 m^3/metric ton of output	1
Organics loading in wastewater (COD)	0.34 kg of organic COD/m^3	2
BOD	0.40 kg/m^3	1
COD:BOD Ratio	2.0	3
Percent secondary treatment	42 percent	1
Percent of wastewater treated anaerobically on site (TA)	25 percent BOD	4
Maximum CH_4 producing potential of wastewater (B_0)	0.25 kg CH_4/kg COD	5
CH_4 correction factor indicating the extent to which organic content degrades anaerobically (MCF)	0.8	1

1. U.S. Environmental Protection Agency, Office of Atmospheric Programs, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2005, EPA 430-R-07-002, (Washington, DC, April 15, 2007).
2. Product of BOD, COD: BOD Ratio, and Percent Secondary Treatment.
3. EPA, Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency, Washington, DC, EPA-600/R-97-091. September 1997.
4. Personal communication with Melissa Weitz (EPA) by Dick Richards, 09/21/07.
5. The Intergovernmental Panel on Climate Change (IPCC), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5, Waste. Prepared by the National Greenhouse Gas Inventories Programme (Japan, 2006) pp. 6.18-6.24.

The sources for the parameters used to estimate methane emissions from wastewater treatment in the meat and poultry packing industry are summarized in Table 2-21.

Table 2-21. Parameters for Estimating Methane Emissions from Wastewater Treatment from Meat and Poultry Packing Industry

Parameter	Value	Source
Volume of wastewater generated (W)		
Meat	5.30 m^3/metric ton of output	1
Poultry Packing	12.50 m^3/metric ton of output	1
Organics loading in wastewater (COD)		
Meat	8.40 kg of organic COD/m3	2
BOD	2.80 kg/m^3	1
COD:BOD Ratio	3.0	3
Poultry Packing	4.50 kg of organic COD/m3	2
BOD	1.50 kg/m^3	1
COD:BOD Ratio	3.0	3
Percent of wastewater treated anaerobically on site (TA)		
Meat	33.0 percent COD	1
Poultry Packing	25.0 percent COD	1
Maximum CH_4 producing potential of wastewater (B_0)	0.25 kg CH_4/kg COD	4
CH_4 correction factor indicating the extent to which organic content degrades anaerobically (MCF)	0.8	1

U.S. Environmental Protection Agency, Office of Atmospheric Programs, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2005, EPA 430-R-07-002, (Washington, DC, April 15, 2007).

Product of BOD and COD:BOD Ratio.

EPA, Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency, Washington, DC, EPA-600/R-97-091. September 1997.

The Intergovernmental Panel on Climate Change (IPCC), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5, Waste. Prepared by the National Greenhouse Gas Inventories Programme (Japan, 2006) pp. 6.18-6.24.

The sources for the parameters used to estimate methane emissions from wastewater treatment in the vegetables, fruits and juices processing industry are summarized in Table 2-22.

Table 2-22. Parameters for Estimating Methane Emissions from Wastewater Treatment from Vegetables, Fruits and Juices Processing Industry

Parameter	Value	Source
Volume of wastewater generated (W)		
Potatoes	10.27 m^3/metric ton of output	1
Other Vegetables	8.64 m^3/metric ton of output	1
Apples	3.66 m^3/metric ton of output	1
Citrus fruit	10.11 m^3/metric ton of output	1
Non-citrus fruit	11.70 m^3/metric ton of output	1
Grapes for wine	1.53 m^3/metric ton of output	1
Organics loading in wastewater (COD)		
Potatoes	2.65 kg of organic COD/m^3	2
Other Vegetables	1.23 kg of organic COD/m^3	2
Apples	3.29 kg of organic COD/m^3	2
Citrus fruit	0.79 kg of organic COD/m^3	2
Non-citrus fruit	1.47 kg of organic COD/m^3	2
Grapes for wine	7.04 kg of organic COD/m^3	2
BOD		
Potatoes	1.765 grams/liter	1
Other Vegetables	0.817 grams/liter	1
Apples	1.317 grams/liter	1
Citrus fruit	0.317 grams/liter	1
Non-citrus fruit	0.982 grams/liter	1
Grapes for wine	2.346 grams/liter	1
COD:BOD Ratio		
Vegetables/Fruit Processing	1.5	3
Juice Production	2.5	3
Alcohol Production	3.0	3
Percent of wastewater treated anaerobically on site (TA)	5.0 percent COD	1
Maximum CH$_4$ producing potential of wastewater (B$_0$)	0.25 kg CH$_4$/kg COD	4
CH$_4$ correction factor indicating the extent to which organic content degrades anaerobically (MCF)	0.8	1

U.S. Environmental Protection Agency, Office of Atmospheric Programs, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2005, EPA 430-R-07-002, (Washington, DC, April 15, 2007).

Product of BOD and COD:BOD Ratio.

EPA, Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency, Washington, DC, EPA-600/R-97-091. September 1997.

The Intergovernmental Panel on Climate Change (IPCC), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5, Waste. Prepared by the National Greenhouse Gas Inventories Programme (Japan, 2006) pp. 6.18-6.24.

2.3 Agricultural Sources

2.3.1 Methane Emissions from Enteric Fermentation

Emissions Sources

The breakdown of carbohydrates in the digestive track of herbivores—including insects, reptiles, birds, animals, and humans—results in the production of methane.[56] The amount of methane produced largely depends upon the nature of the animal's digestive system.[57] The volume of methane produced from this process (enteric fermentation) is highest in those animals with a *ruminant* digestive system (i.e., possess a rumen, or forestomach), such as cattle, buffalo, goats, sheep, and camels. The forestomach allows these animals to digest large quantities of cellulose found in coarse plant material. This digestion is accomplished by microorganisms in the rumen, some of which are methanogenic bacteria. These bacteria produce methane while removing hydrogen from the rumen. The majority (about 90 percent) of the methane produced by the methanogenic bacteria is released through normal animal respiration and eructation (belching). The remainder is released as flatus. In contrast, the digestion process in *pseudo-ruminant* animals, such as horses, mules, and asses, and *monogastric* animals, such as swine, involves significantly less fermentation and thus less production of methane gas.[58]

Estimation Methodology

The level of methane emissions from enteric fermentation in domesticated animals is a function of several variables, including: (1) the quantity and quality of feed intake, (2) the growth rate of the animal, (3) its productivity (reproduction and/or lactation), and (4) its mobility. To estimate emissions from enteric fermentation, the animals are divided into distinct, relatively homogeneous groups. An emission factor for each cattle category is developed based on the U.S. EPA methodology for estimating methane emissions from enteric fermentation from cattle, documented in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2001*. The factor is then multiplied by population data for that animal group to calculate an overall emissions estimate. This method for estimating methane emissions from enteric fermentation is broken down into the following steps.

Step 1: Characterize Cattle Populations

The U.S. cattle population is separated into dairy and beef cattle. Dairy cattle are characterized into two groups: heifers (defined as female cattle that have never given birth) and cows (females that have borne a calf). Beef cattle are divided into six subclasses: calves, feedlot beef cattle (which include heifers and steers), heifers (not on feed), steers (not on feed), cows, and bulls. Cattle populations are estimated based on data obtained from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS). The cattle population values used to estimate annual emissions are the average of the NASS January and July populations for each animal category.

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[56] P.J. Crutzen, I. Aselmann, and W.S. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," Tellus, Vol. 38B (1986), p. 272.

[57] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.3 http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[58] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.3 http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 2: Develop Enteric Fermentation Emission Factors for Cattle

To estimate emissions from enteric fermentation in cattle, EIA developed adjusted methane emission factors which reflect the greater detail that U.S. EPA incorporated into the Tier 2 methodology outlined in the IPCC *Good Practice Guidance*.[59] The EIA-adjusted enteric fermentation emission factors for each cattle class were developed by dividing U.S. EPA's estimated total annual methane emissions from enteric fermentation in cattle by the U.S. EPA population estimates for each cattle subclass, which U.S. EPA estimated using a complex model that simulates each stage in the cattle lifecycle, from birth to slaughter, on a per-month basis. The U.S. EPA cattle population lifecycle model tracks calving rates, average weights and weight gains, feedlot placements, pregnancy and lactation, death rates, number of animals per category each month, and animal characteristic data.[60] The total annual methane emissions from enteric fermentation in cattle, as estimated by U.S. EPA, are based on gross energy, digestible energy, net energy for various activities, and methane conversion rates for the various animal subcategories, which reflect regional diet characterization.

Step 3: Characterize Other Animal Populations by Class

Average swine and sheep populations are obtained from the U.S. Department of Agriculture, NASS. Goat and horse populations are interpolated or extrapolated from available data for the years 1987, 1992, 1997, and 2002 which are obtained from the U.S. Department of Commerce, *Census of Agriculture*. Consistent with IPCC standards, populations of sheep, pigs, goats, and horses are not disaggregated below the species level.

Step 4: Characterize Enteric Fermentation Emission Factors for Other Animal Populations

For other animal categories, EIA applied the Tier 1 emission factors recommended in the *Revised 1996 IPCC Guidelines*.[61] These methane emission factors for other animals are shown in Table 2-23, below.

Table 2-23. Methane Emission Factors for Other Animals (kg per head per year)

Class	Emission Factor
Swine	1.5
Sheep	8.0
Horse	18.0
Goats	5.0

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), pg. 4-10, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

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[59] Intergovernmental Panel on Climate Change, *Good Practice Guidance* (Montreal, May 2000) Chapter 4, Agriculture, http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

[60] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, Annex L, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[61] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, Vol. 3 (Paris, France, 1997), p. 4.10, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 5: Estimation of Methane Emissions from Enteric Fermentation

Once characterized, values for animal populations and emission factors (Table 2-24) for each group are multiplied to estimate total methane emissions from enteric fermentation, as shown in the following formula:

$$CH_{4(EF)} = \sum\left[P_T \times EF_T\right] \times 10^{-6}$$

where,

$CH_{4(EF)}$ = Methane emissions from enteric fermentation (million metric tons)

P_T = Number of animals of type T in the U.S. (in thousands)

EF_T = Methane emission factor for enteric fermentation (kg CH_4 per head per year)

Data Sources

Table 2-24. Data Sources for Methane Emissions from Enteric Fermentation

Data Utilized	Citation
Cattle population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Cattle," January and July, Agricultural Statistics Board, (Washington, D.C., various years), http://www.nass.usda.gov.
Swine population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Monthly Hogs and Pigs" Agricultural Statistics Board, (Washington, D.C., various years), http://www.nass.usda.gov.
Poultry population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Chickens and Eggs," Agricultural Statistics Board, Poultry 1-1, (Washington, D.C., various years), http://www.nass.usda.gov.
Population data for goats and horses	U.S. Department of Commerce, Census of Agriculture, *United States Summary and State Data, Vol. 1*, "Geographic Area Series," Part 51 (Washington, D.C., various years).
Emission factors for swine, sheep, goats, and horses	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.10, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factors for cattle	Derived from: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, Annex L, "Methodology for Estimating CH_4 Emissions from Enteric Fermentation" (Washington, D.C., April 2003), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html.

2.3.2 Methane Emissions from Solid Waste of Domesticated Animals

Emissions Sources

This section addresses methane emissions occurring as a result of storing, handling, or otherwise managing manure. Livestock manure is principally organic in composition. Certain bacteria produce methane when this organic material decomposes in an anaerobic environment. Such conditions commonly occur when large numbers of livestock are managed in a confined area, such as a dairy farm, beef feedlot, or swine or poultry farm. In such situations, methane is most readily produced in anaerobic conditions where manure is stored in or disposed of in lagoons, ponds, tanks, or pits.[62] In contrast, in manure that is handled aerobically (in stacks or pits, as a solid or left on open pasture, range, or paddock lands) anaerobic bacterial activity does not occur, little or no methane production results.[63]

The volume of methane produced varies according to the amount of organic material susceptible to decomposition within the waste (volatile solids) and the manner in which the waste is managed. Liquid-based waste management systems, in addition to providing a suitable anaerobic environment, provide the moisture necessary for "methanogenic" bacterial cell production and acid stabilization.[64] Thus, they result in the greater methane emissions.

Other factors that affect the amount of methane produced include ambient temperature and moisture—increases of each contribute to methane production by bacteria active in the manure. The majority of manure in the U.S. is treated as a solid, although the use of liquid systems is increasing, particularly in large-scale dairy and swine production. Smaller dairies, in turn, are relying to an increasing degree on on-site manure storage. The composition of manure may also differ based on the animal type and diet. Methane is generally produced in increased quantities in feed that is higher in caloric value. As a result, the manure of feed cattle typically produces higher levels of methane than that of range cattle. Correspondingly, the manure of dairy cattle tends to produce an even higher level of methane.[65]

Estimation Methodology

In estimating methane emissions from the solid waste of domesticated animals, EIA follows IPCC Tier 2 requirements, dividing the animal population into classes and subclasses, applying manure production volumes as appropriate to each animal subclass, and weighing the manner in which manure is handled for each animal type.[66] Methane emissions from animal waste are estimated by linking emissions to the volume of solid waste produced by a given animal, the volatile solids in that waste, and the manner in which the waste is handled.

Methane emissions from the handling of animal waste are estimated using the following information:

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[62] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.1 and 4.4, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm; see also U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001* (Washington, D.C., 2003), p.5-5, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[63] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.4, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm; see also U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001* (Washington, D.C., 2003), p.5-5, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[64] U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, D.C., April 1993).

[65] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001* (Washington, D.C., 2003), p.5-5, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[66] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.4, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. This methodology is also upheld for use in the Intergovernmental Panel on Climate Change *Good Practice Guidance*, (Montreal, May 2000), http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

Annual animal population data, by animal type;

Animal mass, by animal type;

The rate of production of volatile solids in manure, based on animal mass, by animal type;

The emission factor for the maximum methane-producing potential of the manure (expressed as volume of methane per kilogram of volatile solids) under anaerobic conditions;

The percentage of animal waste handled in various animal waste management systems, by animal type; and

Conversion factors for methane of animal waste handled in various animal waste management systems.

EIA breaks out the three-step Tier 2 estimation process provided by the IPCC into the following five steps:

Step 1: Estimate Animal Populations by Animal Category

Animal populations are derived from sources published by the U.S. Department of Agriculture, and are collected for the following animal groups: (1) beef cattle, including feedlot beef cattle, calves, heifers, steers, cows, and bulls; (2) dairy cattle, including heifers and cows; (3) swine, including market swine and breeding swine; (4) poultry, including layers and broilers; and (5) other animals, including sheep, goats, and horses. (See Section 2.1.1 for estimating methane emissions from enteric fermentation).

Step 2: Characterize Typical Animal Mass for Each Animal Type

For this report, EIA updated the typical animal masses used in the estimate of methane emissions from animal waste. For all animals except poultry, EIA obtained data on typical animal mass from the U.S. EPA report, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001.*[67] For poultry, EIA adopts animal mass values directly from U.S. EPA, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*.[68]

Step 3: Identify Daily Production Rate of Volatile Solids, Maximum Methane Production Capacity of Volatile Solids under Anaerobic Conditions, and the Percentage of Waste Handled in Waste Management Systems

Values for the amount of volatile solids produced per kilogram of animal weight, the maximum methane-producing capacity of the waste of each animal type, and the share of waste handled in each management system are adopted from the work of Safley, *et al* (exceptions are described in notes to Tables).[69] These values are provided in Table 2-25, Table 2-26, and Table 2-27. For this report, the percent of waste handled in various waste management systems was updated for

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[67] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, Annex M (Washington, D.C., April 2003), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[68] U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*. (Washington, D.C., April 1993).

[69] L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions from Livestock and Poultry Manure* (Washington, D.C.: U.S. Environmental Protection Agency, February 1992), p. 18.

feedlot beef cattle and dairy heifers. For feedlot beef cattle, EIA now assumes that 100 percent of waste is handled in drylots, based on U.S. EPA *Cost Methodology Report for Beef and Dairy Animal Feeding Operations*.[70] EIA does not take into account any feedlots that may have solids separation and runoff from the drylots. For dairy heifers, EIA assumes that 100 percent of waste is handled in dry storage, based on the same U.S. EPA *Cost Methodology Report*.[71] As the amount of volatile solids produced per kilogram of animal weight is available to EIA from other sources, EIA does not follow the IPCC recommendations for independently calculating the volatile solid excretion rate.[72]

Table 2-25. Volatile Solids Calculation Factors

Class / Subclass	Daily Volatile Solids Production Rate (kg/day / 1,000 kg animal mass)*	Maximum Methane-Producing Potential of Volatile Solids (m3 per kg volatile solids)**
Beef Cattle		
Feedlot Beef Cattle	7.2	0.33
Calves	6.41	0.17
Heifers	7.5	0.17
Steers	8.0	0.17
Cows	7.0	0.17
Bulls	6.04	0.17
Dairy Cattle		
Heifers	7.0	0.17
Cows	10.0	0.24
Swine		
Market Swine	8.5	0.48
Breeding Swine	2.6	0.48
Poultry		
Layers	10.43	0.34
Broilers	16	0.30
Other Animals		
Sheep	9.2	0.19
Goats	9.5	0.17
Horses	10.0	0.33

Source: L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions from Livestock and Poultry Manure* (Washington, D.C.: U.S. Environmental Protection Agency, February 1992). Source of Daily Volatile Solids Production Values for Other beef cattle, breeding swine, and poultry is adopted from the U.S. EPA *Inventory*, or approximated to more closely conform with the U.S. EPA methodology documented in U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, Annex M (Washington, D.C., 2004). Source of Maximum Methane Generation Potential value for swine and dairy heifers is U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, Annex M (Washington, D.C., 2004).

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[70] U.S. Environmental Protection Agency, Office of Water, *Final Cost Methodology Report for Beef and Dairy Animal Feeding Operations*, EPA-821-R-01-019 (Washington, D.C., January 2001).

[71] U.S. Environmental Protection Agency, Office of Water. *Final Cost Methodology Report for Beef and Dairy Animal Feeding Operations*, EPA-821-R-01-019 (Washington, D.C., January 2001).

[72] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.23, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Table 2-26. Share of Waste Handled in Various Waste Management Systems by Animal Type, Selected Years (fraction)

Animal Manure Management System Type	Beef Cattle*	Dairy Cows**	Swine	Poultry: Layers	Poultry: Broilers	Sheep	Goats	Horses
Anaerobic Lagoons	0.005	0.11	0.29	0.14				
Liquid Slurry	0.10	0.21		0.10				
Daily Spread	0.005	0.41						
Solid Storage	0.89	0.18						
Drylot			0.20					
Pit Storage (less than 1 mo.)			0.12					
Pit Storage (more than 1 mo.)			0.32					
Deep Pit				0.56				
Litter					1.00			
Pasture						0.92	0.84	0.66
Paddock								0.27
Other		0.08	0.07	0.20		0.08	0.16	0.07

Note: Specific values for dairy cattle and swine are not included in this table. Blank cells are not applicable. Values apply to beef cattle not on feed. For feedlot beef cattle, 100 percent of waste is assumed to be handled in drylots. Values apply to dairy cows. For dairy heifers, 100 percent of waste is assumed to be handled in dry storage.

Source: L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions from Livestock and Poultry Manure* (Washington, D.C., February 1992).

Step 4: Characterize the Methane Conversion Factor for Each Animal Waste Management System

EIA utilizes the methane conversion factors provided in the *Revised 1996 IPCC Guidelines* for temperate climates. For certain types of manure management systems and for certain states (i.e., Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas), EIA adopts state-level conversion factors based on a weighted average of each state's manure management technique (see Table 2-27). EIA used the methane conversion factors for anaerobic lagoons and liquid/slurry systems in the states listed above by adopting the values reported by the U.S. EPA.[73]

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[73] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001*, Annex M (Washington, D.C., 2003), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Table 2-27. Methane Conversion Factors by Waste Management System (fraction)

Manure Management System	National-Level	Arizona	Florida	Nevada	North Carolina	North Dakota	Texas
Anaerobic Lagoons	0.90	0.79	0.79	0.7	0.75	0.66	0.78
Liquid Slurry	0.35	0.47	0.52	0.26	0.33	0.23	0.45
Daily Spread	0.005	.004	.006	.003	.003	.002	.005
Solid Storage	0.015	.014	.015	.012	.013	.007	.014
Drylot	0.015	NA	0.015	0.012	0.013	0.007	0.014
Pit Storage (less than 1 mo.)	0.18	NA	0.18	0.18	0.18	0.18	0.147
Pit Storage (more than 1 mo.)	0.35	0.35	0.35	0.35	0.35	0.35	0.294
Deep Pit	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Litter	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Pasture	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Digester	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Burned for Fuel	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Other	0.01	NA	0.01	0.01	0.01	0.01	0.20

Source: National-level values are obtained from the "Table 4-8: Manure Management Systems and Methane Conversion Factors (MFCs)," *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.25. State-level values for daily spread and solid storage are based on a weighted average of each state's manure management technique, which is obtained from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, U.S. EPA-236-R-00-001 (Washington, D.C., April 2000) p. I-4. State-level values for anaerobic lagoons and liquid slurry are based on U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, Annex M (Washington, D.C., 2004).

Step 5: Estimate Methane Emissions from Animal Waste Management Systems

EIA combines the second and third steps of the Tier 2 estimation process provided in the *Revised 1996 IPCC Guidelines*.[74] Methane emissions are estimated taking the values obtained in Steps 1 through 4, above, by multiplying the following values: animal population (by type); mass of animal (by type); volatile organic solids production per mass; the emission factor for the maximum methane-producing potential of volatile solids; the sum of the product of the fraction of waste handled in each management system (by animal type) and applicable methane conversion factor; the number of days per year; and a factor for converting volume of methane to mass, and divide by one thousand to yield Kmt of CH_4. This is summarized in the following formula:

$$CH_{4(\mathrm{AWMS})} =$$

$$\mathrm{P_T} \times \mathrm{M_T} \times \mathrm{R_{VS}} \times \mathrm{F_{MAX\text{-}VS}} \times \left[\mathrm{Frac_{AWMS}} \times \mathrm{CF_{AWMS}}\right] \times \mathrm{N_{YEAR}} \times \mathrm{CF_{VOL\text{-}MASS}} \times 10^{-3}$$

where,

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[74] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.26, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm

$CH_{4(AWMS)}$ = Methane emissions from animal waste management systems (thousand metric tons)

P_T = Number of animals of type T in the U.S.

M_T = Mass of animal of type T in the U.S. (10^3 kg)

R_{VS} = Production rate for volatile solids produced per animal mass (kg volatile solids per day per 10^3 kg animal mass)

$F_{MAX\text{-}VS}$ = Factor for maximum methane production potential of volatile solids under anaerobic conditions (m^3 methane production capacity per kg of volatile solids)

$Frac_{AWMS}$ = Fraction of animal waste handled in various animal waste management systems for animal type T

CF_{AWMS} = Methane conversion factor by waste management systems and by animal type T

N_{YEAR} = Number of days in a given calendar year

$CF_{VOL\text{-}MASS}$ = Conversion factor for mass of methane per cubic meter of methane emitted per day (0.677237×10^{-3} metric tons CH_4 per m^3 CH_4)

Data Sources

Table 2-28. Data Sources for Methane Emissions from Animal Wastes

Data Utilized	Citation
Calculation methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Equation 2, p. 4.4, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Cattle population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Cattle," January and July, Agricultural Statistics Board, (Washington, D.C., various years), http://www.nass.usda.gov.
Swine population data	U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock Branch. "Agricultural Statistics," (Washington, D.C., various years).
Poultry population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Chickens and Eggs," Agricultural Statistics Board, Poultry 1-1, (Washington, D.C., various years), http://www.nass.usda.gov.
Population data for goats and horses	U.S. Department of Commerce, Census of Agriculture, United States Summary and State Data, Vol. 1, "Geographic Area Series," Part 51 (Washington, D.C., various years).
Animal mass (by type)	U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, D.C., April 1993), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html; U.S. Department of Agriculture, National Agricultural Statistics Service, http://www.nass.usda.gov.
Production rate for volatile solids produced per animal mass	L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, Global Methane Emissions from Livestock and Poultry Manure (Washington, D.C., February 1992), p. 18.
Emission factor for maximum methane production capacity of volatile solids under anaerobic conditions	L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, Global Methane Emissions from Livestock and Poultry Manure (Washington, D.C., February 1992), p. 18.
Fraction of animal waste handled in various animal waste management systems	L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, Global Methane Emissions from Livestock and Poultry Manure (Washington, D.C., February 1992), p. 18.
Methane conversion factor by waste management systems	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, "Table 4-8: Manure Management Systems and Methane Conversion Factors (MFCs)," (Paris, France, 1997), p. 4.25, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Methane conversion factor by waste management systems weighted on a state-by-state basis	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, U.S. EPA-236-R-00-001 (Washington, D.C., April 2000) p. I-4, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

2.3.3 Methane Emissions from Rice Cultivation

Emissions Sources

Methane is produced when organic material in flooded rice fields decomposes in the absence of oxygen (anaerobically). Between 60 and 90 percent of the methane generated is oxidized by bacteria in the soil, while an additional portion leaches into the groundwater. The majority of the methane that remains is transported through rice plants and is transpired into the atmosphere. A smaller amount of methane reaches the atmosphere by bubbling from the soil and by diffusing through the water column.

Estimation Methodology

Step 1: Calculate U.S.-specific Emission Factors for CH_4

A range of daily emissions rates has been developed from United States-specific rice field measurements in California,[75] Louisiana,[76] and Texas.[77] Table 2-29 below provides the emission estimates range (0.1065 and 0.5639 grams of methane per square meter of land cultivated).

Table 2-29. Emission Estimates Range for United States Rice Fields (gCH_4/sq m/day)

Low End of Emissions Range	0.1065
High End of Emissions Range	0.5639

Sources: R. Sass, F. Fisher, S. Lewis, M. Jund, and F. Turner, "Methane Emissions From Rice Fields: Effect of Soil Properties," *Global Biogeochemical Cycles*, Vol. 8 (1994), p. 135. R.J. Cicerone, J.D. Shetter, and C.C. Delwiche, "Seasonal Variation of Methane Flux From a California Rice Paddy," *Journal of Geophysical Research*, Vol. 88 (1983), pp. 7203-7209. C.W. Lindau and P.K. Bolich, "Methane Emissions From Louisiana First and Ratoon Rice Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48.

Step 2: Calculate a Seasonally Adjusted Figure for Area Harvested

For each State, an estimate is produced which incorporates the total area harvested for each rice-producing State with the length of each States' growing season. Table 2-30 below provides the season length for each of the States' growing season.

Table 2-30. Season Length for rice-producing States (Days)

Arkansas	88
California	138
Florida	105
Louisiana	105
Mississippi	79
Missouri	90
Texas	70
Oklahoma	105

Source: U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production - Annual Summary*.

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[75] R. Sass, F. Fisher, S. Lewis, M. Jund, and F. Turner, "Methane Emissions from Rice Fields: Effect of Soil Properties," *Global Biogeochemical Cycles*, Vol. 8 (1994), p. 135.

[76] R.J. Cicerone, J.D. Shetter, and C.C. Delwiche, "Seasonal Variation of Methane Flux from a California Rice Paddy," *Journal of Geophysical Research*, Vol. 88 (1983), pp. 7203-7209.

[77] C.W. Lindau and P.K. Bolich, "Methane Emissions from Louisiana First and Ratoon Rice Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48.

Consistent with the methodology provided in the *Revised 1996 IPCC Guidelines*, EIA calculates a seasonally-adjusted figure for the area harvested in each State by multiplying the State's daily estimate of area harvested by the number of days in that State's growing season, as shown in the formula below:

$$AH_S = H_S \times S_S$$

where,

AH_S = Seasonally adjusted harvest of an individual State (hectares)

H_S = Area harvested daily in an individual State (hectares)

S_S = Season length for a particular State (days)

Step 3: Calculate Additional Area Harvested for States with Ratoon Crops

In states with a second ("ratoon") crop, the additional area harvested is incorporated into the estimates.

$$RH_S = H_S \times RP_S$$

where,

RH_S = Ratoon harvest of an individual State (hectares)

H_S = Area harvested daily in an individual State (hectares)

RP_S = Percentage of an individual State's harvest that is ratoon crop (percent)

Step 4: Derive both High and Low CH_4 Emissions Estimates for Rice Cultivation

Two emission estimates for each State can be derived by multiplying the seasonally adjusted figure for total area harvested by both the high and low ends of the emission estimates range (0.1065 and 0.5639 grams of methane per square meter of land cultivated) provided in Step 1. EIA utilizes the following formula to calculate both a high and low methane emission estimate for rice cultivation in each State:

$$CH_{4(SHL)} = AH_S \times EF_{(HL)} \times 0.01$$

where,

$CH_{4(SHL)}$ = High and low estimate of an individual State's methane emissions (metric tons of CH_4)

AH_S = Seasonally adjusted figure for total area harvested (includes ratoon crop estimate, in hectares)

$EF_{(HL)}$ = Emission factor for high and low methane emissions estimates (grams CH_4 per square meter per day).

Step 5: Average the two CH_4 emissions estimates

After summing all State sources for both high and low emissions estimates, a single CH_4 emissions estimate for rice cultivation is calculated by combining the high and low emissions estimates and dividing the sum by two.

$$CH_{4(RC)} = \left(\frac{\mathrm{CH}_{4(H)} + \mathrm{CH}_{4(L)}}{2} \right)$$

where,

$CH_{4(RC)}$ = Total methane emissions from rice cultivation (metric tons)

$CH_{4(H)}$ = Total methane emissions using the high-end emission factor (metric tons)

$CH_{4(L)}$ = Total methane emissions using the low-end emission factor (metric tons)

Data Sources

Activity data for methane emissions from rice cultivation include data for area of rice harvested and the length of growing season obtained from the USDA *Crop Production 2001 Summary* (USDA 2001). For 1990-2001, data on Florida rice harvests are from University of Florida, Institute of Food and Agricultural Sciences, Cooperative Extension Service, "Florida's 2000 Rice Variety Census," and "An Overview of the Florida Rice Industry." For 2002 onward, data on Florida rice harvests are from the University of Florida Everglades Research and Education Center. Data for Oklahoma rice harvests were available for the years 1990, 1997-1999, and 2000 onward from the U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. EPA obtained these data from the Oklahoma Farm Services Agency).[78] For states with ratoon crops, the percentages of rice harvested in this crop were taken from the U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.[79] Emission factors for the calculation of methane from rice cultivation are United States-specific figures derived from rice field measurements in accordance with IPCC *Good Practice Guidance* (*See* Table 2-31).

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[78] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003* (Washington, D.C., 2005), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[79] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003* (Washington, D.C., 2005), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Table 2-31. Data Sources for CH_4 Emissions from Rice Cultivation

Data Utilized	Citation
Production figures	U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production - Annual Summary* (Washington, D.C., various years), http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban.
Emissions ratios	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Estimation methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), pp. 4.81-4.86, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Florida rice data	University of Florida, Institute of Food and Agricultural Sciences, Cooperative Extension Service, *Florida's 2000 Rice Variety Census*, "An Overview of the Florida Rice Industry," http://edis.ifas.ufl.edu.
Oklahoma rice data	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*, (Washington, D.C., April 2005), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Emission factors	R. Sass, F. Fisher, S. Lewis, M. Jund, and F. Turner, "Methane Emissions From Rice Fields: Effect of Soil Properties," *Global Biogeochemical Cycles*, Vol. 8 (1994), p. 135.
Emission factors	R.J. Cicerone, J.D. Shetter, and C.C. Delwiche, "Seasonal Variation of Methane Flux From a California Rice Paddy," *Journal of Geophysical Research*, Vol. 88 (1983), pp. 7203-7209.
Emission factors	C.W. Lindau and P.K. Bolich, "Methane Emissions From Louisiana First and Ratoon Rice Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48.

2.3.4 Methane Emissions from Burning of Crop Residues

Emissions Sources

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. Between 40 and 50 percent of dry matter in crop residue is carbon.[80] When crop residues are burned for fodder, land supplementation, or fuel, incomplete combustion produces methane emissions. Field burning of crop residues is a net source of $CH_{4.}$ 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 U.S. are wheat, rice, sugarcane, corn, barley, soybeans, and peanuts.

Estimation Methodology

This report assumes that 3 percent of all crop residues are burned, with the exception of rice, which is combusted at various levels over time. Because of a legislated reduction in rice straw

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[80] A. Strehler and W. Stutzle, "Biomass Residues," in D.O Hall and R.P. Overend (eds.), *Biomass: Regenerable Energy* (Chichester, UK: John Wiley and Sons, 1987), p. 85.

burning, the share of rice crop residues in California estimated to be combusted declined from 75 percent in 1990 to 13 percent in 2002.

The estimation methodology involves the following two steps in accordance with IPCC *Good Practice Guidance*:

Step 1: Estimate Total Carbon Released from Burning of Crop Residues by Crop Type

Methane emissions from crop residues are calculated first by estimating the carbon content for each group of crops based on the carbon content of dry matter residues that are burned. The overall amount of crop residue is determined as a fraction of total crop product (see Table 2-32).

$$\mathrm{C}_{\mathrm{CR(T)}} = \mathrm{CP}_{\mathrm{T}} \times \mathrm{Frac}_{\mathrm{RES/CR(T)}} \times \mathrm{Frac}_{\mathrm{DM(T)}} \times \mathrm{Frac}_{\mathrm{C(T)}} \times \mathrm{Frac}_{\mathrm{BURNED(T)}} \times \mathrm{Comb}_{\mathrm{T}}$$

where,

$\mathrm{C}_{\mathrm{CR(T)}}$ = Carbon content released from burning of crop residues by crop type (thousand metric tons)

CP_{T} = total annual crop production by type (metric tons)

$\mathrm{Frac}_{\mathrm{RES/CR(T)}}$ = the ratio of crop residue to crop product of crop type (crop residue/crop product)

$\mathrm{Frac}_{\mathrm{DM(T)}}$ = the average dry matter content contained in crop residue of crop type (dry matter/tons of biomass)

$\mathrm{Frac}_{\mathrm{C(T)}}$ = fraction of carbon in crop residue of crop type (tons of carbon/tons of dry matter)

$\mathrm{Frac}_{\mathrm{BURNED(T)}}$ = fraction of crop residue burned in the field of crop type (0.03 kg crop burned per kg crop product)

$\mathrm{Comb}_{\mathrm{(T)}}$ = combustion efficiency of crop type (the fraction of carbon oxidized completely)

Table 2-32. Factors Used in Estimating Methane Emissions from Crop Residue Burning

Crop Type	Residue/ Crop Ratio	Dry Matter Content (Percent)	Carbon Content (Percent)	Fraction of Residue Burned
Barley	1.2	0.93	0.4485	0.03
Beans	2.1	0.8535	0.45	0.03
Corn	1.0	0.91	0.4478	0.03
Oats	1.3	0.92	0.42	0.03
Peas	1.5	0.87	0.45	0.03
Peanut	1.0	0.86	0.45	0.03
Potatoes	0.4	0.867	0.4226	0.03
Rice	1.4	0.91	0.3806	Variable
Rye	1.6	0.90	0.4853	0.03
Sorghum	1.4	0.91	0.34	0.03
Soybean	2.1	0.87	0.45	0.03
Sugarbeet	0.2	0.9	0.4072	0.03
Sugarcane	0.8	0.62	0.4235	0.03
Wheat	1. 3	0. 93	0. 4428	0. 03

Sources: A. Strehler and W. Stutzle, "Biomass Residues," in D. Hall and R. Overend (eds.), Biomass: Regenerable Energy (Chichester, UK: John Wiley and Sons, 1987), C. Li, S. Frolking and R. Harriss, "Modeling Carbon Biogeochemistry in Agricultural Soils," Global Biogeochemical Cycles, Vol. 8 (September 1994), E. Darley, "Emission Factors from Burning Agricultural Wastes Collected in California," Final Report, CAL/ARB Project 4-011 (Riverside, CA: University of California, 1977), U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* (Washington, D.C., various years), and G. Barnard, "Use of Agricultural Residues as Fuel," in J. Pasztor and L. Kristoferson (eds.), *Bioenergy and the Environment* (Boulder, CO: Westview Press, 1990).

Step 2: Calculate CH_4 Emissions

Once the total carbon released for each crop type has been estimated, CH_4 emissions from the burning of crop residues can be derived by first multiplying the figure for total carbon released by the IPCC's default CH_4 emission ratio, followed by the methane-carbon ratio of 4:3, as shown in the equation below:

$$MTCH_{4(CR)} = \mathrm{C}_{\mathrm{CR(T)}} \times EF_M \times EF_{MC}$$

where,

$\mathrm{MTCH}_{4(\mathrm{CR})}$ = Total methane emissions from crop residue burning (metric tons of CH_4)

$\mathrm{C}_{\mathrm{CR(T)}}$ = Carbon content released from burning of crop residues by crop type (thousand metric tons)

EF_{M} = the IPCC's default CH_4 emission ratio (0.05)

EF_{MC} = the methane-carbon ratio to convert to full molecular weight (1.33)

Data Sources

Activity data for methane emissions from field burning of crop residues include annual crop production figures obtained from the USDA's *Crop Production Summary* (USDA various years), with the exception of production statistics for Florida Rice which were estimated by applying average primary and ratoon crop yields for the State. Emission factors for methane emitted during the burning of crop residues from wheat, rice, sugarcane, corn, barley, soybeans, and peanuts were obtained from the U.S. EPA *Inventory*, which were in turn determined from various state-level greenhouse gas emission inventories and publications on agricultural burning in the United States. Emissions ratios for the calculation of methane were obtained from the IPCC's *Greenhouse Gas Inventory Reference Manual*. (See Table 2-33).

Table 2-33. Data Sources for CH_4 Emissions from Burning of Crop Residues

Data Utilized	Citation
Production figures	U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production - Annual Summary* (Washington, D.C., various years), http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban.
Residue/crop ratio	A. Strehler and W. Stutzle, "Biomass Residues," in D.O. Hall and R.P. Overend (eds.), *Biomass: Regenerable Energy* (Chichester, UK: John Wiley and Sons, 1987), p. 85.
Emission factors, methodology	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Emission factors, emissions ratios, Methodology	Intergovernmental Panel on Climate Change *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), pp. 4.81-4.86. http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
California rice data	U. S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production - Annual Summary* (Washington, D.C., various years), http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban.

2.4 Industrial Processes

2.4.1 Methane Emissions from Chemical Production

Emissions Sources

A wide variety of organic compounds (those containing carbon) are used as feedstocks in chemical production. High temperatures are often used to "crack" the molecular bonds of the compounds, with different temperatures producing specific chemicals. The process of cracking produces a number of chemical byproducts, including methane.

Estimation Methodology

The methodology for estimating methane emissions from the production of chemicals follows that of the general methodology for estimating emissions associated with most industrial processes. Production figures, i.e., the amount of chemical produced or consumed, for ethylene, dichloroethylene, styrene, methanol and carbon black are multiplied by their corresponding emission factor. The estimation methodology involves utilizing the following formula, in accordance with IPCC *Good Practice Guidance*:

$$CH_{4(CP)} = \mathrm{CP_T} \times EF_{M(T)}$$

where,

$\mathrm{CH_{4(CP)}}$ = Total methane emissions from chemical production (metric tons of $\mathrm{CH_4}$)

$\mathrm{CP_T}$ = Total annual production of chemical by chemical type (thousand metric tons)

$\mathrm{EF_{M(T)}}$ = the IPCC's default $\mathrm{CH_4}$ emission factor for chemical type (Table 2-34).

Table 2-34. Methane Emission factors for Industrial Processes (g $\mathrm{CH_4}$/kg of chemical produced)

Industrial Product	Methane Emission factor
Coke	0.5
Sinter	0.5
Pig Iron	0.9
Carbon Black	11.0
Ethylene	6.0
Dichloroethylene	0.4
Styrene	4.0
Methanol	2.3

Source: Intergovernmental Panel on Climate Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3, Industrial Processes and Product Use, Prepared by the National Greenhouse Gas Inventories Programme. (Japan, 2006).

Data Sources

Activity data for methane emissions from chemical production include production figures obtained from the American Chemistry Council (formerly the Chemical Manufacturers Association), and IPCC emission factors for methane emitted during the production of carbon black, ethylene, dichloroethylene, styrene and methanol.[81] (See Table 2-35).

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[81] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 2.23, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm

Table 2-35. Data Sources for CH_4 Emissions from Chemical Production

Data Utilized	Citation
Emission factors, methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 2.23, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Production figures	American Chemistry Council (formerly the Chemical Manufacturers Association), *Guide to the Business of Chemistry*, Table 3.12 "Production of the Top 100 Chemicals," (Washington, D.C., 2005).

2.4.2 Methane Emissions from Iron and Steel Production

Emissions Sources

Coke, sinter, and pig iron are the principal material inputs for the production of iron and steel. Coke is produced by heating coal in the absence of oxygen. One of the gaseous byproducts of this process is methane. During the next step in the production process, coke, iron ore, and flux materials are combined to form sinter. The coke is burned to create heat, causing the sinter to agglomerate. During agglomeration, methane is released. Coke and iron are then added to flux materials in a blast furnace and reduced to iron, slag, and exhaust gases. Methane is one of the exhaust gases.

Estimation Methodology

The methodology for estimating methane emissions from the production of iron and steel follows that of the general methodology for estimating emissions associated with most industrial processes. Production figures for iron and steel inputs, i.e., the amount of material produced or consumed, are simply multiplied by the corresponding emission factor. The estimation methodology involves utilizing the following formula, in accordance with IPCC *Good Practice Guidance*:

$$CH_{4(IS)} = \mathrm{CP}_{\mathrm{IS}} \times EF_{M(T)}$$

where,

$CH_{4(IS)}$ = Total methane emissions from iron and steel production (metric tons of $CH_{4)}$

CP_{IS} = Total annual production of iron and steel inputs (thousand metric tons)

$EF_{M(T)}$ = the IPCC's default CH_4 emission factor for iron and steel inputs

Data Sources

Emission factors for methane emitted during the production of coke, sinter, and pig iron,[82] and coke, sinter and pig iron production data are published by the American Iron and Steel Institute in its Annual Statistical Report (Table 2-36).

Table 2-36. Data Sources for CH_4 Emissions from Iron and Steel Production

Data Utilized	Citation
Emission factors, calculation Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 2.23, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Production figures	American Iron and Steel Institute, *Annual Statistical Report*, Tables 26, 31, 32 (Washington, D.C., various years).

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[82] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 2.23, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

3. Nitrous Oxide Emissions

This chapter describes methods for estimating emissions of nitrous oxide from **energy use**, including mobile combustion and stationary combustion; **agricultural emissions** from nitrogen fertilization of agricultural soils, crop residue burning, and solid waste from domesticated animals; and emissions from **waste**, including waste combustion and human sewage in wastewater. The two primary sources of nitrous oxide from **industrial processes** - production of adipic acid and nitric acid - are also addressed.

3.1 Energy Use

3.1.1 Nitrous Oxide Emissions from Mobile Combustion

Like methane emissions from mobile combustion, the data sources and methodologies used to estimate nitrous oxide emissions from mobile sources since 1990 have changed, resulting in revised emissions estimates. EIA now utilizes internal estimates from its Office of Integrated Analysis and Forecasting for vehicle use data based on the most recent Polk[83] data on vehicle stocks. The data sources replace those taken historically from subscription publications such as *Wards Automotive Yearbook*.

Emissions Sources

Nitrous oxide emissions from mobile sources are produced as a byproduct of fuel combustion. During combustion, nitrous oxide (N_2O) is produced as a result of chemical interactions between nitrogen oxides (NO, NO_2, and NO_3) and other combustion products. Since nitrous oxide decomposes at high temperatures, most stationary combustion systems (such as those used for larger-scale electric power generation) emit little nitrous oxide. Under some conditions, however, the catalytic converters fitted as pollution control devices on most U.S. vehicles will convert nitrogen oxides into nitrous oxide. Production of nitrous oxide is greatest when the catalytic converter is warming up, before it reaches normal operating temperature, when the catalytic converter is not working properly, or when the catalyst is affected by excessive levels of sulfur in the gasoline.

Estimation Methodology

The estimation methodology for nitrous oxide emissions from mobile combustion is largely equivalent to that used to estimate methane emissions. In general, EIA estimates nitrous oxide emissions from highway vehicles by multiplying national-level vehicle miles traveled data by the appropriate emission factors (grams of nitrous oxide per mile driven), as follows:

$$\mathbf{N_2O\ from\ highway\ vehicles = Emission\ Factor\ (g\ N_2O/mile)\ x\ VMT}$$

Research indicates that emissions rates differ among motor vehicles by vehicle type, and, for light-duty vehicles, by type of catalytic converter (associated with the vintage of the motor

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[83] R. L. Polk & Co, http://usa.polk.com/.

vehicle). Consequently, EIA partitions national-level vehicle miles traveled by vehicle type (i.e., by passenger cars, light-duty trucks, buses, motorcycles, and heavy-duty trucks), as well as by motor vehicle vintage (model year) for cars and light-duty trucks.

For non-highway sources, rather than using VMT, EIA uses fuel consumption data to calculate nitrous oxide emissions, by applying an emission factor in grams of nitrous oxide per unit of fuel consumed. Since off-road vehicles rarely have catalytic converters (and vintage data are scarce) no attempt is made to track vehicle vintages for the non-highway sources. The following equation is then used to estimate off-highway vehicle N_2O emissions:

N_2O from non-highway vehicles = Emission Factor (g N_2O/unit of fuel) * fuel consumption

The following data are used to estimate nitrous oxide emissions from mobile sources:

> Vehicle miles traveled for the U.S. fleet of cars and trucks by model year (vintage), and for motorcycles, buses, and heavy-duty trucks;
>
> Fuel consumption data for ships, locomotives, farm and construction equipment, jet and piston-powered aircraft, and recreational boats; and
>
> Emission factors for each vehicle type.

EIA applies the following process to estimate nitrous oxide emissions from mobile combustion:

> Step 1: Partition Vehicle Use Data by Vehicle Type, as well as by Vehicle Vintage for Passenger Cars and Light-Duty Trucks

Historically, EIA compartmentalized vehicle use data by utilizing annual statistics from a variety of sources, including the American Automobile Manufacturer Association's *AAMA Vehicle Facts and Figures*, and Ward's *Automotive Yearbook* and *Automotive Report*, for the U.S. fleet of cars and trucks by model year. As mentioned above, EIA now utilizes internal estimates from its Office of Integrated Analysis and Forecasting for vehicle use data based on the most recent Polk data on vehicle stocks.

> Step 2: Determine Total Distance Traveled by Each Vehicle Vintage for Passenger Cars and Light-Duty Trucks

For motor vehicles, it is necessary to know how many miles are traveled by various vehicle types and models. Data used to calculate vehicle miles traveled (VMT) for light-duty vehicles (passenger cars and light-duty trucks) during the years 1990-2000 are now based on the most recent Polk data on vehicle stocks, with VMT modified by the Oak Ridge National Laboratory (ORNL). The data for 1996-2000 are further adjusted to incorporate fleet-vehicle data, and the methodology adjusts for the aging population of vehicles by applying survival curves. For the years 2001 onward, nitrous oxide emissions from mobile sources are estimated using data from fleet vehicles and econometrically modeled VMT, while also adjusting for the aging population of vehicles.

> Step 3: Determine Total Distance Traveled by Non-household Vehicles, Motorcycles, Buses, and Heavy-Duty Trucks.

Vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks are obtained for previous years from *Highway Statistics*, published by the U.S. Department of

Transportation, Federal Highway Administration. EIA's Office of Integrated Analysis and Forecasting provides preliminary data to calculate current year estimates of VMT.

Step 4: Determine Emission factors for Nitrous Oxide Emissions for Cars and Light-Duty Trucks

To develop estimates of mobile source nitrous oxide emissions, this report uses emission factors published by the IPCC, expressed in grams of nitrous oxide per kilometer traveled. To use these coefficients, information is required on the types of fuels consumed in the transportation sector, the combustion technologies used, and the extent to which emission control measures are employed. Because the vintage of each vehicle is associated with the type of catalytic converter it employs, IPCC emission factors have been broken down by a vehicle's emissions technology type, as in Tables 3-1 and 3-2, below.

Table 3-1. Nitrous Oxide Emission Factors for Passenger Cars and Light-Duty Trucks

	EF (gram/km)	
Catalytic Converter Usage	**Passenger Cars**	**Light-Duty Trucks**
Uncontrolled	0.0103	0.0129
Non-Catalyst Control	0.0103	0.0129
Oxidation Catalyst	0.0322	0.0403
Three-way Catalyst	0.0507	0.0635
Three-way Catalyst Control	0.0288	0.0361
Low Emission Vehicle Technology	0.0176	0.0220

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001,* Annex E, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Table 3-2 Nitrous Oxide Emission Factors for Motorcycles, Buses, and Heavy-Duty Trucks

Motorcycles	0.002
Buses	0.031
Heavy-Duty Trucks	0.025

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.1.75, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 5: Calculate Total Nitrous Oxide Emissions for Highway Vehicles Based on Vehicle Use and Miles Traveled Activity Data

Nitrous oxide emissions from highway vehicles are estimated by applying emission factors provided by the U.S. EPA (per vehicle miles traveled) to vehicle use data.

$$N_2O_{(HV)(T)} = VMT_{HV(T)} \times R_{KM/M} \times EF_{HV}$$

where,

$N_2O_{(HV)(T)}$ = Total annual nitrous oxide emissions for each vehicle type (thousand metric tons)

$VMT_{HV(T)}$ = VMT per vehicle type (million miles)

$R_{KM/M}$ = Ratio of kilometers to miles (1.609344 km per mile)

EF_{HV} = emission factor for each highway vehicle type (grams of N_2O/km)

T = Vehicle type

Step 6: Determine Annual Nitrous Oxide Emissions from Aircraft, Ships, Locomotives, Recreational Boats, and Farm and Construction equipment

In accordance with IPPC *Good Practice Guidance*, U.S.-specific emission coefficients are applied directly to annual fuel consumption data to calculate nitrous oxide emissions from non-highway mobile sources, as follows.

$$N_2O_{(NHV)(T)} = FC_T \times R_{J/BTU} \times EF_T$$

where,

$N_2O_{(NHV)(T)}$ = Total annual nitrous oxide emissions from each non-highway mobile source type (thousand metric tons)

FC_T = Annual fuel consumption data for each vehicle type (trillion Btu)

$R_{J/Btu}$ = Ratio of joules to Btu (1055.1)

EF_T = IPCC emission factor for each source type (g/MJ)

T = Vehicle type

Table 3-3. Nitrous Oxide Emission Factors for Non-Highway Mobile Sources

Vehicle Type	Emission Factor (grams per MJ)
Recreational Boats	0.005
Locomotives	0.006
Farm Equipment	0.011
Construction	0.004
Domestic Trade Ships	0.006
Jet Aircraft	0.0005
Aviation Gas	0.06

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.1.89, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 7: Calculate Total Nitrous Oxide Emissions from All Mobile Sources

To calculate the total amount of nitrous oxide emitted from all mobile sources, the aggregate sum of all years is computed for each vehicle type.

$$N_2O_{(MS)} = N_2O_{(HV)(T)} + N_2O_{(NHV)(T)}$$

where,

$N_2O_{(MS)}$ = Total annual nitrous oxide emissions from all mobile sources (thousand metric tons)

$N_2O_{(HV)(T)}$ = Total annual nitrous oxide emissions from the aggregate sum of each highway vehicle type (thousand metric tons)

$N_2O_{(NHV)(T)}$ = Total annual nitrous oxide emissions from the aggregate sum of each non-highway vehicle type (thousand metric tons)

T = Vehicle type

Data Sources

Emission factors for all vehicles are provided in the IPCC *Revised 1996 IPCC Guidelines*, Vol. 3 (Paris, France, 1997) and the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, Annex 3 – Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Mobile Combustion, Table 3-18, pg. 111.

Vehicle miles traveled for light-duty vehicles (passenger cars and light-duty trucks) during the years 1990-2000 are based on the most recent Polk[84] data on vehicle stocks, with VMT modified by the Oak Ridge National Laboratory (ORNL). The data for 1996-2000 are further adjusted to incorporate fleet-vehicle data. For the years 2001 onward, econometrically modeled VMT from EIA are used. Vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks were obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics* (Washington, D.C., various years).

Fuel consumption for ships, locomotives, and farm and construction equipment is based on data from EIA's *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, D.C., various years). Jet and piston-powered aircraft fuel consumption data are contained in EIA's *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, D.C., various years). Data on fuel consumption by recreational boats are taken from Oak Ridge National Laboratory, Center for Transportation Analysis, *Transportation Energy Data Book* (Oak Ridge, TN, various years). (See Table 3-4).

Table 3-4. Data Sources for Nitrous Oxide Emissions from Mobile Combustion

Activity Data	**Citation**
Activity data for miles traveled in personal transportation vehicles (cars and light-duty trucks)	Internal estimates from Energy Information Administration's Office of Integrated Analysis and Forecasting based on Polk company (R. L. Polk & Co, http://usa.polk.com/) data.
Activity data for U.S. fleet of cars and trucks by model year	Internal estimates from Energy Information Administration's Office of Integrated Analysis and Forecasting based on Polk company (R. L. Polk & Co, http://usa.polk.com/) data.
Activity data for vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks	U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics* (Washington, D.C., various years), www.fhwa.dot.gov/ohim/ohimstat.htm.
Fuel consumption data for ships, locomotives, farm and construction equipment	Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, D.C., various years).
Fuel consumption data for jet and piston-powered aircraft	Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, D.C., various years).
Fuel consumption data for recreational boats	Oak Ridge National Laboratory, Center for Transportation Analysis, *Transportation Energy Data Book* (Oak Ridge, TN, various years), http://www-cta.ornl.gov/publications/tedb.html.
Emission Factors	**Citation**
Emission factors	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), pp. 1.64-1.68, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002,* Annex 3 – Methodology for Estimating Emissions of CH_4, N_2O, and Ambient Air Pollutants from Mobile Combustion, (Washington, D.C., April 2004), Table 3-18, pg.111, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.
Calculation Methodology	**Citation**
Calculation methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), p.1.63, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

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[84] R. L. Polk & Co, http://usa.polk.com/.

3.1.2 Nitrous Oxide Emissions from Stationary Combustion

Emissions Sources

As with mobile sources, nitrous oxide emissions from stationary combustion are a byproduct of fuel combustion. The three fuels of primary importance burned by stationary sources are coal, fuel oil, and natural gas. Combustion systems powered by coal produce the most nitrous oxide—approximately 64 percent of annual emissions from this source. Since 1990, electric utilities as a sector have consistently accounted for more than one-half of total nitrous oxide emissions from stationary combustion. Other important sources are commercial facilities, industrial facilities, and residences.

Estimation Methodology

Emissions of nitrous oxide from stationary combustion of fossil fuels and wood are calculated by multiplying total fuel consumption (measured in Btu) by an emission factor appropriate to the fuel type. Total emissions for each type of fuel consumed by each sector are then summed to derive total emissions for each fuel type and sector. EIA utilizes the following information to calculate total U.S. nitrous oxide emissions from each fuel type and sector:

- annual total U.S. fuel consumption by fuel type and by sector;
- the emission factor for nitrous oxide emissions from stationary combustion; and
- appropriate factors for converting lower heating value (LHV) to higher heating value (HHV).

Nitrous oxide emissions are estimated using the three-step process outlined as follows.

Step 1: Determine Fuel Consumption for Each Fuel Type and Sector

Fuel consumption is collected from several sources published by EIA, including the *State Energy Data Report*, the *Annual Energy Review*, and the *Monthly Energy Review*.

Step 2: Determine Emission Factor for Nitrous Oxide Emissions from Stationary Combustion

EIA relies on the default (uncontrolled) nitrous oxide emission factors for stationary combustion published in the *Revised 1996 IPCC Guidelines* (see Table 3-5).

Table 3-5. Emission Factors for Nitrous Oxide from Stationary Combustion

Fuel Type	Emission Factor (kg N_2O per terajoule)
Oil	0.6
Coal	1.4
Natural Gas	0.1
Wood	4.0

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.1.50, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

EIA applies factors to convert the lower heating value of fossil fuels to higher heating value in order to effectively account for heat content that is lost during combustion due to the creation of water vapor (see Table 3-6). Higher heating value (gross heating value) is the total amount of heat released when a fuel is burned.[85]

Table 3-6. Factors for Converting Lower Heating Value to Higher Heating Value

Fuel Type	Conversion Factor
Oil	1.05
Coal	1.05
Natural Gas	1.10
Wood	1.07

Source for oil, coal, and natural gas: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.1.24, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm . Source for wood: PHYLLIS, a database containing information on the composition of biomass and waste; value represents the ratio of the average HHV (kJ/kg) to average LHV (kJ/kg), for the group: untreated wood. http://www.ecn.nl/phyllis/cgi-bin.

Step 3: Calculate Emissions Based on Fuel Consumption Activity Data

Nitrous oxide emissions from stationary combustion are estimated by multiplying fuel consumption figures for each fuel type and stationary source by emission factors for each type of fuel. Nitrous oxide emissions from stationary combustion include emissions from the consumption of wood in the residential, commercial, industrial, and electric utility sectors. Consistent with the methodology provided in the *Revised 1996 IPCC Guidelines*, EIA estimates emissions by applying emission factors for coal, oil, natural gas, and wood to EIA's consumption data for each fuel in the commercial, residential, industrial, and electric utility sectors, as shown in the formula below:

$$N_2O_{(SC)} = \frac{\mathrm{E}_{\mathrm{SC(T)(S)}} \times \mathrm{EF}_{\mathrm{SC}} \times \mathrm{CF}_{\mathrm{SC}}}{\mathrm{CF}_{\mathrm{HV}}}$$

where,

$N_2O_{(SC)}$ = Nitrous oxide emissions from the stationary combustion of fossil fuels and wood (thousand metric tons N_2O per year)

$E_{SC(T)(S)}$ = Fuel consumption for each fuel type in each sector (quadrillion Btu)

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[85] Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce carbon dioxide and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat content. Lower heating value (net heating value), in contrast, does not include the heat spent in transforming the water into steam. The U. S. Energy Information Administration uses a simplified methodology based on International Energy Agency default values.

$EF_{SC(T)}$ = Emission factor for nitrous oxide emissions from stationary combustion

CF_{SC} = conversion factor (1.05587 terajoule per quadrillion Btu)

$CF_{HV(T)}$ = factor for converting lower heating value (LHV) to higher heating value (HHV)

T = Fuel type

S = Sector

Nitrous oxide emissions from stationary combustion comprise the total emissions from each sector and fuel type.

Data Sources

Table 3-7 provides a list of data sources relating to nitrous oxide emissions from stationary combustion.

Table 3-7. Data Sources for Nitrous Oxide Emissions from Stationary Combustion

Data Utilized	**Citation**
Emission coefficients for stationary Fuel	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), p. 1.36, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Fuel consumption data	Energy Information Administration, State Energy Data, (Washington, D.C., various years), http://www.eia.doe.gov/emeu/states/_use_multistate.html. Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035 (Washington, D.C., various years), http://www.eia.doe.gov/emeu/mer/contents.html. Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384 (Washington, D.C., various years), http://www.eia.doe.gov/emeu/aer/contents.html.
Residential wood fuel consumption data	Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384 (Washington, D.C., various years), http://www.eia.doe.gov/emeu/aer/contents.html.

3.2 Agriculture

3.2.1 Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils

Emissions Sources

Emission of nitrous oxide from certain types of soil bacteria is stimulated with the addition of nitrogen to agricultural soils through the application of natural or synthetic fertilizers. This occurs to a greater or lesser extent depending on the particular chemical, biological, and thermal conditions of the soil. The exact degree to which this addition of nitrogen stimulates the nitrous oxide emissions is uncertain. This is due in part to the natural condition of the soil, moisture content, the presence of competitor bacteria, degree of soil compaction, oil acidity or alkalinity, and temperature. Following the *Revised 1996 IPCC Guidelines* for estimating nitrous oxide emissions from animal manure used as fertilizer, synthetic fertilizer, and crop residues, EIA assumes that 1.25 percent of the nitrogen applied is emitted to the atmosphere as nitrous oxide (M) and 30 percent escapes into the environment (L). Some 2.5 percent (IE) of the nitrogen that escapes is ultimately converted into nitrous oxide in the form of emissions from streams and bodies of water. A further 10 percent of the nitrogen applied to soils is assumed to be released as gas in the form of nitrogen oxides and ammonia, and 1 percent of that nitrogen is assumed to ultimately be converted into nitrous oxide.[86]

Methodology for Total Direct and Indirect N_2O Emissions from All Fertilizer

The process for estimating nitrous oxide emissions from fertilizer involves separate calculations of emissions from the following sources:

- animal manure used as fertilizer;
- synthetic fertilizer;
- crop residues;
- mineralization in cultivated high organic content soils (histosols);
- nitrogen-fixing crops;
- fertilizer and manure runoff; and
- atmospheric deposition (re-emitted as nitrous oxide from soils and soil runoff).

Each of these sources is estimated using the detailed methodologies described in this section. The sum of these sources for nitrous oxide emissions from fertilizer is calculated as follows:

$$\begin{aligned} &N_2O_{(F)} = \\ &N_2O_{(F)AM} + N_2O_{(F)SF} + N_2O_{(F)CR} + N_2O_{(F)SM} + \\ &N_2O_{(F)NF} + N_2O_{(SF-AM)RUNOFF} + N_2O_{(F)AD} \end{aligned}$$

where,

$N_2O_{(F)}$ = N_2O emissions from fertilizer (thousand metric tons)

$N_2O_{(F)AM}$ = N_2O emissions from animal manure (thousand metric tons)

$N_2O_{(F)SF}$ = nitrous oxide emissions from in synthetic fertilizer applied to agricultural lands in given year (thousand metric tons)

$N_2O_{(F)CR}$ = nitrous oxide emissions from crop residues used as fertilizer (thousand metric tons)

$N_2O_{(F)SM}$ = direct N_2O emissions from soil mineralization (thousand metric tons)

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[86] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 1.53, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

$N_2O_{(F)NF}$ = direct N_2O emissions from nitrogen-fixing crops (thousand metric tons)

$N_2O_{(SF\text{-}AM)RUNOFF}$ = indirect N_2O emissions from fertilizer and manure runoff (thousand metric tons)

$N_2O_{(F)AD}$ = total nitrous oxide emissions from atmospheric deposition (thousand metric tons)

Estimation Methodology for N_2O from Animal Manure Used as Fertilizer

Estimates of nitrous oxide from the use of animal manure as fertilizer are not as accurate as estimates for synthetic fertilizer, but can be determined based on animal population data and an understanding of manure management and application practices. The methodology for estimating nitrous oxide emissions from animal manure applied as fertilizer is based on estimates of nitrogen content in animal manure, taking into account that a portion of the nitrogen—about double the portion for synthetic fertilizers—will volatilize into ammonia (NH_3) and oxides of nitrogen (NO_X) after it is applied to an agricultural field.[87] For information about the estimation of animal populations, see Section 3.2.3 on Solid Waste of Domesticated Animals.

Nitrous oxide emissions from animal manure used as fertilizer are estimated using the following information:

- number of animals by category and subclass in the U.S.;
- daily volatile solids produced per animal (based on animal mass), by animal category and subclass;
- share of daily spread of animal waste by animal category and subclass;
- nitrogen content in animal manure utilized in given year; and
- fraction of nitrogen volatilized as NH_3/NO_X for manure.

The methodology for determining nitrous oxide emissions from animal manure used as fertilizer involves the following three steps:

Step 1: Determine Nitrogen Content for Manure by Animal Type

The calculation of nitrous oxide emissions from animal manure used as fertilizer first requires a determination of the total nitrous oxide emissions generated from animal manure, calculated as the sum for each animal category and subclass. As shown in the following formula, total emissions for each animal category/subclass are based on the animal population, daily volatile solids produced per ton of animal mass in each category/subclass, and the percentage of animal waste contributing to daily spread:

$$N_{AM} = P_T \times EF_{VOL-SOL} \times Frac_{SPREAD}$$

where,

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[87] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.89, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

N_{AM} = nitrogen content in animal manure produced in given year (thousand metric tons)

P_T = number of animals of type T in the U.S.

$EF_{VOL\text{-}SOL}$ = daily volatile solids produced per 1,000 kg animal mass, by animal category and subclass

$Frac_{SPREAD}$ = share of daily spread of animal manure by animal category and subclass

T = type/category of animal

Step 2: Determine Fraction of Nitrogen Volatilized as NH_3/NO_X and Nitrous Oxide Emission factor for Animal Manure Used as Fertilizer

Values for the fraction of nitrogen volatilized as NH_3/NO_X and the emission factor for nitrous oxide emissions from animal manure are both obtained from the *Revised 1996 IPCC Guidelines*.

Step 3: Calculate Nitrous Oxide Emissions for Animal Manure Used as Fertilizer

Total nitrous oxide emissions from animal manure applied as fertilizer to agricultural soils are calculated based on the total nitrogen content in animal manure utilized in a given year, the total nitrogen remaining after subtracting out the nitrogen volatilized as NH_3/NO_X, and the emission factor for animal manure used as fertilizer, as follows.

$$N_2O_{(F)AM} = N_{AM} \times (1 - Frac_{VOL-AM}) \times EF_{(F)} \times CF_{N2O-N}$$

where,

$N_2O_{(F)AM}$ = direct N_2O emissions from soil manure (thousand metric tons)

N_{AM} = nitrogen content in animal manure produced in given year (thousand metric tons)

$Frac_{VOL\text{-}AM}$ = fraction of nitrogen volatilized as NH_3/NO_X for manure (0.2 NH_3-N per ton manure)

$EF_{(F)}$ = emission factor for nitrous oxide emissions (0.0125 kg N_2O-N per kg N)

$CF_{N2O\text{-}N}$ = conversion factor mass N_2O per N ($^{44}/_{28}$ N_2O/N)

Data Sources

EIA uses a calculation methodology consistent with the *Revised 1996 IPCC Guidelines* for estimating N_2O emissions from animal manure used as fertilizer. Cattle population data are taken from the USDA NASS. Manure production is derived from the *Revised 1996 IPCC Guidelines*, L.M. Safley, *et al*, and the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. The fraction of manure nitrogen volatilized and the emission factor for animal manure used as fertilizer are also from the *Revised 1996 IPCC Guidelines*. Share of daily spread of animal manure and the emission factor for N_2O emissions are provided by U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. (See Table 3-8).

Table 3-8. Data Sources for Nitrous Oxide Emissions from Animal Manure Used as Fertilizer

Data Utilized	**Citation**
Calculation methodology	Based on Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Equation 1, p. 4.92, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Cattle population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Cattle," January and July, Agricultural Statistics Board, (Washington, D.C.), (various years), http://www.nass.usda.gov.
Animal manure production	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), pp. 4.88-4.93, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. L.M. Safley, M.E. Casada et al., *Global Methane Emissions From Livestock and Poultry Manure* (Washington, D.C., February 1992). U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2002* (April 2004), http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2003.html.
Faction of nitrogen volatilized as NH_3/NO_X for manure	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-19, p. 4.94, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Daily volatile solids produced per 1,000 kg animal mass	L.M. Safley, M.E. Casada et al., *Global Methane Emissions From Livestock and Poultry Manure* (Washington, D.C., February 1992).
Share of daily spread of animal manure	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, U.S. EPA-236-R-01-001 (Washington, D.C., April 2001), http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2001.html.
Emission factor for animal manure used as fertilizer	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-18, p. 4.89, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factor for nitrous oxide emissions per ton nitrogen produced in animal manure	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, U.S. EPA-236-R-01-001 (Washington, D.C., April 2001), http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2001.html.

Estimation Methodology for N_2O from Synthetic Fertilizer

The addition of synthetic fertilizers to agricultural soils is a significant source of N_2O. Nitrous oxide is emitted from the application of synthetic fertilizers by contributing additional nitrogen to the natural biogenic production of N_2O in soil from nitrification and denitrification processes. These emissions are calculated by (1) multiplying the total known nitrogen in synthetic fertilizers applied to soils, (2) calculating the fraction of nitrogen volatilized as NH_3 or NO_X, and (3) applying emission and conversion factors to derive nitrous oxide from nitrogen emitted.

Nitrous oxide emissions from synthetic fertilizer are estimated using the following information:

- nitrogen content in synthetic fertilizer;

- fraction of nitrogen in synthetic fertilizer volatilized as NH_3/NO_X; and
- the emission factor for nitrous oxide emissions synthetic fertilizer.

The estimation process involves the following three steps:

Step 1: Determine Nitrogen Content in Synthetic Fertilizer

Nitrogen content in synthetic fertilizer for 1995 through the present was obtained from the Fertilizer Institute. Data for 1994 and earlier was obtained from the Tennessee Valley Authority Fertilizer Research Center. (See Table 3-9).

Nitrogen values applied to this estimation methodology are taken as the average of the current reported year and the prior year, as shown in the formula below.

$$N_{SF} = \left(0.5 \times NC_{SF(YR)}\right) + \left(0.5 \times NC_{SF(YR+1)}\right) \times CF_{METRIC}$$

where,

N_{SF} = nitrogen content in synthetic fertilizer produced in given year (thousand metric tons)

$N_{SF(YR)}$ = nitrogen content in synthetic fertilizer reported in given year (thousand short tons)

YR = year in which nitrogen content was reported

CF_{METRIC} = factor for conversion of short tons to metric tons (0.9072 metric ton per short ton)

Step 2: Identify Fraction of Nitrogen Volatilized and Emission Factor for Synthetic Fertilizer

Values for the fraction of nitrogen volatilized as NH_3/NO_X and the emission factor for nitrous oxide emissions from synthetic fertilizers are both obtained from the *Revised 1996 IPCC Guidelines*.

Step 3: Calculate Nitrous Oxide Emissions for Synthetic Fertilizer

Total nitrous oxide emissions from synthetic fertilizers applied to agricultural soils are calculated based on the total nitrogen content in fertilizers utilized in a given year, the total nitrogen remaining after subtracting out the nitrogen volatilized as NH_3/NO_X, and the emission factor for fertilizer:

$$N_2O_{(F)SF} = N_{SF} \times \left(1 - Frac_{VOL-SF}\right) \times EF_{(F)} \times CF_{N2O-N}$$

where,

$N_2O_{(F)SF}$ = nitrous oxide emissions from synthetic fertilizer applied to agricultural lands in given year (thousand metric tons)

N_{SF} = nitrogen content in synthetic fertilizer produced in given year (thousand metric tons)

$Frac_{VOL\text{-}SF}$ = fraction of nitrogen volatilized as NH_3/NO_X for synthetic fertilizer (0.1 kg NH_3-N and NO_X-N per kg synthetic fertilizer)

$EF_{(F)}$ = emission factor for nitrous oxide emissions (0.0125 kg N_2O-N per kg N)

$CF_{N2O\text{-}N}$ = conversion factor mass N_2O per N ($^{44}/_{28}$ N_2O/N)

Data Sources

The calculation methodology for nitrous oxide emissions from agricultural fields, as well as the fraction of nitrogen volatilized and the emission factor for nitrous oxide emissions from synthetic fertilizer, were derived from the *Revised 1996 IPCC Guidelines*. Annual data on total U.S. synthetic fertilizer consumption were obtained from the Tennessee Valley Authority Fertilizer Research Center and The Fertilizer Institute. Information on nitrogen content of U.S. commercial fertilizer was obtained from *Commercial Fertilizers*, published by the Association of American Plant Food Control Officials.

Table 3-9. Data Sources for Nitrous Oxide Emissions from Synthetic Fertilizer

Data Utilized	Citation
Calculation methodology	Modified from Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.92, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Estimates of total U.S. synthetic fertilizer consumption, 1986-1991 and 1993-1994	J.T. Berry et al., *Commercial Fertilizers* (Muscle Shoals, AL: Tennessee Valley Authority, Fertilizer Research Center, Reports for 1986-1991 and 1993-1994.
Estimates of total U.S. synthetic fertilizer consumption, 1995-2004	Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, D.C., various years).
Total nitrogen content of U.S. commercial fertilizer consumption, 1995-2004	Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, D.C., various years).
Fraction of nitrogen volatilized as NH_3/NO_X for fertilizer	Intergovernmental Panel on Climate Change, Revised 1996 IPCC Guidelines, (Paris, France, 1997), Table 4-19, p.4.94, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factor for animal manure used as fertilizer	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-18, p. 4.89, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Estimation Methodology for N_2O from Crop Residues

As reported in the *Revised 1996 IPCC Guidelines*, there is limited understanding as to the total nitrous oxide emissions from crop residues, although a significant amount is known about the amount of nitrogen that is typically recycled back into agricultural soils. Nitrous oxide emissions are nonetheless derived based on the estimated amount of nitrogen re-entering the soil, using crop production data.

The following information is used to estimate nitrous oxide emissions from crop residues applied as soil fertilizer:

- nitrogen content in unburned residues of soybeans and pulses, and other crop types;
- total crop production by crop type;

- the fraction of residue for total crop product;
- the fraction of dry matter contained in crop residue;
- the fraction of nitrogen in crop residue;
- the fraction of crop residue burned; and
- an emission factor for nitrous oxide emissions.

The estimation methodology involves the following three steps.

Step 1: Determine Nitrogen Content in Unburned Crop Residue by Crop Type

Nitrous oxide emissions from crop residues applied to agricultural fields are calculated first by estimating nitrogen content for each group of crops based on the nitrogen content of dry matter residues that are not burned. The overall amount of crop residue is determined as a fraction of total crop product.

$$N_{UNBURNEDCR(T)} = Frac_{N(T)} \times Frac_{RES/CR(T)} \times Frac_{DRYMATTER(T)} \times \left(1 - Frac_{BURNED(T)}\right) \times 10^{-3}$$

where:

$N_{UNBURNEDCR(T)}$ = nitrogen content in unburned residues of crop type T (soybeans and pulses) (thousand metric tons)

$Frac_{N(T)}$ = fraction of nitrogen in crop residue of crop type T

$Frac_{RES/CR(T)}$ = fraction of residue for total crop product of crop type T

$Frac_{DRYMATTER(T)}$ = fraction of dry matter contained in crop residue of crop type T

$Frac_{BURNED(T)}$ = fraction of crop residue burned (0.03 kg crop burned per kg crop product) of crop type T

T = crop type

This formula differs slightly from the methodology prescribed in the *Revised 1996 IPCC Guidelines* because data are available in the United States on the fraction of crop residue for each crop type. The *IPCC Guidelines*, rather, require calculation based on the subtraction of the fraction of crop removed (i.e., at harvest) from the total crop. (See Table 3-10).

Table 3-10. Calculation Variables

Crop Type	Residue/Crop Product	Dry Matter Content	Nitrogen Content	Fraction Burned
Corn	1.0	0.9100	0.0058	0.03
Sorghum	1.4	0.9100	0.0108	0.03
Oat	1.3	0.9200	0.0070	0.03
Barley	1.2	0.9300	0.0077	0.03
Wheat	1.3	0.9300	0.0062	0.03
Rice	1.4	0.9100	0.0072	0.03
Rye	1.6	0.9000	0.0048	0.03
Soybean	2.1	0.8700	0.0230	0.03
Peanut	1.0	0.8600	0.0106	0.03
Bean	2.1	0.8535	0.0230	0.03
Pea	1.5	0.8700	0.0142	0.03
Potato	0.4	0.8670	0.0110	0.03
Sugarbeet	0.2	0.9000	0.0228	0.03
Sugarcane	0.8	0.6200	0.0040	0.03

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Step 2: Determine Total Nitrogen Content in Crop Residues by Crop Type

As recommended by the *Revised 1996 IPCC Guidelines*, crops are separated into two groups representing soybeans and pulses (nitrogen-fixing crops) and all other crops. The total nitrogen content for each of these groups is calculated by summing the nitrogen content calculated for each crop type, converted to thousand metric tons.

$$N_{(RES)NF} = \mathrm{CP_T} \times N_{UNBURNEDCR(T)} \times 10^{-3}$$

$$N_{(RES)OTH} = \mathrm{CP_T} \times N_{UNBURNEDCR(T)} \times 10^{-3}$$

where,

$N_{(RES)NF}$ = nitrogen content in unburned residues of nitrogen-fixing crops (soybeans and pulses) (thousand metric tons)

$N_{(RES)OTH}$ = nitrogen content in unburned residues of other crop types (thousand metric tons)

$\mathrm{CP_T}$ = total crop production by type (metric tons)

$N_{UNBURNEDCR(T)}$ = nitrogen content in unburned residues of crop type T (soybeans and pulses) (thousand metric tons)

T = crop type

This step provides a more thorough and accurate calculation than that recommended by the *Revised 1996 IPCC Guidelines*. EIA performs calculations on the nitrogen content of crop residue for each crop type, rather than for entire classes of crops (i.e., nitrogen-fixing vs. other crop types).

Step 3: Calculate Nitrous Oxide Emissions Based on Nitrogen Content

Using the following formula, total nitrous oxide emissions are estimated based on the combined nitrogen content of soybeans/pulses and other crop types for all crop production in the United States, multiplied by the emission factor for nitrous oxide emissions from agricultural soils:

$$N_2O_{(F)CR} = \left(N_{(RES)NF} + N_{(RES)OTH}\right) \times EF_{(F)} \times CF_{N2O-N}$$

where,

$N_2O_{(F)CR}$ = nitrous oxide emissions from crop residues used as fertilizer (thousand metric tons)

$N_{(RES)NF}$ = nitrogen content in unburned residues of nitrogen-fixing crops (soybeans and pulses) (thousand metric tons)

$N_{(RES)OTH}$ = nitrogen content in unburned residues of other crop types (thousand metric tons)

$EF_{(F)}$ = emission factor for nitrous oxide emissions (0.0125 kg N_2O-N per kg N)

CF_{N2O-N} = conversion factor mass N_2O per N ($^{44}/_{28}$ N_2O/N)

Data Sources

U.S. crop production data are obtained from the USDA NASS). Calculation variables, including residue per crop product, dry matter content, nitrogen content, and fraction burned for various crop types were obtained from U.S. EPA's, *Inventory of U.S. Greenhouse Gas Emissions and Sinks (various years).* (See Table 3-11).

Table 3-11. Data Sources for Nitrous Oxide Emissions from Crop Residues

Data Utilized	Citation
Calculation methodology	Based on Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, "Methodology for Estimating Direct N_2O Emissions from Agricultural Fields," (Paris, France, 1997), Equation 1, p. 4.92, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Residue/crop product; dry matter content; nitrogen content; and fraction burned	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html.
Crop production	U.S. Department of Agriculture, *Annual Crop Production Summary*, Table "Crop Summary Yield and Production," (Washington, D.C., various years), http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban/. For rice data by state: U.S. Department of Agriculture, Statistics Database, http://www.nass.usda.gov.
Emission factor for nitrous oxide emissions	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), p. 4.89, Table 4.18, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Estimation Methodology for N_2O from Mineralization of Cultivated High Organic Content Soils (Histosols)

Nitrous oxide emissions from soil mineralization are calculated based on the land area of U.S. histosols located in temperate and subtropical zones. Histosols are defined as soils with high organic nitrogen content, typically with over 20 to 30 percent organic matter by weight.[88] The rate of mineralization is dependent on the nitrogen content in the histosol, soil management practices, and climate zone.

The information required for estimating nitrous oxide emissions from the soil mineralization of histosols includes:

- histosol land area for temperate and subtropical zones, and
- emission factors for nitrous oxide emissions from histosols in temperate and subtropical zones, respectively.

Nitrous oxide emissions from soil mineralization of histosols are estimated through the following two steps:

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[88] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2001* (April 2003), p. N-1, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Step 1: Identify Histosol Area for Temperate and Sub-Tropical Climate Zones

Total land area data for histosols in temperate and subtropical climate zones were obtained from U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks.*

Step 2: Calculate Nitrous Oxide Emissions Based on Histosol Area

Nitrous oxide emissions from histosols are estimated by multiplying the land area value of histosols for each zone by an emission factor, as applicable, as provided in the formula below. EIA uses the updated default emission value of 8 kg N_2O-N per hectare per year for temperate soils and 16 kg N_2O-N per hectare per year for temperate soils, as published in the IPCC *Good Practice Guidance*.

$$N_2O_{(F)SM} = \left[\left(\mathrm{H}_{\mathrm{TEMP}} \times E\mathrm{F}_{\mathrm{H\text{-}TEMP}}\right) + \left(\mathrm{H}_{\mathrm{SUBTROP}} \times E\mathrm{F}_{\mathrm{H\text{-}SUBTROP}}\right)\right] \times \mathrm{CF}_{\mathrm{N2O\text{-}N}} \times 10^{-3}$$

where,

$N_2O_{(F)SM}$ = direct N_2O emissions from soil mineralization (thousand metric tons)

H_{TEMP} = U.S. histosol area in temperate zones

$H_{SUBTROP}$ = U.S. histosol area in subtropical zones

$EF_{H\text{-}TEMP}$ = emission factor for Histosol emissions of nitrogen (N_2O-N) per hectare in temperate zones (8 kg N_2O-N per hectare per year)

$EF_{H\text{-}SUBTROP}$ = emission factor for Histosol emissions of nitrogen (N_2O-N) per hectare in subtropical zones (16 kg N_2O-N per hectare per year)

$CF_{N2O\text{-}N}$ = conversion factor mass N_2O-N per N ($^{44}/_{28}$ N_2O-N/N)

Data Sources

The calculation methodology and the emission factor for nitrous oxide emissions from cultivated high organic content soils are adapted from the *Revised 1996 IPCC Guidelines.* Total land area data for histosols in temperate and subtropical climate zones were obtained from U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. (See Table 3-12).

Table 3-12. Data Sources for Nitrous Oxide Emissions from Mineralization of Cultivated High Organic Content Soils (Histosols)

Data Utilized	Citation
Calculation methodology	Adapted from Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, "Methodology for Estimating Direction N_2O Emissions from Agricultural Fields," Equation 1, (Paris, France, 1997), p. 4.92, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factors for N_2O emissions from soil mineralization	Intergovernmental Panel on Climate Change, *Good Practice Guidance*, 4.60, http://www.ipcc-nggip.iges.or.jp/public/gp/english/.
Total U.S. histosol area	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks (various years). http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html

Estimation Methodology for Emissions from Nitrogen-Fixing Crops

As documented by the IPCC, atmospheric nitrogen that is fixed by nitrogen-fixing legumes can be nitrified and denitrified in much the same manner as nitrogen from synthetic fertilizer, and thus lead to nitrous oxide emissions.[89]

Information required for the estimation of nitrous oxide emissions from nitrogen-fixing crops includes the following:

- total crop production of nitrogen-fixing crops;
- the ratio of crop residue to crop production;
- the fraction of crop mass as dry matter;
- fraction of nitrogen content for nitrogen-fixing crops (assumed to be 3 percent, using the IPCC default value); and
- the emission factor for nitrous oxide emissions.

EIA estimates nitrous oxide emissions from nitrogen-fixing crops—including alfalfa, beans, lentils, peanuts, and soybeans—based on annual production statistics from the U.S. Department of Agriculture's *Crop Production* annual reports using the five steps listed here and detailed below. Crop product values for these crops are converted to total crop dry biomass (crop product plus crop residue, expressed in mass units of dry matter) by applying residue-to-crop ratios and dry matter fractions. The total crop values in dry biomass units are then used to calculate the crop nitrogen content that is released in the form of nitrous oxide. Finally, nitrous oxide emission

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[89] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), pp.4.89-4.90, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

factors are applied to calculate nitrous oxide emissions from the biological fixation of nitrogen in crops.[90]

Step 1: Calculate Quantity of Nitrogen-Fixing Crop Residue Biomass Based on Total Crop Production

Total biomass of residue of nitrogen-fixing crops is calculated based on total crop production for each crop type multiplied by the ratio of crop residue to crop production (see Table 3-13). EIA converts crop production data to metric tons from units of 1,000 Cwt (a Cwt is how data are generally published in USDA's *Crop Production*, and is equal to 100 pounds). The following equation demonstrates the estimation of total biomass:

$$Biomass_{(NF)RES(\mathrm{T})} = \mathrm{CP}_{\mathrm{NF(T)}} \times \mathrm{Frac}_{\mathrm{RES\text{-}CP(T)}}$$

where,

$\mathrm{Biomass}_{\mathrm{(NF)RES(T)}}$ = crop residue biomass of nitrogen-fixing crops (metric tons)

$\mathrm{CP}_{\mathrm{NF(T)}}$ = total crop production of nitrogen-fixing crop by type (metric tons)

$\mathrm{Frac}_{\mathrm{RES\text{-}CP(T)}}$ = ratio of crop residue to crop production by crop type

T = crop type

Table 3-13. Ratio of Crop Residue Mass to Crop Production Mass

Crop Type	Ratio
Soybeans	2.1
Beans	2.1
Peanuts	1.0
Peas	1.5
Alfalfa	2.1
Lentils	2.1

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, Table 4-17, (Paris, France, 1997), p. 4.85, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Note: Factors for alfalfa and lentils data are assumed to be the same as for soybeans and beans.

Step 2: Calculate Combined Biomass from Nitrogen-Fixing Crop Production and Crop Residue

Total crop biomass—combining crop production and crop residue values—is calculated by adding the value of crop production (mass) and crop residue (mass) for each crop type, as follows:

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[90] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), pp. 4.85-4.94, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

$$Biomass_{(NF)CROP(\mathrm{T})} = \mathrm{CP}_{\mathrm{NF(T)}} + Biomass_{(NF)RES(\mathrm{T})}$$

where,

$\mathrm{Biomass}_{\mathrm{(NF)CROP(T)}}$ = total crop biomass (metric tons)

$\mathrm{CP}_{\mathrm{NF(T)}}$ = total crop production of nitrogen-fixing crop by type (metric tons)

$\mathrm{Biomass}_{\mathrm{(NF)RES(T)}}$ = crop residue biomass of nitrogen-fixing crops (metric tons)

T = crop type

Step 3: Calculate Total Nitrogen-Fixing Crop Biomass as Dry Matter

Total crop biomass can then be applied to calculate total dry matter of nitrogen-fixing crop biomass that may generate nitrous oxide. Total dry matter is calculated as a percentage (fraction) of total crop biomass for each crop type (Table 3-14), provided as follows:

$$Biomass_{(NF)DRY(\mathrm{T})} = Biomass_{(NF)CROP(\mathrm{T})} \times \mathrm{Frac}_{\mathrm{DRYMATTER(T)}}$$

where,

$\mathrm{Biomass}_{\mathrm{(NF)DRY(T)}}$ = total crop biomass in dry matter units (metric tons)

$\mathrm{Biomass}_{\mathrm{(NF)CROP(T)}}$ = total crop biomass, crop production plus crop residue (metric tons)

$\mathrm{Frac}_{\mathrm{DRYMATTER(T)}}$ = fraction of crop mass as dry matter

Table 3-14. Fraction of Dry Matter by Crop Type

Crop Type	Fraction Dry Matter
Soybeans	0.86700
Beans	0.85350
Peanuts	0.90050
Peas	0.90200
Alfalfa	0.80000
Lentils*	0.86025

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4.17, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

* Value represents average of soybean and bean.

Step 4: Calculate and Sum Nitrogen Content of Total Nitrogen-Fixing Crop Biomass

Total nitrogen contained in nitrogen-fixing crop biomass can then be calculated and summed for each crop type, based on the fraction of nitrogen content in the dry matter of nitrogen-fixing crops (using the IPCC default value of 3 percent), as follows:

$$N_{NF} = Biomass_{(NF)DRY(\mathrm{T})} \times \mathrm{Frac}_{\mathrm{N(T)}}$$

where,

N_{NF} = nitrogen from nitrogen-fixing crops (soybeans and pulses) (thousand metric tons)

$Biomass_{(NF)DRY(T)}$ = total crop biomass in dry matter units (metric tons)

$Frac_{N(T)}$ = fraction of nitrogen content for nitrogen-fixing crops (0.03 kg N per kg dry matter biomass)

Step 5: Estimate Total Nitrous Oxide Emissions from Nitrogen-Fixing Crops

Finally, total direct nitrous oxide emissions can be calculated based on total nitrogen from all nitrogen-fixing crops, multiplied by the default emission factor for nitrous oxide emissions and a conversion factor, as follows:

$$N_2O_{(F)NF} = \mathrm{N}_{\mathrm{NF}} \times E\mathrm{F}_{\mathrm{(F)}} \times C\mathrm{F}_{\mathrm{N2O\text{-}N}}$$

where,

$N_2O_{(F)NF}$ = direct N_2O emissions from nitrogen-fixing crops (thousand metric tons)

N_{NF} = nitrogen from all nitrogen-fixing crops (thousand metric tons)

$EF_{(F)}$ = emission factor for nitrous oxide emissions (0.0125 kg N_2O-N per kg N)

CF_{N2O-N} = conversion factor mass N_2O-N per N ($^{44}/_{28}$ N_2O-N/N)

Data Sources

The calculation methodology for nitrous oxide emissions from nitrogen-fixing crops is adapted from the *Revised 1996 IPCC Guidelines.* The ratio of crop residue to crop production, fraction of nitrogen content for nitrogen-fixing crops, and the emission factor for N_2O from nitrogen fixing crops are also from the *Revised 1996 IPCC Guidelines*. Total nitrogen-fixing crop production is from USDA, and the fraction of nitrogen fixing crop mass as dry matter has historically been obtained from U.S. EPA. (See Table 3-15).

Table 3-15. Data Sources for Direct Nitrous Oxide Emissions from Nitrogen-Fixing Crops

Data Utilized	Citation
Calculation methodology	Adapted from Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, "Methodology for Estimating Direction N_2O Emissions from Agricultural Fields," Equation 1, (Paris, France, 1997), p. 4.92, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Total crop production of nitrogen-fixing crop by type	U.S. Department of Agriculture, National Agricultural Statistics Service, "Crop Production" Summary (various years), reports are listed by commodity at http://www.usda.gov/nass/pubs/estindx.htm.
Ratio of crop residue to crop production by crop type	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, Table 4-17, p. 4.85, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Fraction of crop mass as dry matter	U.S. Environmental Protection Agency, *Inventory of Greenhouse Gas Emissions and Sinks*, (various years); http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Fraction of nitrogen content for nitrogen-fixing crops	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, Table 4-19, (Paris, France, 1997), p. 4.94, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factor for nitrous oxide emissions	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, Table 4-18, (Paris, France, 1997), p. 4.89, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Estimation Methodology for N_2O Emissions from Fertilizer and Manure Runoff

In addition to estimating direct nitrous oxide emissions from synthetic fertilizer and animal manure, EIA estimates indirect emissions resulting from fertilizer and manure runoff. It is estimated that between 10 and 80 percent of all agricultural fertilizer and manure is lost through leaching and runoff into groundwater, wetlands, rivers, and coastal areas.[91]

Information required for the estimation of indirect nitrous oxide emissions from fertilizer and manure runoff includes:

- animal population by animal type;
- animal population by animal type in the following states: Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas;
- the fraction of waste handled in various management systems by animal type; and
- the fraction of nitrogen excreted per animal per year.

The estimation methodology for nitrous oxide from fertilizer and manure runoff is calculated by determining nitrogen content of manure produced (for certain select states for which data are available, and for all other states combined), and the nitrogen content of synthetic fertilizer. Nitrogen content data are then converted to nitrous oxide emissions based on the fraction leached and an emission factor.

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[91] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.106, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

The estimation method for nitrous oxide emissions from fertilizer and manure runoff has been updated in the most recent inventory and thus shows a slight change over estimates provided in previous years. The estimation process involves the following four steps.

Step 1: Determine Nitrogen Content of Manure Produced, Nationally and by State (as Applicable)

EIA calculates nitrogen content of manure fertilizer based on specific manure utilization data for the states of Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas, and national-level data for all other states. The methodology begins by calculating the amount of manure utilized on a national basis ($N_{AM(NATL)}$), minus that used in those specific states, using the following equation:

$$N_{AM(NATL)} = \left[P_T - \sum\left(\mathrm{P}_{\mathrm{T(STATE)}}\right)\right] \times \mathrm{Frac}_{\mathrm{SPREAD}} \times \mathrm{Frac}_{\mathrm{N\text{-}EXCR}} \times 10^{-3}$$

where,

$N_{AM(NATL)}$ = nitrogen content in animal manure produced and utilized nationally (metric tons)

P_T = animal population by animal type

$P_{T(STATE)}$ = animal population by animal type in the following states: Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas

Frac_{SPREAD} = fraction of waste handled in various management systems by animal type

$\mathrm{Frac}_{N\text{-}EXCR}$ = fraction of nitrogen excreted per animal per year (70 kilograms per head of dairy cattle per year; 100 kilograms per head of non-dairy cattle per year)

T = animal type

EIA conducts a separate calculation to determine the amount of manure utilized by state for Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas, as provided in the calculation for $N_{AM(STATE)}$, below:

$$N_{AM(STATE)} = P_{T(STATE)} \times \mathrm{Frac}_{\mathrm{SPREAD}} \times \mathrm{Frac}_{\mathrm{N\text{-}EXCR}} \times 10^{-3}$$

where,

$N_{AM(STATE)}$ = nitrogen content in animal manure produced and utilized in Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas (metric tons)

$P_{T(STATE)}$ = animal population by animal type in the following states: Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas

Frac_{SPREAD} = fraction of waste handled in various management systems by animal type

$Frac_{N\text{-}EXCR}$ = fraction of nitrogen excreted per animal per year (70 kilograms per head of dairy cattle per year; 100 kilograms per head of non-dairy cattle per year)

T = animal type

Step 2: Determine Nitrogen Content of Manure Fertilizer

Next, total nitrogen content for manure fertilizer is calculated as the sum of state-specific nitrogen content and all other national-level nitrogen content of animal manure, using the following equation:

$$N_{AM} = N_{AM\,(NATL)} + N_{AM\,(STATE)}$$

where,

N_{AM} = nitrogen content in animal manure produced in given year (metric tons)

$N_{AM(NATL)}$ = nitrogen content in animal manure produced nationally minus manure produced and utilized in Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas (metric tons)

$N_{AM(STATE)}$ = nitrogen content in animal manure produced and utilized in Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas (metric tons)

Step 3: Determine Nitrogen Content in Synthetic Fertilizer

Nitrogen content in synthetic fertilizer for 1995 through the present was obtained from the Fertilizer Institute. Data for 1994 and earlier was obtained form the Tennessee Valley Authority's Fertilizer Research Center. Nitrogen values applied to this estimation methodology are taken as the average of the current reported year and the prior year, as shown in the equation below.[92]

$$N_{SF} = \left[\left(0.5 \times N_{SF\,(YR)}\right) + \left(0.5 \times N_{SF\,(YR+1)}\right)\right] \times CF_{METRIC}$$

where,

N_{SF} = nitrogen content in synthetic fertilizer produced in given year (thousand metric tons)

$N_{SF(YR)}$ = nitrogen content in synthetic fertilizer reported in given year (thousand short tons)

YR = year in which nitrogen content was reported

CF_{METRIC} = factor for conversion of short tons to metric tons (0.9072 metric ton per short ton)

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[92] Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, D.C., various years).

Step 4: Estimate Indirect Nitrous Oxide Emissions from Synthetic Fertilizer and Animal Manure Runoff

Finally, nitrous oxide emissions for fertilizer and manure runoff is calculated by adding the nitrogen content of synthetic fertilizer and of animal manure, and multiplying the product by the percentage of fertilizer and manure leached (assumed to be 30 percent) and the share of indirect emissions from leached fertilizer and manure.

$$N_2O_{(SF-AM)RUNOFF} = \left(\mathrm{N}_{\mathrm{SF}} + \mathrm{N}_{\mathrm{AM}}\right) \times \mathrm{Frac}_{\mathrm{LEACH}} \times \mathrm{EF}_{\text{SF-AM}} \times \mathrm{CF}_{\text{N2O-N}}$$

where,

$N_2O_{(SF-AM)RUNOFF}$ = indirect N_2O emissions from fertilizer and manure runoff (thousand metric tons)

N_{SF} = nitrogen from synthetic fertilizer applied per year (thousand metric tons)

N_{AM} = nitrogen from animal manure used as fertilizer per year (metric tons)

$Frac_{LEACH}$ = fraction of fertilizer and manure leached (0.3000 kg leached per kg applied to soil)

EF_{SF-AM} = emission factor for indirect emissions from leached fertilizer and manure (0.0250 N_2O-N/ N from runoff)

CF_{N2O-N} = conversion factor mass N_2O-N per N ($^{44}/_{28}$ N_2O-N/N)

Data Sources

Cattle population data used in estimation of nitrous oxide emissions from fertilizer and manure runoff is taken from the USDA NASS. EIA uses the value of the fraction of waste handled in waste management systems as published in L.M. Safley (1992). Nitrogen content in synthetic fertilizer is taken from the Association of American Plant Food Control Officials and the Tennessee Valley Authority. The fraction of nitrogen excreted per animal, fraction of fertilizer and manure leached, and emission factor for atmospheric deposition of nitrous oxide are all taken from the *Revised 1996 IPCC Guidelines.* (See Table 3-16).

Table 3-16. Data Sources for Nitrous Oxide Emissions from Fertilizer and Manure Runoff

Data Utilized	Citation
Calculation Methodology	Adapted from Intergovernmental Panel on Climate Change, *Revised 1996 IPPC Guidelines*, (Paris, France, 1997), pp.4.106-4.107, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Cattle population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Cattle," January and July, Agricultural Statistics Board, (Washington, D.C., various years), http://www.nass.usda.gov.
Fraction of waste handled in various management systems by animal type	L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions from Livestock and Poultry Manure,* (Washington, D.C., February 1992), p. 18.
Fraction of nitrogen excreted per animal per year	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, Table 4-20, (Paris, France, 1997), p.4.99, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Nitrogen content in synthetic fertilizer reported in given year	Association of American Plant Food Control Officials, Commercial Fertilizers (Washington, D.C., various years); Tennessee Valley Authority (various years).
Fraction of fertilizer and manure leached	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, Table 4-24, (Paris, France, 1997), p.4.106, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factor for indirect emissions from leached fertilizer and manure	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.105, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Estimation Methodology for N_2O from Atmospheric Deposition (from Soils and Soil Runoff)

Atmospheric deposition of both naturally-occurring and anthropogenic nitrogen oxides (NO_X) and ammonia (NH_3) can result in the generation of nitrous oxide emissions. Often, anthropogenic causes of these deposits can be considerable. For the purposes of this inventory, and as recommended under the *Revised 1996 IPCC Guidelines*, nitrous oxide emissions from atmospheric deposition are estimated based only on the application of fertilizers to agricultural soil. In releasing nitrogen oxides and ammonia into the atmosphere that are re-deposited on soils and released into soil runoff, these fertilizers can, in turn, become significant sources of additional nitrous oxide emissions.

Information required for this estimation includes:

- animal population by animal type;
- the fraction of waste handled in various management systems by animal type;
- the fraction of nitrogen excreted per animal per year;
- the nitrogen content in synthetic fertilizer reported in a given year;
- the fraction of fertilizer and manure volatilized in agricultural soils;
- the fraction of fertilizer and manure volatilized in soil runoff;

- the fraction of fertilizer and manure leached into runoff; and
- the emission factor for nitrous oxide emissions from atmospheric deposition.

The estimation of nitrous oxide emissions from the atmospheric deposition of nitrogen oxides and ammonia is provided in six steps (see below), starting with estimates of total nitrogen content of animal manure fertilizer and synthetic fertilizer consumed (see Steps 1 through 3, which are identical to those under the estimation methodology for nitrous oxide emissions from fertilizer and manure runoff). Using these data, nitrous oxide atmospheric deposition emissions are calculated separately for soils and soil runoff. In the case of soils, the sum of total nitrogen content in manure and synthetic fertilizer is converted to total nitrous oxide emissions based on the fraction of nitrogen volatilized, the emission factor for emissions from atmospheric deposition, and other appropriate conversion factors. In the case of soil runoff, the sum of total nitrogen content in manure and synthetic fertilizer is converted to total nitrous oxide emissions based on the fraction of nitrogen volatilized, the fraction of nitrogen that leaches, the emission factor for emissions from atmospheric deposition, and other appropriate conversion factors.

The estimation method for nitrous oxide emissions from atmospheric deposition has been updated in the most recent inventory and thus shows a slight change over estimates provided in previous years. The estimation process involves the following six steps:

Step 1: Determine Nitrogen Content of Manure Produced Nationally and by State (as Applicable)

EIA calculates nitrogen content of manure fertilizer based on specific manure utilization data for the states of Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas, and national-level data for all other states. The methodology begins by calculating the amount of manure utilized on a national basis ($N_{AM(NATL)}$), minus that used in those specific states, using the following equation:

$$N_{AM(NATL)} = \left[P_T - \sum \left(\mathrm{P}_{\mathrm{T(STATE)}}\right)\right] \times \mathrm{Frac}_{\mathrm{SPREAD}} \times \mathrm{Frac}_{\mathrm{N\text{-}EXCR}} \times 10^{-3}$$

where,

$N_{AM(NATL)}$ = nitrogen content in animal manure produced nationally minus manure produced and utilized in Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas (metric tons)

P_T = animal population by animal type

$P_{T(STATE)}$ = animal population by animal type in the following states: Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas

$Frac_{SPREAD}$ = fraction of waste handled in various management systems by animal type

$Frac_{N-EXCR}$ = fraction of nitrogen excreted per animal per year (70 kilograms per head of dairy cattle per year; 100 kilograms per head of non-dairy cattle per year)

T = animal type

EIA conducts a separate calculation to determine the amount of manure utilized by state for Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas, as provided in the calculation for $N_{AM(STATE)}$, below.

$$N_{AM\,(STATE)} = P_{T\,(STATE)} \times \mathrm{Frac}_{\mathrm{SPREAD}} \times \mathrm{Frac}_{\mathrm{N\text{-}EXCR}} \times 10^{-3}$$

where,

$N_{AM(STATE)}$ = nitrogen content in animal manure produced and utilized in Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas (metric tons)

$P_{T(STATE)}$ = animal population by animal type in the following states: Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas

$\mathrm{Frac}_{\mathrm{SPREAD}}$ = fraction of waste handled in various management systems by animal type

$\mathrm{Frac}_{\mathrm{N\text{-}EXCR}}$ = fraction of nitrogen excreted per animal per year (70 kilograms per head of dairy cattle per year; 100 kilograms per head of non-dairy cattle per year)

T = animal type

Step 2: Determine Nitrogen Content of Manure Fertilizer

Next, total nitrogen content for manure fertilizer is calculated as the sum of state-specific nitrogen content and all other national-level nitrogen content of animal manure, using the following equation:

$$N_{AM} = N_{AM\,(NATL)} + N_{AM\,(STATE)}$$

where,

N_{AM} = nitrogen content in animal manure produced in given year (metric tons)

$N_{AM(NATL)}$ = nitrogen content in animal manure produced nationally minus manure produced and utilized in Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas (metric tons)

$N_{AM(STATE)}$ = nitrogen content in animal manure produced and utilized in Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas (metric tons)

Step 3: Determine Nitrogen Content in Synthetic Fertilizer

Nitrogen content in synthetic fertilizer for 1995 through the present was obtained from the Fertilizer Institute. Data for 1994 and earlier was obtained form the Tennessee Valley Authority

Fertilizer Research Center. Nitrogen values applied to this estimation methodology are taken as the average of the current reported year and the prior year, as shown in the equation below.[93]

$$N_{SF} = \left[\left(0.5 \times NC_{SF(YR)}\right) + \left(0.5 \times NC_{SF(YR+1)}\right)\right] \times CF_{METRIC}$$

where,

N_{SF} = nitrogen content in synthetic fertilizer produced in given year (thousand metric tons)

$N_{SF(YR)}$ = nitrogen content in synthetic fertilizer reported in given year (thousand short tons)

YR = year in which nitrogen content was reported

CF_{METRIC} = factor for conversion of short tons to metric tons (0.9072 metric ton per short ton)

Step 4: Estimate Total Nitrous Oxide Emissions from Soils Based on Nitrogen Content of Animal Manure and Synthetic Fertilizer Utilized

$$N_2O_{(AD)SOILS} = \left(N_{AM} + N_{SF}\right) \times Frac_{VOL} \times EF_{AD} \times CF_{N2O-N}$$

where,

$N_2O_{(AD)SOILS}$ = total nitrous oxide emissions from atmospheric deposition from soils (thousand metric tons)

N_{AM} = nitrogen content in animal manure produced in given year (thousand metric tons)

N_{SF} = nitrogen content in synthetic fertilizer produced in given year (thousand metric tons)

$Frac_{VOL-RUNOFF}$ = fraction of nitrogen volatilized as NH_3 or NO_X (0.10 kg NH_3/NO_X-N per kg N)

$EF_{(AD)SOILS}$ = nitrous oxide emission factor for atmospheric deposition to soils (0.01 kg N_2O-N per kg soil N)

CF_{N2O-N} = conversion factor mass N_2O-N per N ($^{44}/_{28}$ N_2O-N/N)

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[93] Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, D.C., various years), http://www.aapfco.org/aapfcopubs.html.

Step 5: Estimate Total Nitrous Oxide Emissions from Soil Runoff Based on Nitrogen Content of Animal Manure and Synthetic Fertilizer Utilized

Total N_2O emissions are estimated based on the fraction of nitrogen volatilized as NH_3 or NO_X from animal manure and synthetic fertilizer separately, and then determined based on the fraction of fertilizer and manure leached, as follows.

$$N_2O_{(AD)RUNOFF} = \left[\left(N_{AM} \times Frac_{VOL-AM}\right) + \left(N_{SF} \times Frac_{VOL-SF}\right)\right] \times Frac_{LEACH} \times EF_{AD} \times CF_{N2O-N}$$

where,

$N_2O_{(AD)RUNOFF}$ = total nitrous oxide emissions from atmospheric deposition from soil runoff (thousand metric tons)

N_{AM} = nitrogen content in animal manure produced in given year (thousand metric tons)

N_{SF} = nitrogen content in synthetic fertilizer produced in given year (thousand metric tons)

$Frac_{VOL-AM}$ = fraction of nitrogen volatilized as NH_3 or NO_X from animal manure (0.20 kg NH_3/NO_X-N per kg N)

$Frac_{VOL-SF}$ = fraction of nitrogen volatilized as NH_3 or NO_X from synthetic fertilizer (0.10 kg NH_3/NO_X-N per kg N)

$Frac_{LEACH}$ = fraction of fertilizer and manure leached (0.30 kg leached per kg applied to soil)

$EF_{(AD)RUNOFF}$ = nitrous oxide emission factor for atmospheric deposition to soil runoff (0.01 kg N_2O-N per kg runoff N)

CF_{N2O-N} = conversion factor mass N_2O-N per N ($^{44}/_{28}$ N_2O-N/N)

Step 6: Combine Atmospheric Deposition Emissions from Soils and Runoff for Total Nitrous Oxide Emissions

Finally, total nitrous oxide emissions from atmospheric deposition to soils and runoff result from the sum of emissions from soils and emissions from soil runoff, as follows:

$$N_2O_{(F)AD} = N_2O_{(AD)SOILS} + N_2O_{(AD)RUNOFF}$$

where,

$N_2O_{(F)AD}$ = total nitrous oxide emissions from atmospheric deposition (thousand metric tons)

$N_2O_{(AD)SOILS}$ = total nitrous oxide emissions from atmospheric deposition from soils (thousand metric tons)

$N_2O_{(AD)RUNOFF}$ = total nitrous oxide emissions from atmospheric deposition from soil runoff (thousand metric tons)

Data Sources

Animal population data used in estimation of nitrous oxide emissions from atmospheric deposition is taken from the USDA NASS. EIA uses the value of the fraction of waste handled in waste management systems as published in L.M. Safley (1992). Nitrogen content in synthetic fertilizer is taken from the Association of American Plant Food Control Officials and the Tennessee Valley Authority. The fraction of nitrogen excreted per animal, fraction of fertilizer and manure leaked, and emission factor for atmospheric deposition of nitrous oxide are all taken from the *Revised 1996 IPCC Guidelines.*(See Table 3-17).

Table 3-17. Data Sources for Nitrous Oxide Emissions from Atmospheric Deposition

Data Utilized	Citation
Calculation Methodology	Adapted from Intergovernmental Panel on Climate Change, *Revised 1996 IPPC Guidelines*, (Paris, France, 1997), pp.4.105-4.106, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Cattle population data	U.S. Department of Agriculture, National Agricultural Statistics Service, “Cattle,” January and July, Agricultural Statistics Board, (Washington, D.C., various years), http://www.nass.usda.gov.
Swine population data	U.S. Department of Agriculture, National Agricultural Statistics Service, “Monthly Hogs and Pigs,” Agricultural Statistics Board, (Washington, D.C., various years), http://www.nass.usda.gov.
Poultry population data	U.S. Department of Agriculture, National Agricultural Statistics Service, “Chickens and Eggs,” Agricultural Statistics Board, Poultry 1-1, (Washington, D.C., various years), http://www.nass.usda.gov.
Population data for goats and horses	U.S. Department of Commerce, Census of Agriculture, *United States Summary and State Data, Vol. 1*, “Geographic Area Series,” Part 51 (Washington, D.C., 1987, 1992, 1997, and 2002).
Fraction of waste handled in various management systems by animal type	L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions from Livestock and Poultry Manure* (Washington, D.C.: U.S. Environmental Protection Agency, February 1992), p. 18.
Fraction of nitrogen excreted per animal per year	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-20, p.4.99, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Nitrogen content in synthetic fertilizer reported in given year	Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, D.C., various years); Tennessee Valley Authority (various years).
Fraction of fertilizer and manure leached	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-24, p.4.106, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factor for atmospheric deposition	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-23, p. 4.105, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

3.2.2 Nitrous Oxide Emissions from Solid Waste of Domesticated Animals

Emissions Sources

As noted above, emissions from animal wastes can be significant.[94] This section addresses nitrous oxide emissions occurring as a result of storing, handling, or otherwise managing manure. Emissions associated with the application of manure to agricultural soils are treated under the section on the Estimation Methodology for N_2O from Animal Manure Used as Fertilizer under *Nitrogen Fertilization of Agricultural Soils*, above.

Nitrous oxide forms as a result of the natural nitrification and denitrification of organic nitrogen contained during the storage and handling of livestock wastes. Typically, very low levels of nitrous oxide are emitted from animal wastes.[95] The volume of nitrous oxide emissions is a function of the amount of manure produced, the nitrogen content of the manure and urine, the type of bacteria involved in the process, and the kind of manure management system being used—particularly with respect to the amount of oxygen and liquids in the system.[96] For example, waste managed by a solid storage or pasture range method may emit 20 times the nitrous oxide per unit of nitrogen content that is emitted from anaerobic lagoon or other liquid systems.[97] Nitrous oxide emissions will be emitted where manure is first processed aerobically by which ammonia or organic nitrogen is converted to nitrates and nitrites, followed by anaerobic conditions, in which the nitrates and nitrites are converted through denitrification to nitrous oxide (N_2O) and nitric oxide (NO) and produce nitrogen gas (N_2).[98]

Estimation Methodology

Nitrous oxide emissions from the solid waste of domesticated animals are calculated for each major animal group and summed to derive the total emissions from all animal waste. Specific emissions rates are based on the amount of waste excreted for each animal group, and the emissions rates for each type of animal waste management system. The methodology used by EIA is consistent with that presented in the *Revised 1996 IPCC Guidelines* and the IPCC's *Good Practice Guidance*. For each animal group, nitrous oxide emissions are estimated using the following information:

- Animal population data for each animal type;

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[94] Intergovernmental Panel on Climate Change, *Revised IPCC 1996 Guidelines*, p. 4.94.

[95] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000* (Washington, D.C., 2002), p. 5-5, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[96] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997) p. 4.95, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.; see also U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000* (Washington, D.C., 2002), p. 5-5, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[97] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.95, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[98] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001* (Washington, D.C., 2003), p. 5-6, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

- Average annual excretion of nitrogen per head for each animal type;
- The fraction of animal excretion managed in each type of applicable animal waste management system; and
- Emission factors for nitrous oxide emissions for the applicable animal waste management system.

Using this information, the *Revised 1996 IPCC Guidelines* provide a formula for calculating nitrous oxide emissions from the solid waste of domesticated animals[99] (see Step 4). The methodology for determining nitrous oxide emissions from animal waste management systems involves the following four steps:

Step 1: Estimation of Animal Populations

Animal populations are derived from sources published by the U.S. Department of Agriculture, and are collected for the following animal groups: (1) beef cattle, including feedlot beef cattle, calves, heifers, steers, cows, and bulls; (2) dairy cattle, including heifers and cows; (3) swine, including market swine and breeding swine; (4) poultry, including layers and broilers; and (5) other animals, including sheep, goats, and horses.

The U.S. cattle population is separated into dairy and beef cattle. Dairy cattle are characterized by two groups: heifers (defined as female cattle that have never given birth) and cows (females that have borne a calf). Beef cattle are divided into six subclasses: calves, feedlot beef cattle (which include heifers and steers), heifers (not on feed), steers (not on feed), cows, and bulls. Cattle populations are estimated based on data obtained from the USDA NASS. The cattle population values used to estimate annual emissions are the average of the NASS January and July populations for each animal category.

Step 2: Determine Total Excretion per Animal Type

EIA utilizes the tentative default values provided by the *Revised 1996 IPCC Guidelines* for nitrogen excreted per head of animal per year, as shown in Table 3-18.

Table 3-18. Default Values for Nitrogen Excretion per Head of Animal

Type of Animal	Nitrogen Excreted (kg per animal per year)
Non-dairy cattle	70.0
Dairy cattle	100.0
Poultry	0.6
Sheep	16.0
Swine	20.0
Other animals	25.0

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-20, p. 4.99, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

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[99] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.98, Equation 2, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 3: Determine Fraction of Manure Managed Per Type of Waste Management System and Nitrous Oxide Emission Factors for Applicable Waste Management Systems

The share of nitrogen produced for each type of waste management system and for each animal type is also obtained from the *Revised 1996 IPCC Guidelines*, as shown in Table 3-19.

Table 3-19. Share of Waste Handled in Various Waste Management Systems by Animal Type (fraction)

Animal Manure Management System Type	Beef Cattle*	Dairy Cows**	Swine	Poultry		Sheep	Goats	Horses
				Layers	Broilers			
Anaerobic Lagoons	0.005	0.11	0.29	0.14				
Liquid Slurry	0.005	0.21		0.10				
Daily Spread		0.41						
Solid Storage		0.18						
Drylot	0.1		0.20					
Pit Storage (less than 1 mo.)			0.12					
Pit Storage (more than 1 mo.)			0.32					
Deep Pit				0.56				
Litter					1.00			
Pasture	0.89					0.92	0.84	0.66
Paddock								0.27
Other		0.08	0.07	0.20		0.10	0.16	0.07

Source: Safley, et al, 1992.

Note: State-specific values for dairy cattle and swine are not included in this table. Blank cells are not applicable.

* Values apply to beef cattle not on feed. For feedlot beef cattle, 100 percent of waste is assumed to be handled in drylots.

** Values apply to dairy cows. For dairy heifers, 100 percent of waste is assumed to be handled in dry storage.

The emission factor for the mass of N_2O-N produced from each type of animal waste management system is also obtained from the *Revised 1996 IPCC Guidelines*, as shown in Table 3-20.

Table 3-20. Nitrous Oxide Emission Factors for Different Animal Waste Management Systems (EF_{ANMS})

Animal Waste Management System	Emission Factor (kg N_2O-N per kg N excreted)
Anaerobic Lagoons	0.001
Liquid Systems	0.001
Daily Spread	0
Solid Storage & Drylot	0.020
Pasture Range & Paddock (grazing)	0.020
Used as Fuel	Not applicable
Other Systems	0.005

Source: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-22, p. 4.104, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Step 4: Estimate Nitrous Oxide Emissions for Animal Waste Management Systems

Using the information collected in steps one through three, the *Revised 1996 IPCC Guidelines* provide the following formula for calculating nitrous oxide emissions from the solid waste of domesticated animals:

$$N_2O_{(AWMS)} = P_T \times N_{(EXCR)T} \times Frac_{(AWMS)T} \times EF_{ANMS}$$

where,

$N_2O_{(AWMS)}$ = Nitrous oxide emissions from animal waste management systems (kg N per year)

P_T = number of animals of type T in the United States

$N_{(EXCR)T}$ = nitrogen excretion per animal of type T in the U.S. (kg N per animal per year)

$Frac_{(AWMS)T}$ = fraction of $N_{(EXCR)T}$ that is managed in the appropriate animal waste managements system for animal type T

EF_{ANMS} = Nitrous oxide emission factor for animal waste management system (kg N_2O-N per kg $N_{(EXCR)T}$)

T = Type of animal

Data Sources

Activity data used in the emissions estimation of nitrous oxide from animal waste management systems is collected for animal populations divided into distinct, relatively homogeneous groups. In following the IPCC estimation guidelines, data on the U.S. cattle population is separated into dairy and non-dairy (beef) cattle. Population data are also collected for poultry, pigs, and other animals including sheep, goats, and horses. (See Table 3-21).

Table 3-21. Activity Data Sources for Nitrous Oxide Emissions from Animal Wastes

Calculation Methodology	**Citation**
Calculation Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Equation 2, p. 4.98, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Animal Population Data	
Cattle population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Cattle," January and July, Agricultural Statistics Board, Mt An 2, (Washington, D.C., various years), http://www.nass.usda.gov.
Swine population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Monthly Hogs and Pigs" Agricultural Statistics Board, Mt An 4, (Washington, D.C., various years), http://www.nass.usda.gov.
Poultry population data	U.S. Department of Agriculture, National Agricultural Statistics Service, "Chickens and Eggs," Agricultural Statistics Board, Poultry 1-1, (Washington, D.C., various years) http://www.nass.usda.gov.
Population data for goats and horses	U.S. Department of Commerce, Census of Agriculture, *United States Summary and State Data, Vol. 1*, "Geographic Area Series," Part 51, (Washington, D.C., various years).
Other Calculation Factors	
Nitrogen Excretion per Head of Animal	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-20, p. 4.99, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Percentage of Manure Nitrogen Produced for Different Animal Waste Management Systems	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-21, p. 4.101, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm; original source: L.M. Safley, M.E. Casada et al., *Global Methane Emissions From Livestock and Poultry Manure* (Washington, D.C., February 1992). U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, U.S. EPA-236-R-01-001 (Washington, D.C., April 2001), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Nitrous Oxide Emission Factors for Different Animal Waste Management Systems	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-22, p. 4.104, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

3.2.3 Nitrous Oxide Emissions from Crop Residue Burning

Emissions Sources

Crop production results in a large quantity of crop residue and waste, some of which is burned. Residues from the production of agricultural crops are commonly disposed of by re-incorporation into the soil, composting and re-application to soils, spreading over the soil surface to prevent erosion, landfilling, as animal bedding, or through burning. Although crop burning is not considered a net contributor to anthropogenic carbon dioxide emissions, because carbon released from plants is considered part of the natural carbon cycle, methane, nitrous oxide, and other emissions are considered significant. Crops considered by EIA include corn, sorghum, oats, barley, wheat, rice, rye, soybeans, peanuts, beans, peas, sugarbeets, and sugarcane.[100]

The burning of crop residues occurs throughout the United States, although it is illegal in certain locations. There are no documented or formal estimates of the amount of crop residue burned in the United States.

Estimation Methodology

Estimates of nitrous oxide emissions from crop residue burning are based on the amount of nitrogen contained in the total crop residue burned for each type of crop in a given year. EIA collects the following information to calculate total U.S. nitrous oxide emissions from the burning of crop residue:

- annual total U.S. production of crop biomass (by crop type);
- the fraction of residue for each crop type;
- the fraction of dry matter contained in the residue;
- nitrogen content for the crop type;
- the percentage of crop burned per year in situ;
- the combustion efficiency in burning the crop;
- an emission factor for nitrous oxide; and
- a nitrous oxide-nitrogen mass conversion factor.

EIA adopts the recommended methodology provided by the *Revised 1996 IPCC Guidelines*, applying the following three steps, culminating in the formula provided in Step 3:[101]

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[100] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.81, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm..

[101] Note, the Intergovernmental Panel on Climate Change *Good Practice Guidance* refers directly to the methodology adopted in the *Revised 1996 IPCC Guidelines.* Intergovernmental Panel on Climate Change, *Good Practice Guidance*, (Montreal, May 2000) p. 4.51, http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

Step 1: Determine Crop Production Levels by Crop Type

Annual crop biomass production data for all crops, except California rice, is obtained directly from the U.S. Department of Agriculture's annually published *Crop Production Summary*. Crop production data for California rice from 1998 to present has been obtained from the U.S. Department of Agriculture's *Agricultural Statistics Database*.[102]

Step 2: Determine Static Calculation Factors

Static calculation factors used in the formula for determining nitrous oxide emissions from crop burning include: residue per crop product; dry matter content of the residue; nitrogen content; the fraction of residue burned; a combustion efficiency factor; a nitrous oxide emission factor; and a conversion factor based on the atomic weights of nitrous oxide to nitrogen. EIA utilizes both dry matter content and nitrogen content values for corn, barley, wheat, rice, peanuts, and sugarcane from U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. The values for the remaining crops of sorghum, oats, rye, soybeans, beans, peas, potatoes, and sugar beets are obtained from the *Revised 1996 IPCC Guidelines.* These values and factors are listed in Table 3-22, below.

Table 3-22. Crop Residue Calculation Factors

Crop	Residue per Crop Product	Dry Matter Content	Nitrogen Content	Fraction Burned	Combust. Efficiency	N_2O Emission Factor	N_2O-N Ratio
Corn	1.0	0.91	0.0058	0.03	0.88	0.007	1.571
Sorghum	1.4	0.88	0.0085	0.03	0.88	0.007	1.571
Oats	1.3	0.901	0.0084	0.03	0.88	0.007	1.571
Barley	1.2	0.93	0.0077	0.03	0.88	0.007	1.571
Wheat	1.3	0.93	0.0062	0.03	0.88	0.007	1.571
Rice	1.4	0.91	0.0072	0.03	0.88	0.007	1.571
Rye	1.6	0.9	0.007	0.03	0.88	0.007	1.571
Soybeans	2.1	0.867	0.023	0.03	0.88	0.007	1.571
Peanuts	1.0	0.905	0.0106	0.03	0.88	0.007	1.571
Beans	2.1	0.8535	0.023	0.03	0.88	0.007	1.571
Peas	1.5	0.902	0.023	0.03	0.88	0.007	1.571
Potatoes	0.4	0.867	0.011	0.03	0.88	0.007	1.571
Sugarbeet	0.2	0.9	0.0228	0.03	0.88	0.007	1.571
Sugarcane	1.16	0.62	0.004	0.03	0.88	0.007	1.571

Sources: Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.35, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. For all combustion efficiency factors; dry matter content and nitrogen content for corn, barley, wheat, rice, peanuts, and sugarcane; and residue/crop product factor for sugarcane, U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1997* (April 1999), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Step 3: Calculate Emissions by Crop Type

EIA assumes that 3 percent of all crop residues are burned, with the exception of rice, which is combusted at various levels over time. The share of rice crop residues in California estimated to

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[102] Note, 1995-1997 data were obtained from the U.S. Department of Agriculture, *Crop Production 1997 Summary*. Data on peas were not collected by U.S. Department of Agriculture until 1986.

be combusted declines from 75 percent in 1990 to 23 percent in 2001. The share of rice combusted throughout the remainder of the United States declines from 16 percent in 1990 to 9 percent in 2001.[103] The amount of crop residue burned is discounted by an assumed combustion efficiency, multiplied by its dry matter content and nitrogen content, and then converted to nitrous oxide using a standard ratio of nitrous oxide to nitrogen content.

$$\mathrm{N_2O_{(CB)}} = $$

$$\mathrm{P_C} \times \mathrm{Frac_{(C)RES}} \times Frac_{(C)DRY} \times N_C \times Frac_{(C)BURNED} \times CEF_{(C)} \times EF_{(C)} \times CF_{N2O-N} \times 10^3$$

where,

$N_2O_{(CB)}$ = Nitrous oxide emissions from the crop residue burning (thousand metric tons N_2O per year)

P_C = Annual production (metric tons of crop biomass produced per year)

$Frac_{(C)RES}$ = fraction of residue for crop product

$Frac_{(C)DRY}$ = fraction of dry matter of residue (MT dry matter per tons of biomass)

N_C = nitrogen content of each crop

$Frac_{(C)BURNED}$ = fraction of crop burned per year in situ

CEF_C = combustion efficiency factor for each crop (0.88)

EF_C = emission factor for nitrous oxide (0.007 tons nitrogen emitted per ton N_C)

CF_C = conversion factor mass N_2O per N ($^{44}/_{28}$ N_2O-N/N)

C = Crop type

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[103] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 - 1999*, EPA-236-R-01-001 (Washington, D.C., April 2001), p.5-23, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Data Sources

Table 3-23. Data Sources for Nitrous Oxide Emissions from Crop Residue Burning

Data Utilized	Citation
Crop Production (all crops except California rice)	U.S. Department of Agriculture, *Crop Production Summary*, Table "Crop Summary Yield and Production," (published annually), http://usda.mannlib.cornell.edu/usda, and http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban/.
Crop Production - California rice	U.S. Department of Agriculture, Statistics Database, http://www.nass.usda.gov:81/ipedb/.
Calculation Factors	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines: Reference Manual (Volume 3)*, (Paris, France, 1997), p. 4.35, available at http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1997* (April 1999), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

3.3 Waste Management

3.3.1 Nitrous Oxide Emissions from Human Sewage in Wastewater

Emissions Sources

Domestic human sewage (known as "blackwater") results from the human consumption of protein in food, and the discharge of wastes into wastewater or septic systems. In each of these systems, nitrous oxide is generated from the nitrification and de-nitrification of the nitrogen present in urea and proteins in the waste. Nitrification results from the breakdown of ammonia-nitrogen (NH_3-N) while other nitrogen-containing compounds persist as organic nitrogen (N). Oxygen-deprived conditions can result in de-nitrification, which involves the conversion of nitrate into nitrogen gas (N_2). The overall process is influenced by temperature, pH/alkalinity, biochemical oxygen demand (BOD), nitrogen concentrations, and the amount of protein originally consumed by humans that is contained in the sewage.[104] Nitrous oxide emissions from human sewage are estimated to comprise about 1 percent of the total nitrogen contained in human sewage.

Estimation Methodology

Nitrous oxide emissions from human sewage are estimated by determining the total nitrogen content in sewage—based on the total population, average protein intake per person (mass), and the nitrogen content in protein (as a percentage of mass)—multiplied by an emission factor for

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[104] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000* (Washington, D.C., 2002), p. 7-8, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html. Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 4.109, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

nitrous oxide emissions from sewage. This calculation is performed using the following formula, as provided by the *Revised 1996 IPCC Guidelines*:[105]

$$N_2O_{(HS)} = US_{POP} \times P_{HS} \times Frac_{NP} \times EF_{HS} \times 10^{-6}$$

where,

$N_2O_{(HS)}$ = Nitrous oxide emissions from human sewage (thousand metric tons N_2O-N per year)

US_{POP} = total U.S. population

P_{HS} = annual average per capita intake of protein (kg per person per year)

$Frac_{NP}$ = fraction of nitrogen in protein (0.16 kg N per kg protein)

EF_{HS} = emission factor for nitrous oxide emissions from sewage (0.01 kg N_2O-N per kg sewage-N produced)

Note, this methodology does not consider the amount of nitrogen removed from wastewater as a result of land and subsurface sewage disposal or wastewater treatment.[106]

Data Sources

U.S. population data are obtained from the Census Bureau of the U.S. Department of Commerce. Average per capita protein intake is based on the daily average intake of protein provided by the Food and Agriculture Organization of the United Nations, multiplied by 365 days to derive yearly intake. The fraction of nitrogen in protein and the emission factor for nitrous oxide emissions from human sewage are obtained from the *Revised 1996 IPCC Guidelines*. (See Table 3-24).

Table 3-24. Data Sources for Nitrous Oxide Emissions from Human Sewage

Data Utilized	Citation
U.S. population data 1980 to 1999	U.S. Department of Commerce, Census Bureau, Monthly Estimates of the United States Population: April 1, 1980 to July 1, 1999, with Short-Term Projections to November 1, 2000 (Washington, D.C., January 2, 2001), http://eire.census.gov/popest/archives/national/nation1/intfile1-1.txt.
U.S. population data 2000 onward	U.S. Department of Commerce, Census Bureau, Annual population estimates by state, State Population Estimates: (Washington, D.C., April 1, 2000 onward), http://eire.census.gov/popest/data/states/tables/ST-EST2002-01.php.
Annual per capita intake of protein	Food and Agriculture Organization of the United Nations, *FAOSTAT Statistical Database, Nutrition Data, Food Balance Sheets - Country USA*, http://apps.fao.org.
Nitrogen content in protein	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 6.28, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Emission factor for nitrous oxide from sewage	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), Table 4-23, p. 4.105; p. 6.28, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

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[105] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 6.28, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[106] This quantity of nitrogen is presumed to be negligible, and is not considered by the U. S. Energy Information Administration.

3.3.2 Nitrous Oxide Emissions from Waste Combustion

Emissions Sources

Like other stationary and mobile combustion processes, the burning of garbage and non-hazardous solid waste produces nitrous oxide emissions. Since 1980, the estimated amount of municipal waste combusted in the United States has varied from 5.5 percent to 11.5 percent.[107] There are 160 municipal waste combustion plants in the United States, with 114 plants generating energy. Emission levels are dependent on the composition of waste burned and combustion temperatures.[108] Very high temperatures reduce nitrous oxide emissions.

Estimation Methodology

Limited guidance is provided by the IPCC in its *Revised 1996 IPCC Guidelines*, although a methodology is included in the *Good Practice Guidance*. This methodology is similar to that used by EIA, except that EIA relies on published sources for *total* waste generation and combustion figures, rather than calculating emissions for each waste type separately and summing the results to arrive at a total.

EIA calculates nitrous oxide emissions from waste combustion based on the total municipal solid waste combusted, multiplied by an emission factor. Total waste combusted is based on the total annual volume of municipal solid waste generated in the United States multiplied by the share of waste incinerated. The emission factor for nitrous oxide emitted from waste combustion is 30 grams of nitrous oxide per metric ton of waste incinerated. Data required for this calculation include: total municipal solid waste generated in the United States; the fraction of that waste combusted; and the applicable emission factor.

The methodology includes the following two-step process:

Step 1: Determine Level of Municipal Solid Waste Combusted

Total municipal solid waste combusted in the United States for the years 1989 to present is determined by multiplying the total waste generated in the United States by the portion of that waste that is incinerated, as provided in the following formula:

$$MSW_{COMB} = MSW_{GEN} \times Frac_{COMB}$$

where,

MSW_{COMB} = total municipal solid waste combusted per year (thousand short tons)

MSW_{GEN} = total municipal solid waste generated per year (thousand short tons)

$Frac_{COMB}$ = fraction of municipal solid waste generated that is combusted (percentage)

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[107] Goldstein, N., “12th Annual Biocycle Nationwide Survey: The State of Garbage in America,” *Biocycle Journal of Composting and Organics Recycling* 41 (4); 30-40 (April 2000).

[108] U.S. Environmental Protection Agency, *U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, D.C., April 2001), p. 7-5.

Step 2: Calculate Nitrous Oxide Emissions

Nitrous oxide emissions from waste combustion in the U.S. are calculated by multiplying total waste combusted by an emission factor and applicable conversion factors, as follows:

$$N_2O_{(\mathrm{WCOMB})} = \mathrm{MSW}_{\mathrm{COMB}} \times \mathrm{EF}_{\mathrm{WCOMB}} \times \mathrm{CF}_{\mathrm{MT}} \times 10^{-3}$$

where,

$N_2O_{(\mathrm{WCOMB})}$ = Nitrous oxide emissions from waste combustion (thousand metric tons N_2O-N per year)

$\mathrm{MSW}_{\mathrm{COMB}}$ = total municipal solid waste combusted per year (thousand short tons)

$\mathrm{EF}_{\mathrm{WCOMB}}$ = emission factor for nitrous oxide emissions from waste combustion (30 g N_2O per metric ton waste combusted)

$\mathrm{CF}_{\mathrm{MT}}$ = conversion factor (0.9071847 metric tons per short tons)

Data Sources

Activity data for U.S. generation and combustion of municipal solid waste from 1988 to 2002, and 2004 were derived from *Biocycle*'s "Nationwide Survey: The State of Garbage in America" (prior to 1988, these data were not collected by *Biocycle*). *Biocycle* conducts the survey through an extensive information gathering exercise involving state waste management officials (note, as of 2000, eight states were not able to provide waste incineration data to *Biocycle,* so rates for these states were estimated). In 2002, Biocycle developed a new survey methodology which substantially reduced the total estimate of municipal solid waste generated by more effectively excluding construction and demolition waste. To ensure a consistent time series of municipal solid waste generation data, EIA adjusted the 1988 through 2001, and 2003 estimates by scaling to an index of housing demolitions. In order to account for categories of waste other than MSW going to landfills between 1960 and 1987, an average ratio of waste generation estimated by *Biocycle* and waste generation estimated by Franklin Associates for 1988 through 1997 was calculated. The annual average ratio during this period was 1.47 to 1. Thus, all Franklin estimates for 1960 through 1987 were multiplied by 1.47 to estimate overall waste generation and landfilling for those years. Waste generation data that were not available for 2001 and 2003 were interpolated, and 2005 estimates are scaled up from previous year values by GDP growth rates.

The emission factor and percent share combusted for nitrous oxide emissions from waste combustion are obtained from U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2001*, which in turn is based on the U.S. EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (U.S. EPA 1997) (the IPCC does not provide an emission factor for nitrous oxide emissions from waste combustion).

EIA's calculation methodology for nitrous oxide emissions from waste combustion is based on methodologies provided in *IPCC Good Practice Guidance* as well as U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*.

Table 3-25. Data Sources for Nitrous Oxide Emissions from Waste Combustion

Data Utilized	Citation
Calculation methodology	Based on methodology provided in Intergovernmental Panel on Climate Change, *Good Practice Guidance*, p. 5.28, http://www.ipcc-nggip.iges.or.jp/public/gp/english/. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, (April 2000), p. 2-38 and p. H-4, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Waste generation data	"Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-2002).
Waste generated and landfilled for the period 1960 through 1987	Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States*, Worksheets, 1992 update, Prepared for the U.S. Environmental Protection Agency, Municipal Solid and Industrial Solid Waste Division (July 1992).
Waste generated and landfilled for the period 1960 through 1987	U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1998 Update*, U.S. EPA-530-S-99-021 (Washington, D.C., July 1999).
U.S. GDP data (for calculation of waste generation after 1987)	Bureau of Economic Analysis, *Real Gross Domestic Product and Related Measures*, http://www.bea.gov/bea/dn/home/gdp.htm.
Emission factor and share combusted	U.S. Environmental Protection Agency, Annex I to *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2001*, (April 2004), p. I-4, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html, based on U.S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors, AP-42 (U.S. EPA 1997).

3.4 Industrial Processes

3.4.1 Nitrous Oxide Emissions from Adipic Acid Production

Emissions Sources

The manufacture of adipic acid is one of the two principal sources of nitrous oxide emissions from industrial processes in the United States. Adipic acid typically forms as a white crystalline powder primarily used in manufacturing synthetic nylon fibers and plastics used in carpet yarn, clothing, and tire cord. Food-grade adipic acid is used in gelatins, beverages, condiments, certain dairy products, fats and oils, puddings, gravies, meat products, and snack foods to provide a "tangy" flavor. Technical-grade adipic acid is also used in the production of plasticizers for polyvinyl chloride and polyurethane resins and foams, wire coatings, synthetic lubricants, adhesives, insecticides, and dyes. About 80 percent of all adipic acid generated in the United States is used to produce nylon.[109]

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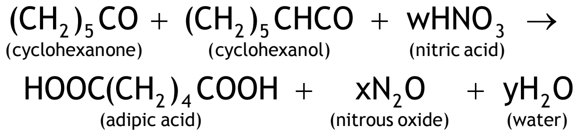
[109] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.2.19, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. Solutia, Product Information, access at http://www.solutia.com/pages/corporate/products/product.asp?product=164 on March 18, 2003. U. S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*, USEPA #430-R-04-003 (Washington, D.C., April 2004) p. 3-21, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Three companies—Dupont, Solutia, and Allied Signal—operate four plants that produce all of the adipic acid in the United States. These companies manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid.[110]

Nitrous oxide gas is an intrinsic byproduct of two-stages of chemical reactions that take place during nitric acid oxidation, as shown below:[111]



$$\underset{\text{(cyclohexanone)}}{(CH_2)_5CO} + \underset{\text{(cyclohexanol)}}{(CH_2)_5CHCO} + \underset{\text{(nitric acid)}}{wHNO_3} \rightarrow \underset{\text{(adipic acid)}}{HOOC(CH_2)_4COOH} + \underset{\text{(nitrous oxide)}}{xN_2O} + \underset{\text{(water)}}{yH_2O}$$

The first stage in the production of adipic acid involves the oxidation of cyclohexane to form a mixture of cyclohexanone and cyclohexanol. The second stage involves oxidizing this mixture with nitric acid to produce adipic acid, generating nitrous oxide as a by-product.[112] Nitrous oxide emissions from the production of adipic acid vary depending on the emissions controls used in a processing plant. These emissions controls are considered to reduce nitrous oxide emissions by as much as 98 percent. Before 1994, 74.7 percent of all adipic acid production was subject to emissions abatement controls. By 2001, three facilities representing 97.4 percent of total estimated U.S. production of adipic acid had implemented abatement control technologies. As of 2001, only one plant, comprising less than 3 percent of total U.S. adipic acid production, was not using emissions controls.[113]

Estimation Methodology

Emissions of nitrous oxide from adipic acid production are quantified by multiplying the mass of adipic acid production by an emission coefficient for adipic acid. The resulting product is further adjusted to reflect the application of emissions abatement controls that cause the thermal decomposition of nitrous oxide. EIA uses the following information to calculate total U.S. nitrous oxide emissions from adipic acid production:

- annual total U.S. production of adipic acid;
- emission factor for nitrous oxide emissions from the generation of adipic acid;
- percentage of adipic acid production facilities using emission abatement controls versus those not using abatement controls; and
- the percentage of nitrous oxide emissions avoided as a result of emission controls for each adipic acid production facility.

EIA applies the following five steps in estimating nitrous oxide emissions from adipic acid production:

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[110] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.2.19, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. Thiemens and Trogler, 1991.

[111] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.2.19, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[112] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*, USEPA #236-R-02-003 (Washington, D.C., April 2002), p. 3-21, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[113] Radian Corporation.

Step 1: Determine Production Levels for Adipic Acid

Total U.S. adipic acid production is reported through a number of separate sources. Activity data for 1980 to 1989 was obtained from SRI International, “Chemical Economics Handbook 2000”. Activity data for 1990 to 1995 was obtained from the U.S. Trade Commission, and from 1996 to the present from the American Chemical Council.

Step 2: Determine Fraction of Emissions Avoided through Abatement Controls

EIA assumes that the standard abatement control technology used in each of the plants with abatement controls produces a 98 percent reduction in total N_2O emissions.[114]

Step 3: Determine Rate of Abatement Control Utilization

Utilization of abatement controls is assumed to be 100 percent.

Step 4: Calculate Emissions Based on Adipic Acid Activity Data

For every metric ton of adipic acid produced, 0.3 metric tons of nitrous oxide is created.[115] Total nitrous oxide emissions are derived by using the following formulas, based on the *Revised 1996 IPCC Guidelines*. One of two formulas is used to derive the appropriate nitrous oxide emissions for each facility, as applicable. The first formula applies to each facility that has abatement controls in operation. The second formula is used for each facility operating without any emission abatement controls in operation.

$$N_2O_{(AA)C} = P_{AA} \times EF_{AA} \times Frac_{ABATE} \times Frac_{(AA)C} \times CF_{METRIC}$$

$$N_2O_{(AA)NC} = P_{AA} \times EF_{AA} \times Frac_{(AA)NC} \times CF_{METRIC}$$

where,

$N_2O_{(AA)C}$ = Nitrous oxide emissions from adipic acid production with abatement controls (thousand metric tons N_2O per year)

$N_2O_{(AA)NC}$ = Nitrous oxide emissions from adipic acid production without abatement controls (thousand metric tons N_2O per year)

P_{AA} = Production level for adipic acid (thousand short tons)

EF_{AA} = Emission factor for adipic acid production (0.3 metric tons N_2O emitted per metric ton adipic acid produced)

$Frac_{ABATE}$ = percentage of N_2O destroyed in facilities using emission abatement controls (98 percent)

$Frac_{(AA)C}$ = percentage of facilities using emission abatement controls

$Frac_{(AA)NC}$ = percentage of facilities not using emission abatement controls

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[114] Radian Corporation.

[115] Thiemens and Trogler, 1991; see also Intergovernmental Panel on Climate Change, 1996, p.2.19.

CF_{METRIC} = conversion factor (0.9071847 metric tons per short tons)

The N_2O destruction factor ($Frac_{CONTR}$) represents the percentage of nitrous oxide destroyed as a result of emissions abatement technology. According to the *IPCC Good Practice Guidance*, the N_2O destruction factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer et al. 1999, Reimer 1999).[116] The abatement system utilization factor ($Frac_{UTIL}$) represents the percent of the time that emissions abatement technology is in operation.

Step 5: Sum Emissions from Controlled Sources and Non-Controlled Sources

After nitrous oxide emissions are calculated for each facility with and without abatement controls, the totals are summed to provide total nitrous oxide emissions from adipic acid production in the United States.

Data Sources

EIA obtained total U.S. production of adipic acid from three sources. Adipic acid production information for 1980 to 1989 was taken from the annual report of Chemical and Engineering News, *Top 50 Industrial Chemicals*.[117] Production information for 1990 to 1995, appearing in *Chemical and Engineering News*, was based on data collected by the U.S. Trade Commission, and information for 1996 to present has been obtained from the American Chemical Council (formerly the Chemical Manufacturers Association). EIA regularly contacts the three U.S. companies producing adipic acid on the application of emissions abatement controls at their facilities. (See Table 3-26).

The emission factor was taken from Thiemens and Trogler (1991). The same emission factor is recommended in the IPCC *Guidelines for National Greenhouse Gas Inventories*, the IPCC *Revised 1996 IPCC Guidelines* and the IPCC *Good Practice Guidance*.

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[116] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*, USEPA #236-R-02-003 (Washington, D.C., April 2002), p. 3-22, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

[117] *Chemical and Engineering News*, “Facts and Figures” and “Production of Top 50 Chemicals,” (various years).

Table 3-26. Data Sources for Nitrous Oxide Emissions from Adipic Acid Production

Data Utilized	Citation
Calculation methodology; adipic acid production process	Intergovernmental Panel on Climate Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3, Industrial Processes and Product Use. Prepared by the National Greenhouse Gas Inventories Programme. (Japan, 2006), pp. 3.28-3.30. Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.2.19, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. Intergovernmental Panel on Climate Change, *Good Practice Guidance*, p.3.31-3.38, http://www.ipcc-nggip.iges.or.jp/public/gp/english/.
U.S. total adipic acid production 1996-onward	Personal communications with T. Kevin Swift, American Chemical Council, (various years).
U.S. total adipic acid production 1980-1995	Chemical and Engineering News, annual report on the "Top 50 Industrial Chemicals," (April issue, various years).
Nitrous oxide emission factor for adipic acid	M.H. Thiemens and W.C. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 22, 1991), p. 932. Intergovernmental Panel on Climate Change, *Good Practice Guidance*, p.3.34, http://www.ipcc-nggip.iges.or.jp/public/gp/english/. Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p.2.19, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. Intergovernmental Panel on Climate Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3, Industrial Processes and Product Use. Prepared by the National Greenhouse Gas Inventories Programme. (Japan, 2006), pp. 3.28-3.30.
Emission abatement controls used in adipic acid production	Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.
	R.A. Reimer, R.A. Parrett, and C.S. Slaten, "Abatement of N_2O Emissions Produced in Adipic Acid," in *Proceedings of the Fifth International Workshop on Nitrous Oxide Emissions* (Tsukuba, Japan, July 1992).
	Personal communications with T. Kevin Swift, American Chemical Council (various years).
	Personal communications with DuPont Corporation (various years).

3.4.2 Nitrous Oxide Emissions from Nitric Acid Production

Emissions Sources

Nitric acid is a primary ingredient in nitrogenous-based synthetic fertilizers, and is also used in the production of adipic acid and explosives (e.g., dynamite), in metal etching, and in processing ferrous metals. The process for manufacturing nitric acid involves oxidizing ammonia with a platinum catalyst. Nitrous oxide emissions are a byproduct of this process.[118] The production of nitric acid results from the following three chemical reactions:

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[118] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p. 2.17, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

$$\underset{\text{(ammonia)}}{4NH_3} + \underset{\text{(oxygen)}}{5O_2} \rightarrow \underset{\text{(nitric oxide)}}{4NO} + \underset{\text{(water)}}{6H_2O}$$

$$\underset{\text{(nitric oxide)}}{2NO} + \underset{\text{(oxygen)}}{5O_2} \rightarrow \underset{\text{(nitrous oxide)}}{2N_2O}$$

$$\underset{\text{(nitric oxide)}}{3NO_2} + \underset{\text{(water)}}{H_2O} \rightarrow \underset{\text{(nitric acid)}}{2HNO_3} + \underset{\text{(nitric oxide)}}{NO}$$

Estimation Methodology

Emissions of nitrous oxide from nitric acid production are calculated by multiplying total nitric acid production figures per year by a nitrous oxide emission coefficient. The resulting product is adjusted to reflect the application of emissions abatement controls that cause the thermal decomposition of nitrous oxide. EIA collects the following information to calculate total U.S. nitrous oxide emissions from adipic acid production:

- annual total U.S. production level of nitric acid; and
- emission factor for nitrous oxide emissions from the production of nitric acid.

EIA applies the following three steps in estimating nitrous oxide emissions from nitric acid production:

Step 1: Determine Production Levels for Nitric Acid

Nitric acid production data are obtained from the U.S. Department of Commerce, *Current Industrial Reports: Quarterly and Annual Reports on Fertilizer Materials – MQ325B and MA325B*.

Step 2: Determine Fraction of Emissions Avoided through Abatement Controls

Citing a 1992 study by Reimer, et al, the IPCC *Revised 1996 Guidelines* provide an emission factor of between 2 to 9 kilograms of nitrous oxide emitted per metric ton of nitric acid manufactured in the United States (IPCC 1996, p.2.18). As a result, EIA applies the midpoint of this range—an emission factor of 5.5 kilograms nitrous oxide per metric ton of product—to calculate total emissions. It should be noted that there is a considerable degree of uncertainty associated with this estimate.

Step 3: Calculate Emissions Based on Nitric Acid Activity Data

Total nitrous oxide emissions are derived by using the following formula and emission factor, based on the methodology provided in the *Revised 1996 IPCC Guidelines*:

$$N_2O_{(NA)} = P_{NA} \times EF_{NA} \times CF_{METRIC}$$

where,

$N_2O_{(NA)}$ = Nitrous oxide emissions from nitric acid production (thousand metric tons N_2O per year)

P_{NA} = Production level for nitric acid (thousand short tons)

EF_{NA} = Emission factor for nitric acid production (0.0055 metric tons N_2O per metric ton adipic acid)

CF_{METRIC} = conversion factor (0.9071847 metric tons per short tons)

Data Sources

Data on U.S. production of nitric acid is available from the *U.S. Chemical Industry Statistical Handbook* (various years), published by the American Chemical Council (formerly the Chemical Manufacturers Association) and from the U.S. Department of Commerce, Bureau of the Census, *Current Industrial Reports: Quarterly and Annual Reports on Fertilizer Materials - MQ325B and MA325B* (various years). (See Table 3-27).

Information on the calculation methodology, nitric acid production process, and nitrous oxide emission factor for nitric acid production is based on the *Revised 1996 IPCC Guidelines*.

Table 3-27. Data Sources for Nitrous Oxide Emissions from Nitric Acid Production

Data Utilized	Citation
Calculation methodology; nitric acid production process; and emission factor	Intergovernmental Panel on Climate Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3, Industrial Processes and Product Use. Prepared by the National Greenhouse Gas Inventories Programme. (Japan, 2006), pp. 3.22-3.23. Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), p 2.17-2.18, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm. Reimer, R.A, R.A. Parrett and C.S. Slaten (1992), “Abatement of N_2O emission produced in adipic acid.” *Proc. of the 5th Int. Workshop on Nitrous Oxide Emissions* (Tsukuba, Japan, 1-3 July 1992).
Nitric acid production)	U.S. Department of Commerce, Bureau of the Census, Current Industrial Reports: Quarterly and Annual Reports on Fertilizer Materials - MQ325B and MA325B (various years). Chemical Council (formerly the Chemical Manufacturers Association), *U.S. Chemical Industry Statistical Handbook* (various years).

4. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

4.1 Estimation Methodology for HFCs and PFCs from the Substitution of Ozone Depleting Substances

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) have hundreds of uses, but the bulk of emissions come from a few broad categories of use:

as refrigerants or working fluids in air conditioning and refrigeration equipment,

as solvents in various industrial processes, and

as blowing agents for making insulating foams.

EIA relies primarily on estimates of HFCs and PFCs presented in the U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks (various years)*. This appendix is largely a product of that report and its supporting annexes with further insights gleaned (where appropriate) from the IPCC *Revised 1996 IPCC Guidelines*.

For equipment and products containing ozone-depleting substances (ODS), the U.S. EPA uses a detailed Vintaging Model to estimate actual versus potential emissions of various ODS substitutes, including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). The model, named for its method of tracking the emissions of annual “vintages” of new equipment that enter into service, is a “bottom-up” model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging Model makes use of this market information to build an inventory of the in-use stocks of the equipment and ODS and ODS substitute in each of the end-uses. The simulation is considered to be a “business-as-usual” baseline case, and does not incorporate measures to reduce or eliminate the emissions of these gases other than those regulated by U.S. law. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical. Emissions from more than 40 different end uses are estimated.

In general, the modeled emissions are a function of the amount of chemical consumed in each end-use market. Estimates of the consumption of ODS alternatives can be inferred by extrapolating forward in time from the amount of regulated ODS used in the early 1990s. Using data gleaned from a variety of sources, assessments are made regarding which alternatives will likely be used, and what fraction of the ODS market in each end-use will be captured by a given alternative. By combining this with estimates of the total end-use market growth, a consumption value can be estimated for each chemical used within each end-use.

The Vintaging Model synthesizes data from a variety of sources, including data from the ODS Tracking System maintained by the Stratospheric Protection Division and information from submissions to U.S. EPA under the Significant New Alternatives Policy (SNAP) program. Published sources include documents prepared by the United Nations Environment Programme (UNEP) Technical Options Committees, reports from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), and conference proceedings from the International Conferences on Ozone Protection Technologies. U.S. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy, the Air-Conditioning and Refrigeration Institute, the Association of Home Appliance Manufacturers, the American Automobile Manufacturers Association, and many of their member companies, have provided valuable information over the years. In some instances the unpublished information that the U.S. EPA uses in the model is classified as Confidential Business Information (CBI). The annual emissions inventories of chemicals are aggregated in such a way that CBI cannot be inferred. Full public disclosure of the inputs to the Vintaging Model would jeopardize the security of the CBI that has been entrusted to the U.S. EPA.

4.1.1 HFC Emissions from Refrigeration and Air-Conditioning

The refrigeration and air-conditioning sector is one of the largest sources of ODS-substitute emissions. Refrigeration and air-conditioning systems in the U.S. range from home refrigerators to frozen food aisles in supermarkets, which are designed to remove heat from the area being cooled and transfer it to the outside. As HFCs continue to replace ODSs in this sector, and as new technologies replace older ones, it is assumed that there will be improvement in emission rates.

Emissions in the refrigeration and air-conditioning sector stem from a number of sources. Refrigerants are used in a closed cycle inside cooling equipment, and they tend to leak out when the equipment is scrapped or serviced. For example, when a product is disposed of, any refrigerant not recovered before its disposal is emitted to the atmosphere. Some portion of the refrigerants is captured and recycled or destroyed, rather than emitted, when equipment is serviced. Other sources of emissions are leaks in pipes, valves, and fittings; and, although U.S. regulations forbid emitting HFCs during servicing, some emissions do occur. Table 4-1 below shows the end-uses modeled by the U.S. EPA for refrigeration and air-conditioning.

Table 4-1. Refrigeration and Air-Conditioning End-Uses

End-Use	Gas
Mobile Air Conditioners	CFC-12
Chillers	CFC-11, CFC-12, R-500, HCFC-22, CFC-14
Retail Food	CFC-12, HCFC-22, R-502
Cold Storage	CFC-12, HCFC-22, R-502
Transport Refrigeration	CFC-12, R-502
Refrigerated Appliances	CFC-12
Dehumidifiers	HCFC-22
Industrial Process Refrigeration	CFC-11, CFC-12, HCFC-22
Ice Makers	CFC-12
Window Units	HCFC-22
Residential Unitary Air Conditioners	HCFC-22
Commercial Unitary Air Conditioners	HCFC-22
Water and Ground-Source and Unitary Heat Pumps; Packaged Terminal Air Conditioners and Heat Pumps	HCFC-22

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Atmospheric Programs, Stratospheric Protection Division

Estimation Methodology

U.S. EPA calculates emissions from refrigeration and air-conditioning products by separating the calculations into two categories: lifetime emissions, which arise from annual leakage and service losses, and disposal emissions, which are the result of a product's disposal. These two emissions estimates are then summed to calculate total emissions from refrigeration and air-conditioning.

Step 1: Calculate Lifetime Emissions

To calculate lifetime emissions, both the amount of chemical leaked during product use and the amount leaked during service recharges from any piece of equipment is accounted for.

$$Es_j = (l_a + l_s) \times \sum Qc_{j-1+1} \qquad for\ i=l \rightarrow k$$

where,

Es = Emissions from equipment serviced. Emissions in year j from normal leakage and servicing (including recharging) of equipment

l_a = Annual leak rate. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge)

l_s = Service leak rate. Average leakage during equipment servicing (expressed as a percentage of total chemical charge)

Qc = Quantity of chemical in new equipment. Total amount of a specific chemical used to charge new equipment in a given year, j, by weight

k = Lifetime. The average lifetime of the equipment

Step 2: Calculate Disposal Emissions

To calculate disposal emissions, it is assumed that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded. Therefore, disposal emissions are a function of the amount of chemical contained in each product retired and the proportion of chemical released at disposal.

$$Ed_j = Qc_{j-k+1} \times \left[1 - (rm \times rc)\right]$$

where,

Ed = Emissions from equipment disposed. Emissions in year j from the disposal of equipment

Qc = Quantity of chemical in new equipment. Total amount of a specific chemical used to charge new equipment in a given year, j, by weight

Rm = Chemical remaining. Amount of chemical remaining in equipment at the time of disposal (expressed as a percentage of total chemical charge)

rc = Quantity of chemical in new equipment. Total amount of a specific chemical used to charge new equipment in a given year, j, by weight

k = Lifetime. The average lifetime of the equipment

Step 3: Calculate Total Emissions

To calculate total emissions from refrigeration and air-conditioning, the lifetime and disposal emissions estimates are summed together.

$$E_j = Es_j + Ed_j$$

where,

E = Total emissions from refrigeration and air-conditioning equipment in year j

Es = Emissions from equipment serviced. Emissions in year j from normal leakage and servicing (including recharging) of equipment

Ed = Emissions from equipment disposed. Emissions in year j from the disposal of equipment

Table 4-2. Example Leak and Disposal Loss Rates from Refrigeration and Air-Conditioning Equipment

End Use	Annual Loss from Service + Leaks (percent)	Lifetime (years)
Mobile Air Conditioners	10.8	12
Chillers		
New Equipment	1 - 14	20 - 27
Existing Equipment	11 - 19.5	
Retail Food		
New Equipment	5 - 30	15 - 20
Existing Equipment	7 - 33	
Cold Storage		
New Equipment	12 - 25	20 - 25
Existing Equipment	22 - 29	
Industrial Process Refrigeration		
New Equipment	4 - 15	25
Existing Equipment	6 - 19	
Transport Refrigeration		
New Equipment	20 - 28	12
Existing Equipment	33	
Ice Makers and Ice Rinks	3 - 7	20
Refrigerated Appliances	<1	20
Residential Unitary A/C		
New Equipment	4 - 12	15
Existing Equipment	5	
Commercial Unitary A/C		
New Equipment	4 - 5	15
Existing Equipment	5	
Water & Ground Source Heat Pumps	2 - 3	20
PTAC/PTHP	2 - 3	12
Window Units	<1	15

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Atmospheric Programs, Stratospheric Protection Division

Data Sources

Activity data for emissions from refrigeration and air-conditioning include leak and service rates, as well as figures for the average lifetime for each equipment type assumed by U.S. EPA's Vintaging Model. Although the IPCC recommends refrigeration and air-conditioning disposal rates, U.S. EPA's Vintaging Model currently utilizes higher disposal rates that seek to more closely resemble actual disposal rates in the U.S. Table 4-2 above provides a range of annual emissions rates used by the Vintaging Model. Although it is not clear exactly how or where U.S. EPA collects chemical consumption data, U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI) that are used as inputs to its Vintaging Model. (See Table 4-3).

Table 4-3. Data Sources for High-GWP Gases from Refrigeration and Air-Conditioning

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Vintaging Model Data	U.S. Environmental Protection Agency, Modeling Emissions of High Global Warming Potential Gases, (Washington, D.C., various years).

4.1.2 HFC Emissions from Aerosols

Ozone-depleting substances, HFCs and several other chemicals are used as propellant aerosols. These chemicals are released into the atmosphere when the product within the pressurized can is consumed via a nozzle. The use of ODSs in consumer aerosols was banned in the U.S. in 1977, with many products transitioned to "not-in-kind" technologies, such as solid deodorants and finger-pump hair sprays, which avoided these kinds of emissions.

Estimation Methodology

To calculate emissions from aerosols, it is assumed that all of the annual production of aerosol propellants is released into the atmosphere, as there is currently no aerosol recycling. The aerosol sector is divided into four end-uses, three for metered dose inhalers (vital medical devices), based on the original ODS propellant (CFC-11, CFC-12, or CFC-114), and one for all other consumer aerosol products that have not been banned in the U.S.

Because the lifetime for aerosols is one year, and 100 percent of the propellant is emitted during that time, total emissions are equal to the quantity of the chemical consumed. The Vintaging Model's aerosol sector, however, is being updated to match the IPCC *Good Practice Guidance*, which recommends that the lifetime of all aerosol products be assumed to be 2 years. The following equation describes the U.S. EPA's current method for estimating emissions for the aerosol sector using its Vintaging Model:

$$E_y = Qc_y$$

where,:

E = Total emissions of a specific chemical from use in aerosol products for year (y), by weight;

Qc = Quantity of specific chemical contained in aerosol products sold in year y, by weight

Data Sources

Activity data for emissions from aerosols include chemical consumption data as well as a figure for the average lifetime of all aerosols assumed by U.S. EPA's Vintaging Model. Although it is not clear exactly how or where U.S. EPA collects chemical consumption data, U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI) that are used as inputs to its Vintaging Model. (See Table 4-4).

Table 4-4. Data Sources for High-GWP Gases from Aerosols

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Vintaging Model Data	U.S. Environmental Protection Agency, Modeling Emissions of High Global Warming Potential Gases, (Washington, D.C., various years).

4.1.3 HFC Emissions from Solvents

Ozone-depleting substances, HFCs, PFCs and other chemicals are used as solvents to clean various items. For example, electronic equipment may need to be cleaned after production in order to remove any manufacturing process oils or residues remaining on the product. Typically, the solvents are applied by moving the equipment through a bath or stream of the solvent.

Generally, most solvents remain in the liquid phase and are not emitted in a gaseous form. Accordingly, these emissions are considered incomplete, and are assumed to be a fixed percentage of the amount of solvent consumed in a given year. HFCs solvent applications are often recycled, but net consumption (after recycling) is probably a good indicator of emissions.

Estimation Methodology

Results from the U.S. EPA Vintaging Model show the solvent lifetime as one year, with emissions estimated to be only 10 percent of total solvent usage. U.S. EPA believes that in reality, actual emissions may be much higher. Like the aerosols sector, the Vintaging Model's solvents sector is being updated to match the IPCC *Good Practice Guidance*, which recommends that the lifetime of all solvents products be assumed to be 2 years, with an emission factor of 50 percent each year.

The U.S. EPA Vintaging Model divides the solvent sector into four end-uses: electronics cleaning, metals cleaning, precision cleaning, and adhesives, coatings and inks. U.S. EPA uses the following equation to calculate emissions from solvent applications:

$$E_j = l \times Qc_j$$

where,

E = Total emissions of a specific chemical from use in solvent applications for year j, by weight

l = Leakage percent. The percentage of the total chemical that is leaked to the atmosphere

Qc = Quantity of a specific chemical used in solvent applications sold in year j, by weight

Data Sources

Activity data for emissions from solvent applications include chemical consumption data as well as a figure for the average lifetime of all solvents assumed by U.S. EPA's Vintaging Model. Although it is not clear exactly how or where U.S. EPA collects chemical consumption data, U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI) that are used as inputs to its Vintaging Model. (See Table 4-5).

Table 4-5. Data Sources for High-GWP Gases from Solvent Applications

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Vintaging Model Data	U.S. Environmental Protection Agency, Modeling Emissions of High Global Warming Potential Gases, (Washington, D.C., various years).

4.1.4 HFC and PFC Emissions from Fire Extinguishing

Ozone-depleting substances, HFCs, PFCs and other chemicals are used as fire-extinguishing agents. These agents include hand-held "streaming" applications as well as "flooding" equipment similar to water sprinkler systems. Although these systems are to a large degree leak-tight, some leaks do occur resulting in emissions of high-GWP gases.

Estimation Methodology

The U.S. EPA's Vintaging Model calculates total emissions from fire extinguishing by assuming that, in aggregate, emissions are equal to a percentage of the total quantity of chemical consumed at a given time. According to U.S. EPA, the Vintaging Model assumes that fire extinguishing equipment leaks at a constant rate for an average equipment lifetime, although at different percentages between the two end-uses.

In streaming systems, emissions are assumed to be 2 percent of all chemical in use for each year, while in flooding systems 1.5 percent of the installed base of chemical is assumed to leak annually. In the Vintaging Model, streaming applications have a 10-year lifetime and flooding applications have a 20-year lifetime.

$$E_j = l \times \sum Qc_{j-i+1} \quad for\ i=l \rightarrow k$$

where,

E = Total emissions of a specific chemical in year j for fire extinguishing equipment, by weight

l = Leakage percent. The percentage of the total chemical in operation that is leaked to the atmosphere

Qc = Total amount of a specific chemical used in new streaming fire extinguishing equipment in a given year, j, by weight

K = Lifetime (the average lifetime of the equipment)

Data Sources

Activity data for emissions from fire extinguishing equipment include chemical consumption data as well as a figure for the average lifetime of both streaming and flooding equipment assumed by U.S. EPA's Vintaging Model. Although it is not clear exactly how or where U.S. EPA collects chemical consumption data, U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI) that are used as inputs to its Vintaging Model. (See Table 4-6).

Table 4-6. Data Sources for High-GWP Gases from Fire Extinguishing

Data Utilized	**Citation**
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Vintaging Model Data	Environmental Protection Agency, *Modeling Emissions of High Global Warming Potential Gases* (Washington, D.C., various years).

4.1.5 HFC Emissions from Foam Blowing

Ozone-depleting substances, HFCs, and other chemicals are used to produce foams. These foams include such items as the foam used for insulation panels around refrigerators and insulation for buildings. The chemical used in foam production creates pockets of gas within a substrate, thereby increasing the insulating properties of the product. HFCs used as blowing agents can be characterized by the type of foam manufactured: HFCs s used to make "open cell" foam are released to the atmosphere immediately, while HFCs used to make "closed cell" foam are trapped within the foam for the life of the foam, which can vary (depending on the use) from a few weeks to many years.

Estimation Methodology

To calculate emissions from foam blowing, foams are given emission profiles which are contingent on the foam type (open cell or closed cell). The U.S. EPA assumes open cell foams emit 100 percent of their emissions in the year of manufacture. Closed cell foams on the other hand emit a portion of the total HFC when manufactured, a portion at a constant rate over their lifetime, and a portion at their disposal. Table 4-7 below provides the emissions profiles of the foam types estimated in the U.S. EPA's Vintaging Model.

Table 4-7. Vintaging Model Emission Profiles for Foam End-Uses of Polyurethane (PU) and Extruded Polystyrene (XPS)

Foam End-Use	Loss at Manufacturing (percent)	Annual Leakage Rate (percent)	Leakage Lifetime (Years)	Loss at Disposal (percent)	Total
Flexible PU	100	0	1	0	100
Polyisocyanurate Boardstock	6	1	50	44	100
Rigid PU Integral Skin	95	2.5	2	0	100
Rigid PU Appliance	4	0.25	15	27.675	35
Rigid PU Commercial Refrigeration	6	0.25	15	90.25	100
Rigid PU Spray	15	1.5	56	1	100
One Component	100	0	1	0	100
Rigid PU Slabstock and Other	37.5	0.75	15	51.25	100
Phenolic	23	0.875	32	49	100
Polyolefin	95	2.5	2	0	100
XPS Sheet/Insulation Board	40	2	25	0	90
XPS Boardstock	25	0.75	50	37.5	100
PU Sandwich Panels	5.5	0.5	50	69.5	100

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Atmospheric Programs, Stratospheric Protection Division

To calculate total emissions from foam blowing, U.S. EPA's Vintaging Model follows the following steps:

Step 1: Calculate Emissions from Open-cell Foam

Because open-cell foams are assumed to be 100 percent emissive in the year of manufacture, total emissions are equal to the quantity of the chemical consumed (similar to calculating emissions from aerosols).

$$E_j = Qc_j$$

where,

E = Total emissions of a specific chemical from used for open-cell foam blowing for year j, by weight

Qc = Quantity of specific chemical used for open-cell foam blowing in year j, by weight.

Step 2: Calculate Emissions from Closed-cell Foam

$$E_j = \sum (ef_i \times Qc_{j-i+1}) \quad for\ i=l \rightarrow k$$

where,

E = Total emissions of a specific chemical for closed-cell foam blowing in year j, by weight

ef = Emission factor. The percentage of the foam's original charge emitted in each year (1 → k). This emission factor is generally variable, including a rate for manufacturing emissions (occurs in the first year of foam life), annual emissions (every year throughout the foam lifetime), and disposal emissions (occurs during the final year of foam life)

Qc = Total amount of a specific chemical used in closed-cell foam blowing in a given year j, by weight

K = Lifetime. The average lifetime of the equipment

Data Sources

Activity data for emissions from foam blowing include chemical consumption data as well as an average lifetime figure for closed-cell foam blowing assumed by U.S. EPA's Vintaging Model. Although it is not clear exactly how or where U.S. EPA collects chemical consumption data or emission factors for foam blowing, U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI) that are used as inputs to its Vintaging Model. (See Table 4-8).

Table 4-8. Data Sources for High-GWP Gases from Foam Blowing

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
Vintaging Model Data	U.S. Environmental Protection Agency, Modeling Emissions of High Global Warming Potential Gases, (Washington, D.C., various years).

4.2 Estimation Methodology for Other Industrial Sources

In addition to those detailed above, there are various other industrial sources of high-GWP gases—PFCs, HFCs and SF_6, including:

PFCs from aluminum production;

HFC-23 from the production of HCFC-22;

HFCs, PFCs and SF_6 from semiconductor manufacturing; and

SF_6 from the magnesium and electric transmission and distribution sectors.

EIA relies primarily on estimates of HFCs, PFCs, and sulfur hexafluoride (SF_6) emissions presented in the U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and (various years)*. This appendix is largely a product of that report and associated annexes with further insights gleaned (where appropriate) from the IPCC *Revised 1996 IPCC Guidelines*.

Although the Vintaging Model is not used to calculate emissions from other industrial sources, U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI) that are used as inputs to its modeling of other industrial source emissions. For example, for some production-related industrial processes, an emission factor is applied that relates the high GWP gas emissions to the output of the process. For other processes, emissions are related to specific characteristics of the production process (e.g. PFC emissions from aluminum smelting depend on the frequency and duration of the process characteristic that produces the gas).

4.2.1 PFC Emissions from Aluminum Production

Two PFCs (perfluoromethane (CF_4) and perfluoroethane (C_2F_6) are emitted during the process of primary aluminum smelting. PFCs are formed during the smelting process, when the aluminum oxide concentration of the electrolytic bath falls below the necessary levels required for electrolysis. This phenomenon is known as the “anode effect.” Generally, the level of emissions associated with aluminum production is contingent on the frequency and duration of the anode effects. The aluminum production industry is the second largest source of PFC emissions in the U.S.

Estimation Methodology

The U.S. EPA derives its methodology from the IPCC *Good Practice Guidance*, using the Tier 3b “slope method,” where PFC emissions are estimated using a per unit production emission factor that is expressed as a function of operating parameters (anode effect frequency and duration). Slope coefficients were either collected based on field measurements or taken directly from the IPCC *Good Practice Guidance*.

Smelter anode effect data collected by aluminum companies were then combined with the slope coefficients to estimate emission factors. To estimate emissions at the smelter-level, emission factors were multiplied by annual production data. Smelter-specific emissions were then aggregated to form a total national emissions estimate.

$$PFC_{CF_4 or C_2F_6} = S \times AE / CD$$

where,

$PFC_{CF4orC2F6}$ = Total emissions of a specific chemical from use in aluminum production (kilograms per metric ton of aluminum)

S = Slope coefficient

AE/CD = Anode Effect Minutes/Cell-Day[119]

Data Sources

U.S. EPA activity data for PFC emissions from aluminum production include aluminum production data obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (Washington, D.C., various years). U.S. EPA emission estimates of PFC were obtained from participants in the Voluntary Aluminum Industrial Partnership (VAIP) program. Where smelter-specific slope coefficients were not available, IPCC *Good Practice Guidance* coefficients were used. Information on anode effect data was obtained from the International Aluminum Institute's anode effect survey (IAI, 2000). (See Table 4-9).

Table 4-9. Data Sources for PFCs from Aluminum Production

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines,* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

4.2.2 HFC Emissions from HCFC-22 Production

Trifluoromethane (HFC-23 or CHF_3) is produced as a by-product during the manufacture of chlorodifluoromethane (HCFC-22), which is primarily used in refrigeration and air-conditioning systems and as a chemical feedstock. Although there are only a small number of plants that produce HCFC-22 (three production plants operated in the U.S. in 2003), production and use has increased significantly since 1990 as it has replaced chlorofluorocarbons (CFCs) in many applications. Because HCFC-22 is a potent greenhouse gas that depletes stratospheric ozone, its use for non-feedstock purposes is scheduled to be phased out by 2020 under the U.S. Clean Air Act.

Estimation Methodology

EIA obtains its emissions estimate for HFC-23 from the U.S. EPA, which is in turn obtained in cooperation with the U.S. manufacturers of HCFC-22. According to the U.S. EPA, the methodology is based upon measurements at individual production plants. Of the three HCFC-22

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[119] Anode Effect Minutes/Cell-Day = Anode Effect Frequency x Anode Effect Duration. As defined by the Intergovernmental Panel on Climate Change, a "cell-day" is the number of cells operating multiplied by the number of days of operation.

production plants in the U.S., two use thermal oxidation to abate their HFC-23 emissions. Plants using thermal oxidation technology monitor the performance of their oxidizers to verify the virtual elimination of all emissions of HFC-23. The remaining plants periodically measure HFC-23 emissions in the vent stream using gas chromatography. To estimate HFC-23 emissions, these measurements are then combined with data on quantities of feed components (e.g. HF) and products to estimate HFC-23 emissions using a material balance approach. Fugitive emissions of HFC-23 (e.g. from valves and water scrubbers) are insignificant at properly run manufacturing facilities.

Data Sources

All U.S. EPA activity data for HFC-23 emissions from HCFC-22 production include HCFC-22 production data obtained from U.S. manufacturers of HCFC-22. Although it is not clear exactly how or where U.S. EPA collects data or emission factors for HCFC-22 production, U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI) that are used as inputs to its modeling of HFC-23 emissions. (See Table 4-10).

Table 4-10. Data Sources for HFC-23 from HCFC-22 Production

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

4.2.3 HFC, PFC, and SF_6 Emissions from Semiconductor Manufacture

The semiconductor industry currently emits fluorocarbons (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3), trifluoromethane (HFC-23), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6). These gases are employed in varying combinations specific to the process of semiconductor manufacture, which is comprised of the following two steps: (1) Plasma etching thin films, and (2) cleaning chemical vapor deposition (CVD) tool chambers. According to U.S. EPA, a single semiconductor wafer may require as many as 100 distinct process steps that employ these gases. Each of the gases used can also be transformed in the plasma-etching process into a different HFC or PFC compound, which is then emitted into the atmosphere. For example, when either CHF_3 or C_2F_6 is used to clean or etch, CF_4 is produced and exhausted as a by-product.

Estimation Methodology

Emissions from semiconductor manufacturing were estimated using three distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, and 2000 and beyond. For 1990 through 1994, emissions were estimated using the most recent version of U.S. EPA's PFC Emissions Vintage Model (PEVM). This model estimates emissions for the period based on the historical consumption of silicon, the estimated average number of interconnecting layers in the chips produced, and an estimated per-layer emission factor.

For the years 1995-1999, emissions estimates were extrapolated from the total annual emissions reported by the participants to U.S. EPA's PFC Emission Reduction Partnership for the

Semiconductor Industry. The participants' reported emissions were multiplied by the ratio of the total layer-weighted capacity of all U.S. semiconductor plants as well as the total layer-weighted capacity of plants operated by program participants. This layer-weighted capacity of a plant consists of the silicon capacity of that plant multiplied by the number of layers used in chips produced at the plant. This method accounts for non-participants as well as it is assumed that all semiconductor producers have similar capacity utilizations and per-layer emission factors.

The U.S. estimate for the years 2000 through 2003—the period during which partners began the consequential application of PFC-reduction measures—used a different estimation method. The emissions reporting by Partnership participants for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions (those from non-partners), however, were estimated using PEVM and the method described above.

According to U.S. EPA, all participants since 2003 use a method on par with that of the IPCC method 2c, which is recommended in its *Good Practice Guidance*. In addition, U.S. EPA partners with relatively high emissions generally use the more accurate IPCC 2a or 2b methods. These more detailed methods require PFC consumption to be multiplied by process-specific emission factors that have either been measured or obtained from tool suppliers.

Data Sources

All U.S. EPA aggregate estimates for emissions from semiconductor manufacturing were obtained from semiconductor manufacturers participating in its PFC Emission Reduction Partnership for the Semiconductor Industry. Estimates of capacities and plant characteristics were derived from the Semiconductor Equipment and Materials International (SEMI) *World Fab Watch* (formerly *International Fabs on Disk*) database for the years 1996 until present. Estimates of silicon consumed by line-width for the years 1990 onward were derived from information from VLSI Research in 2003. U.S. EPA's figure for the number of layers per line-width was obtained from International SEMATECH's *International Technology Roadmap: 1998 till present.* It is not clear exactly how or where U.S. EPA collects other data or emission factors for the semiconductor manufacturing industry, although U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI). (See Table 4-11).

Table 4-11. Data Sources for High-GWP Gases from Semiconductor Manufacturing

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

4.2.4 SF_6 Emissions from Electrical Transmission and Distribution Equipment

Sulfur hexafluoride (SF_6) is used for electrical insulation, arc quenching, and current interruption in electrical transmission and distribution equipment. The electric power industry in the U.S. has used SF_6 since the 1950s, and is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 emissions from electrical transmission and distribution systems are the largest global source category for SF_6.

Emissions of SF_6 stem from a number of sources including, switch gear through seals (especially from older equipment), equipment installation, servicing and disposal. According to U.S. EPA, some electric utilities in the past vented SF_6 to the atmosphere during servicing and disposal; however, the relatively high cost of the gas as well as greater awareness has reduced this practice.

Estimation Methodology

The estimates of emissions from electric transmission and distribution are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

Emissions from Electric Power Systems from 1999 to present

Emissions from electric power systems from 1999 onward were estimated based on (1) reporting from utilities participating in U.S. EPA's SF_6 Emissions Reduction Partnership for Electric Power Systems, which began in 1999, and (2) utilities' transmission miles as reported in the 2001 and 2004 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV). Between 1999 and 2003, participating utilities represented between 31 percent and 35 percent of total U.S. transmission miles. The emissions reported by participating utilities each year were added to the emissions estimated for non-reporting utilities in that year. Emissions from non-reporting utilities were estimated using the results of a regression analysis that showed that the emissions of reporting utilities were most strongly correlated with their transmission miles. As described further below, the transmission miles of the various types of non-reporting utilities were multiplied by the appropriate regression coefficients, yielding an estimate of emissions. Transmission miles are clearly physically related to emissions, since in the United States, SF_6 is contained primarily in transmission equipment rated at or above 34.5 kV.

The regression equations reflect two distinctions among non-reporting utilities: (1) between small and large utilities (i.e., with less or more than 10,000 transmission miles, respectively), and (2) between utilities that do not participate in the SF_6 Emission Reduction Partnership (non-partners) and those that participate but that have not reported in a given year (non-reporting partners). (Historically, these non-reporting partners have accounted for 5 percent or less of total estimated partner emissions.) The distinction between small and large utilities was made because the regression analysis showed that the relationship between emissions and transmission miles differed for small and large facilities. The distinction between non-partners and non-reporting partners was made because the emission trends of these two groups were believed to be different. Reporting partners have reduced their emission rates significantly since 1999. The emission trend of non-reporting partners was believed to be similar to that of the reporting partners, because all partners commit to reducing SF_6 emissions through technically and economically feasible means. However, non-partners were assumed not to have implemented any changes that would have reduced emissions over time.

To estimate emissions from non-partners in every year since 1999, the following regression equations were used. These equations were developed based on the 1999 SF_6 emissions reported by 49 partner utilities (representing approximately 31 percent of U.S. transmission miles), and 2000 transmission mileage data obtained from the 2001 UDI Directory of Electric Power Producers and Distributors:

Non-partner small utilities (less than 10,000 transmission miles, in kilograms):
Emissions = 0.874 × Transmission Miles

Non-partner large utilities (more than 10,000 transmission miles, in kilograms):
Emissions = 0.558 × Transmission Miles

To estimate emissions from non-reporting partners in each year, the regression equations based on the emissions reported by partners in that year were used. To estimate non-reporting partner emissions, the regression equations are based on the SF_6 emissions reported by 51 partner utilities, and updated transmission mileage data obtained from the latest UDI Directory of Electric Power Producers and Distributors. The resulting equations:

Non-reporting partner small utilities (less than 10,000 transmission miles, in kilograms):
Emissions = 0.398 × Transmission Miles

Non-reporting partner large utilities (more than 10,000 transmission miles, in kilograms):
Emissions = 0.387 × Transmission Miles

UDI Directories of Electric Power Producers and Distributors are used to obtain U.S. transmission system growth.

For each year, total emissions were then determined by summing the partner-reported emissions, the non-reporting partner emissions (determined with that year's regression equation for the partners), and the non-partner emissions (determined using the 1999 regression equation).

1990 to 1998 Emissions from Manufacture of Electric Equipment

Because most participating utilities reported emissions only for 1999 onward, modeling SF_6 emissions from electric power systems for the years 1990 through 1998 was necessary. To do so, it was assumed that during this period, U.S. emissions followed the same trajectory as global emissions from this source. To estimate global emissions, the RAND survey of global SF_6 sales to electric utilities was used, together with the following equation, which is derived from the equation for emissions in the IPCC *Good Practice Guidance*:

Emissions (kilograms) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms)

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, lowering the amount of SF_6 purchased by utilities for this purpose.

Sulfur hexaflouride purchased to refill existing equipment in a given year was assumed to be approximately equal to the SF_6 purchased by utilities in that year. Gas purchases by utilities and equipment manufacturers from 1961 through 2001 are available from the RAND (2002) survey. To estimate the quantity of SF_6 released from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 77.5 percent of the amount of gas purchased by electrical equipment manufacturers 30 years previous (e.g., in 1990, the nameplate capacity of retiring equipment was assumed to equal 77.5 percent of the gas purchased in 1960). The remaining 22.5 percent was assumed to have been emitted at the time of manufacture. The 22.5 percent emission rate is an average of IPCC SF_6 emission rates for Europe and Japan for years before 1996. The 30-year lifetime for electrical equipment is also drawn from IPCC (2001).

The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1998.

To estimate U.S. emissions for 1990 through 1998, estimated global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. To estimate historical U.S. emissions, the factor for each year was multiplied by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be 15.8 Tg CO_2 Eq.).

Emissions from Manufacture of Electrical Equipment

Emissions estimates for original equipment manufacturers (OEMs) were derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF_6 charged into new equipment. The quantity of SF_6 charged into new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000; the quantities of SF_6 charged into new equipment for 2001 onward were assumed to equal that charged into equipment in 2000. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002.

Data Sources

U.S. EPA estimates for SF_6 emissions from the use of electrical transmission and distribution equipment were based on activity data from utilities participating in its SF_6 Emissions Reduction Partnership for Electric Power Systems, and equipment manufacturing statistics obtained from the National Electrical Manufacturers Association. The International Council on Large Electric Systems (CIGRE) formulated an emissions rate for OEMs in February 2002. It is not clear exactly how or where U.S. EPA collected other data or emission factors for this industry, although U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI). (See Table 4-12).

Table 4-12. Data Sources for High-GWP Gases from Electrical Transmission and Distribution Equipment

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

4.2.5 SF_6 Emissions from Magnesium Production and Processing

The magnesium industry uses SF_6 as a cover gas in foundries to prevent the oxidation of molten magnesium in the presence of air. It is assumed that all SF_6 used as a cover gas is emitted directly to the atmosphere, although a minute portion of the gas does react during magnesium production. SF_6 has largely replaced sulfur dioxide (SO_2) and salt fluxes over the last twenty years, as it is less toxic and corrosive than the other gases.

Estimation Methodology

Emission estimates for the magnesium industry incorporate information provided by industry participants in U.S. EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. The partnership started in 1999 and, currently, participating companies represent 100 percent of U.S. primary production and over 80 percent of the casting sector (i.e., die, gravity, wrought, and anode casting). Emissions for 1999 through the present from primary production, some secondary production (i.e., recycling), and a large fraction of die casting were reported by participants.

Emissions from 1999 onward from the remaining secondary production and casting were estimated by multiplying industry emission factors (kg SF_6 per metric ton of Mg produced or processed) by the amount of metal produced or consumed in the five major processes (other than primary production) that require SF_6 melt protection: 1) secondary production; 2) die casting; 3) gravity casting; 4) wrought products; and 5) anodes. (See Table 4-13).

Die casting emissions for 1999 onward, which accounted for 48 to 75 percent of all SF_6 emissions from U.S. casting and recycling processes during this period, were estimated based on information supplied by industry partners. From 2000 to 2003, partners accounted for all U.S. die casting that was tracked by USGS. In 1999, partners did not account for all die casting tracked by USGS, and, therefore, it was necessary to estimate the emissions of die casters who were not partners. Die casters who were not partners were assumed to be similar to partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emissions estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. The emission factors for the other industry sectors (i.e., secondary production, gravity, wrought, and anode casting) were based on discussions with industry representatives.

Table 4-13. SF_6 Emission Factors, Selected Years (kg SF_6 per ton of magnesium)

Year	Secondary	Die Casting	Gravity	Wrought	Anodes
1999	1	2.14[a]	2	1	1
2000	1	0.73	2	1	1
2001	1	0.77	2	1	1
2002	1	0.70	2	1	1
2003	1	0.84	2	1	1

[a] The 1999 factor is a weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Atmospheric Programs, Stratospheric Protection Division.

To estimate emissions for 1990 through 1998, industry emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. The primary production emission factors were 1.2 kg per metric ton for 1990 through 1993, and 1.1 kg per metric ton for 1994 through 1996. For die casting, an emission factor of 4.1 kg per metric ton was used for the period 1990 through 1996. For 1996 through 1998, the emission factors for primary production and die casting were assumed to decline linearly to the level estimated based on partner reports in 1999.

Data Sources

U.S. EPA estimates for SF_6 emissions from the magnesium industry are based on activity data from companies participating in its SF_6 Emissions Reduction Partnership for the Magnesium Industry, as well as U.S. magnesium metal production and consumption data for the years 1990-2001 from the USGS. Emission factors for the years 1999-2001 were derived from information from participants. Emission factors for earlier years were obtained from a number of sources including, U.S. primary producers and international survey data. It is not clear exactly how or where U.S. EPA collected other data or emission factors for this industry, although U.S. EPA does coordinate extensively with numerous trade associations and individual companies to attain certain data classified as Confidential Business Information (CBI). (See Table 4-14).

Table 4-14. Data Sources for SF_6 from Magnesium Production and Processing

Data Utilized	Citation
Emission factors, Methodology	U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* (Washington, D.C., various years), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.
Methodology	Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

5. Sequestration from Land Use Change and Forestry

5.1 Carbon Dioxide Sequestration from Land Use Change and Forestry

Types of Sequestration

The following greenhouse gas fluxes are reported - Forest Land Remaining Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, and Land Converted to Grassland. Fluxes resulting from Settlements Remaining Settlements include those from urban trees and soil fertilization. Landfilled yard trimmings and food scraps are accounted for separately under Other. This categorization follows the IPCC *Good Practice Guidance for Land Use, Land-Use Change and Forestry*[120] (*LULUCF GPG*) .

Five forest and two product carbon pools are assessed. The five forest pools are: above-ground biomass (includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage, and the live understory), below-ground biomass, dead wood (includes all non-living woody biomass either standing, lying on the ground excluding litter, or in the soil), litter (includes the litter, fumic, and humic layers, and all non-living biomass with a diameter less than 7.5 cm at transect intersection, lying on the ground), soil organic carbon (including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the aboveground pools); and the two product pools are harvested wood products (HWP) in use and harvested wood products in solid waste disposal sites (SWDS).

For the cropland and grassland categories, the carbon stocks assessed include changes in organic carbon stocks in mineral and organic soils due to land use and management, and liming (emissions of carbon dioxide due to the application of crushed limestone and dolomite).

Estimation Methodology

All of the sequestration estimates for this chapter are derived directly from the U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.[121] The U.S. EPA estimates of carbon dioxide flux from each of the five forest pools were derived from U.S. forest inventory data, using methodologies that are consistent with the *LULUCF GPG and the Revised 1996 IPCC Guidelines*.[122] Except for carbon dioxide from wood products, urban trees, and liming, the flux

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[120] Intergovernmental Panel on Climate Change, *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (Hayama, Japan, 2003), www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm.

[121] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005*, EPA 430-R-07-002 (Washington, DC, April 2007), www.epa.gov/climatechange/emissions/usinventoryreport.html.

[122] Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme, *Good Practice Guidance for Land Use, Land-Use Change and Forestry*, (Hayama, Japan, 2003), www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_ contents.htm.

estimates were based on activity data collected at multiple-year intervals, which are in the form of forest, land-use, and municipal solid waste surveys. Carbon dioxide fluxes from forest carbon stocks (except the wood product components) and from agricultural soils (except the liming component) are calculated on an average annual basis from data collected in intervals ranging from 1 to 10 years. The resulting annual averages are applied to years between surveys. The five forest carbon pools are estimated using inventory data and a collection of conversion factors and models. Estimates of the HWP carbon pool are based on methods described in Skog (in preparation) using the WOODCARB II model, which are consistent with IPCC national inventory guidelines.[123] The United States uses the production accounting approach to report HWP contribution.

As compared to previous years, this year's inventory includes a dramatic change in the difference between the early and later year estimates of forest carbon stocks. This is largely due to the increased use of sub-state classification of the survey data. For the current inventory, the emphasis was on improving consistency between successive surveys or portions of surveys when sub-state portions of inventory data provided better continuity. The new calculations of forest carbon stocks in 1990 decreased the estimate of carbon sequestration by 23 percent while increasing carbon sequestration estimates for forest carbon stocks in 2004 by 9 percent. State-level inventory data changed more dramatically for some particular states as compared to others. For the state of California, past inventories included chaparral ecosystems in forest inventory data. Since much of this ecological community type fails to meet the definition of forestland, the non-forest component is not included in inventory data. Maintaining consistency across the time series required removing non-forest chaparral estimates from California's total stock estimates in earlier inventories. This caused a dramatic decrease in forest carbon stock estimates at the early part of the time series for the state of California compared to those California estimates used for the previous inventory submission.

Agricultural mineral and organic soil carbon flux calculations are based primarily on national surveys, so these results are largely constant over multi-year intervals, with large discontinuities between intervals. Carbon fluxes in mineral soils for the agricultural categories was determined using the Century biogeochemical model or an IPCC Tier II method.[124] Carbon dioxide emissions from the degradation of limestone and dolomite applied to agricultural soils were calculated by multiplying the annual amounts of limestone and dolomite applied by carbon dioxide emission factors from the *LULUCF GPG*. For the landfilled yard trimmings and food scraps source, periodic solid waste survey data were interpolated so that annual storage estimates could be derived. In addition, because the most recent national forest, land-use, and municipal solid waste surveys were completed prior to 2005, the estimates of carbon dioxide flux from forests, agricultural soils, and landfilled yard trimmings and food scraps are based in part on extrapolation. Changes in the carbon stocks of urban trees were estimated based on field measurements in ten U.S. cities made over the period 1990 through 1999 and data on national urban tree cover, using a methodology consistent with the *LULUCF GPG*. Changes in the carbon

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[123] Skog, K. E. (in preparation) "Sequestration of carbon in harvested wood products for the United States."; IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, H.S. Eggleston, L. Buenida, K. Miwa, T Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES).Hayama, Kanagawa, Japan.

[124] The CENTURY model is a soil organic matter model which embodies the best understanding to date of the biogeochemistry of carbon, nitrogen, phosphorus, and sulphur. The primary purposes of the model are to provide a tool for ecosystem analysis, to test the consistency of data and to evaluate the effect of changes in management and climate on ecosystems. www.nrel.colostate.edu/projects/century5/

stocks of yard trimmings and food scraps in landfills were estimated using an analysis of life-cycle greenhouse gas emissions and sinks associated with solid waste management.

Data Sources

The estimates of carbon stocks, with the exception of those from wood products, urban trees and liming, are based on periodic activity data in the form of forest, land-use, and municipal solid waste surveys. The estimates of changes in forest carbon stocks were made using the newer USDA Forestry Inventory and Analysis Database (FIADB 2.1) datasets. To achieve consistent representation (spatial and temporal), older FIA plot- and tree-level data and Resources Planning Act Assessment (RPA) databases, are used mostly to provide the data at or before 1990.[125] Estimates of the HWP variables and the HWP Contribution under the production accounting approach use data from U.S. Census and USDA Forest Service surveys of production and trade. Factors to convert wood and paper from original units to C units are based on estimates by industry and Forest Service published sources. Changes in forest soil organic carbon were derived from changes in forest area and estimates of the organic carbon content of soils from the USDA State Soil Geographic (STATSGO) database.[126] Soil carbon stock changes were estimated for Cropland Remaining Cropland and agricultural land falling in the other cropland and grassland categories according to land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2000).[127]. Mineral soil carbon fluxes were based on NRI data, annual data on tillage activity from the Conservation Technology Information Center (CTIC 1998), fertilizer use from the USDA Economic Research Service Cropping Practices Survey, and additional data from the National Agricultural Statistics Service.[128] The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys.*[129] For the carbon stocks in landfilled yard trimmings and food scraps, periodic solid waste survey data from U.S. EPA from 2003 and earlier years were interpolated so that annual storage estimates could be derived.[130]

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[125] The U.S. Department of Agriculture's Forest Inventory and Analysis (FIA) Program provides the information needed to assess forests in the United States. Through an annual survey, FIA reports on status and trends in forest area and location. http://fia.fs.fed.us.

The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) requires the Secretary of Agriculture to conduct an assessment of the Nation's renewable resources every 10 years, www.fs.fed.us/pl/rpa/what.htm.

[126] The State Soil Geographic (STATSGO) database is a 1:250,000 scale generalized soils database, prepared by the National Resources Conservation Service of the U.S. Department of Agriculture, www.ncgc.nrcs.usda.gov/products/datasets/statsgo.

[127] The National Resource Inventory (NRI) is a statistically-based sample of all non-federal land, and includes about 400,000 points in agricultural land of the conterminous United States and Hawaii. It is prepared by the United States Department of Agriculture, Natural Resources Conservation Service www.nrcs.usda.gov/technical/NRI/.

[128] The Conservation Technology Information Center is a national, public-private partnership that envisions agriculture using environmentally beneficial and economically viable natural resource systems. www.ctic.purdue.edu/.

The Economic Research Service is a primary source of economic information and research in the U.S. Department of Agriculture, www.ers.usda.gov/AboutERS/.

The National Agricultural Statistics Service provides timely, accurate, and useful statistics in service to U.S. agriculture, www.nass.usda.gov/.

[129] Both publications are published by the United States Geological Survey, Reston, VA.

[130] United States Environmental Protection Agency. *Municipal Solid Waste in the United States*: *Facts and Figures*, (various years), Office of Solid Waste and Emergency Response, Washington, DC.

Part II

Variables Used in Emission Estimates

6. Carbon Coefficients

This documentation presents the background and methodology for estimating the carbon coefficients of fossil fuels combusted in the United States. The carbon coefficient of a particular fossil fuel represents the maximum potential emissions to the atmosphere if all carbon in the fuel is oxidized during combustion. The carbon coefficients used in earlier editions of this report were developed using methods first outlined in the EIA report, *Emissions of Greenhouse Gases in the United States: 1987 – 1992*. The carbon coefficients in that report were developed to replace, in part, the more general coefficients originally developed by Marland and Pippin and subsequently adopted by the IPCC.[131] The IPCC coefficients were intended to be suitable for all countries, and to support the division of petroleum consumption into the products defined by the International Energy Agency (IEA). Because U.S. fuels sometimes differ in composition from those used abroad and EIA divides petroleum product consumption into more than 20 different categories, rather than the six described by the IEA, the development of U.S. specific carbon coefficients improved the precision of U.S. carbon emission estimates.

This documentation provides a detailed list of methods and data sources for estimating the carbon coefficients of coal (by consuming sector), natural gas (broken into pipeline-quality and flared gas), and petroleum products. Though the methods for estimating carbon contents for coal, natural gas, and petroleum products differ in their details, they each follow the same basic approach. First, because carbon coefficients are presented in terms of mass/unit-energy (i.e., million metric tons carbon per quadrillion Btu or MMTC/QBtu), those fuels that are typically described in volumetric units (petroleum products and natural gas) are converted to units of mass using an estimated density. Next, carbon contents are derived from fuel sample data, using descriptive statistics to estimate the carbon share of the fuel by weight. The heat content of the fuel is then estimated based on the sample data, or where sample data are unavailable or unrepresentative, by default values that reflect the characteristics of the fuel as defined by market requirements. A summary of carbon coefficients used in this report appears in Table 6-1.

This documentation also supplies a detailed discussion of each fuel and its derived carbon coefficient below. The discussion begins with the carbon contents of coal because about one-third of all U.S. carbon emissions from fossil fuel combustion are associated with coal consumption. The estimated carbon coefficients of coal were revised in October, 2004 to reflect the composition of a new set of coal samples from the U.S. Geological Survey, Coal Quality Database Version 2.0. This appendix then discusses the methods and sources for estimating the carbon content of natural gas. About one-fifth of U.S. greenhouse gas emissions from fossil fuel combustion are attributable to natural gas consumption. Finally, this documentation examines carbon contents of petroleum products. There are more than 20 different petroleum products accounted for in U.S. energy consumption statistics.

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[131] G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol.14 (1990), pp. 319-336. Intergovernmental Panel on Climate Change, *Estimation of Greenhouse Gases and Sinks*, (1991), p.2.18.

Table 6-1. Carbon Dioxide Coefficients Used in *Emissions of Greenhouse Gases in the United States*, selected years (Million Metric Tons Carbon Dioxide per Quadrillion Btu)

Fuel Type	1990	1995	2000	2004	2005	P2006
Coal						
Coal (Residential)	95.03	95.35	95.35	95.35	95.35	95.35
Coal (Commercial)	95.03	95.35	95.35	95.35	95.35	95.35
Coal (Industrial Coking)	93.53	93.62	93.71	93.71	93.71	93.71
Coal (Industrial Other)	93.80	93.98	93.98	93.98	93.98	93.98
Coal (Electric Power Sector)	94.17	94.39	94.50	94.70	94.70	94.70
Natural Gas						
Natural Gas (Pipeline)	53.06	53.06	53.06	53.06	53.06	53.06
Natural Gas (Flared)	54.71	54.71	54.71	54.71	54.71	54.71
Petroleum						
Asphalt and Road Oil	75.61	75.61	75.61	75.61	75.61	75.61
Aviation Gasoline	69.19	69.19	69.19	69.19	69.19	69.19
Crude Oil	73.91	74.17	74.19	74.54	74.54	74.54
Distillate Fuel	73.15	73.15	73.15	73.15	73.15	73.15
Jet Fuel	71.14	70.90	70.88	70.88	70.88	70.88
Kerosene	72.31	72.31	72.31	72.31	72.31	72.31
LPG	62.29	62.32	62.27	62.28	62.28	62.28
Lubricants	74.21	74.21	74.21	74.21	74.21	74.21
Motor Gasoline	71.17	71.06	70.91	70.88	70.88	70.88
Petrochemical Feed.	71.02	71.02	71.02	71.02	71.02	71.02
Petroleum Coke	102.12	102.12	102.12	102.12	102.12	102.12
Residual Fuel	78.80	78.80	78.80	78.80	78.80	78.80
Waxes	72.64	72.64	72.64	72.64	72.64	72.64

Note: All coefficients based on Higher Heating (Gross Calorific) Value and assume 100 percent combustion
p=Preliminary

Sources: Carbon coefficients for coal from U.S. Geological Survey, U.S. Coal Quality Database Version 2.0 (1998) and analysis prepared by Science Applications International Corporation (SAIC) for the U.S. Environmental Protection Agency, Office of Air and Radiation, Market Policies Branch, October 2002. Carbon coefficients for natural gas from *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573 (Washington, D.C., November, 1994,) Appendix A based on Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States.* Carbon coefficients for petroleum products from *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573 (Washington, D.C., November, 1994,) Appendix A with coefficients for Motor Gasoline updated annually by Science Applications International Corporation. Carbon coefficients change very little from year to year, but for a full time series contact the author of this report.

6.1 Coal

Approximately one-third of all U.S. carbon dioxide emissions from fossil fuel combustion are associated with coal consumption. Because EIA collects coal consumption data by consuming sector, EIA adopted carbon coefficients by consuming sector. Because the carbon content of coal varies by the state in which it was mined and by coal rank, and the sources of coal for each consuming sector vary by year, the weighted average carbon coefficient for coal combusted in each consuming sector also varies over time. Carbon coefficients by coal rank and consuming sector for selected years appear in Table 6-2. Since the IPCC guidelines provide carbon coefficients by rank, EIA also adopted carbon coefficients by rank for comparison with other nations' carbon coefficients.

Table 6-2. Carbon Dioxide Coefficients for Coal by Consuming Sector and Coal Rank, Selected Years (Million Metric Tons per Quadrillion Btu)

	1990	1995	2000	2004	2005	P2006
Consuming Sector						
Electric Power	94.17	94.39	94.50	94.70	94.70	94.70
Industrial Coking	93.53	93.62	93.71	93.71	93.71	93.71
Other Industrial	93.80	93.98	93.98	93.98	93.98	93.98
Residential/Commercial	95.03	95.35	95.35	95.35	95.35	95.35
Coal Rank						
Anthracite	103.63	103.63	103.63	103.63	103.63	103.63
Bituminous	93.25	93.39	93.45	93.45	93.45	93.45
Sub-bituminous	97.15	97.14	97.10	97.10	97.10	97.10
Lignite	96.03	97.21	97.43	97.43	97.43	97.43

P = Preliminary
Note: All coefficients based on Higher Heating (Gross Calorific) Value and assume 100 percent combustion.

Sources: U.S. Geological Survey, U.S Coal Quality Database Version 2.0 (1998) and analysis prepared by Science Applications International Corporation (SAIC) for the U.S. Environmental Protection Agency, Office of Air and Radiation, Market Policies Branch, October 2002. Carbon coefficients change very little from year to year, but for a full time series contact the author of this report.

Estimation Methods

Carbon coefficients are estimated on the basis of 6,588 coal samples collected by the U.S. Geological Survey between 1973 and 1989. These coal samples are classified according to rank and state of origin. For each rank in each state, the average heat content and carbon content of the coal samples are calculated. Dividing the carbon content (reported in pounds carbon dioxide) by the heat content (reported in million Btu) yields an average carbon coefficient. This coefficient is then converted into units of million metric tons per quadrillion Btu.

U.S. energy statistics provide data on the origin of coal used in four areas: 1) the electric power industry 2) industrial coking, 3) all other industrial uses, and 4) the residential and commercial end-use sectors. Because U.S. energy statistics do not provide the distribution of coal rank consumed by each consuming sector, it is assumed that each sector consumes a representative mixture of coal ranks from a particular state that matches the mixture of all coal produced in that state during the year. Sectoral carbon coefficients are then calculated by multiplying the share of coal purchased from each state by rank by the carbon coefficient estimated above. The resulting partial carbon coefficients are then totaled across all states and ranks to generate a national sectoral carbon coefficient.

Although not used to calculate emissions, national-level carbon contents by rank are more easily compared to carbon contents of other countries than are sectoral carbon contents. State-level carbon coefficients by rank developed above are weighted by overall coal production by state and rank (consumption by rank is unavailable in U.S. energy statistics) to support this comparison. Each state-level carbon coefficient by rank is multiplied by the share of national production of that rank that each state represents. The resulting partial carbon coefficients are then summed across all states to generate an overall carbon coefficient for each rank.

The estimates of carbon coefficients for coal were updated and revised in 2002. The methodology employed for these estimates was unchanged from previous years; however, the underlying coal data sample set was updated. Previously, a set of 5,426 coal samples from the EIA coal analysis file was used to develop carbon content estimates. The results from that sample set appear above in Table 6-2. The EIA Coal Analysis File was originally developed by the U.S. Bureau of Mines and contained over 60,000 coal samples obtained at numerous coal seams throughout the United States. Many of the samples were collected as early as the 1940s and 1950s, with sample collection continuing until the 1980s. The updated sample set included 6,588 coal samples collected by the U.S. Geological Survey between 1973 and 1989.

Data Sources

Ultimate analyses of 6,588 coal samples were obtained from the U.S. Geological Survey, CoalQual Database Version 2.0 (1998). Data contained in the CoalQual Database are largely derived from samples taken between 1973 and 1989, and were largely reported on in State Geological Surveys.

Coal distribution by state and consumption by sector from EIA, *Coal Industry Annual* (Washington, D.C., various years) Table 10 and Table 63. www.eia.doe.gov/cneaf/coal/cia/cia_sum.html.

Coal production by state and rank from EIA, *Coal Industry Annual* (Washington, D.C., various years) Table 9.www.eia.doe.gov/cneaf/coal/cia/cia_sum.html.

6.2 Natural Gas

Natural gas is predominantly composed of methane, which is 75 percent carbon by weight and contains 14.2 million metric tons carbon per quadrillion Btu (Higher Heating Value), but it may also contain many other compounds that can lower or raise its overall carbon content. These other compounds may be divided into two classes: 1) natural gas liquids (NGLs) and 2) non-hydrocarbon gases. The most common NGLs are ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and, to a lesser extent, pentane (C_5H_{12}) and hexane (C_6H_{14}). Because the NGLs have more carbon atoms than methane (which has only one) their presence increases the overall carbon content of natural gas. NGLs have a commercial value greater than that of methane, and therefore are usually separated from raw natural gas at gas processing plants and sold as separate products. Ethane is typically used as a petrochemical feedstock, propane and butane have diverse uses, and natural gasoline[132] contributes to the gasoline/naphtha "octane pool" used primarily to make motor gasoline.

Raw natural gas can also contain varying amounts of non-hydrocarbon gases, such as carbon dioxide, nitrogen, helium and other noble gases, and hydrogen sulfide. The share of non-hydrocarbon gases is usually less than 5 percent of the total, but there are individual natural gas reservoirs where the share can be much larger. The treatment of non-hydrocarbon gases in raw gas varies. Hydrogen sulfide is always removed. Inert gases are removed if their presence is substantial enough to reduce the energy content of the gas below pipeline specifications. Otherwise, inert gases will usually be left in the natural gas. Because the raw gas that is usually flared contains NGLs and carbon dioxide, it will typically have a higher overall carbon content than gas that has been processed and moved to end-use customers via transmission and distribution pipeline.

Estimation Methods

In the United States, pipeline-quality natural gas is expected to have an energy content greater than 970 Btu per cubic foot but less than 1,100 Btu per cubic foot. Hydrogen sulfide content must be negligible. Typical pipeline-quality natural gas is about 95 percent methane, 3 percent NGLs, and 2 percent non-hydrocarbon gases, of which perhaps 1 percent is carbon dioxide.

However, there is a range of gas compositions that are consistent with pipeline specifications. The minimum carbon coefficient for natural gas would match that for pure methane, 1,005 Btu per standard cubic foot. Gas compositions with higher or lower Btu content tend to have higher carbon emission factors, because the "low" Btu gas has a higher content of inert gases (including carbon dioxide offset with more NGLs), while "high" Btu gas tends to have more NGLs.

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

> There may be no market for some batches of natural gas, the amount may be too small or too variable, or the quality too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of carbon dioxide). All natural gas flared for these reasons is probably "rich" associated gas, with a relatively high energy content, high NGL content, and high carbon content.
>
> Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.
>
> Data on the energy content of flare gas, as reported by states to EIA, indicates an energy content of 1,130 Btu per standard cubic foot. Flare gas may have a higher energy content than reported by EIA since rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot.

A relationship between carbon content and heat content may be used to develop a carbon coefficient for natural gas consumed in the United States. In 1994, EIA examined the composition (and therefore carbon contents) of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 States. To demonstrate that these samples

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[132] A term used in the gas processing industry to refer to a mixture of liquid hydrocarbons (mostly pentanes and heavier hydrocarbons) extracted from natural gas.

were representative of actual natural gas "as consumed" in the U.S., their heat content was compared to that of the national average. For the most recent year, the average heat content of natural gas consumed in the U.S. was 1,025 Btu per cubic foot, varying by less than 1 percent (1,025 to 1,031 Btu per cubic foot) over the past 5 years. Meanwhile the average heat content of the 6,743 samples was 1,027 Btu per cubic foot and the median heat content was 1,031 Btu per cubic foot. Thus, the average heat content of the sample set falls well within the typical range of natural gas consumed in the United States, suggesting that these samples continue to be representative of natural gas "as consumed" in the U.S. The average and median composition of these samples appears in Table 6-3.

Table 6-3. Composition of Natural Gas (Percent)

Compound	Average	Median
Methane	93.07	95.00
Ethane	3.21	2.79
Propane	0.59	0.48
Higher Hydrocarbons	0.32	0.30
Non-hydrocarbons	2.81	1.43
Higher Heating Value (Btu per cubic foot)	1,027	1,032

Source: Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States.*

Carbon coefficients were then calculated for eight separate sub-samples based on heat content and shown in Table 6-4.

Table 6-4. Carbon Content of Pipeline-Quality Natural Gas by Energy Content (Million Metric Tons per Quadrillion Btu)

Sample	Average Carbon Coefficient
GRI Full Sample	14.51
Greater than 1,000 Btu	14.47
1,025 to 1,035 Btu	14.45
975 to 1,000 Btu	14.73
1,000 to 1,025 Btu	14.43
1,025 to 1,050 Btu	14.47
1,050 to 1,075 Btu	14.58
1,075 to 1,100 Btu	14.65
Greater than 1,100 Btu	14.92
Weighted National Average	14.47

Note: All coefficients based on Higher Heating (Gross Calorific) Value and assume 100 percent combustion

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573 (Washington, D.C., November, 1994,) Appendix A.

Because there is some regional variation in the energy content of natural gas consumed, a weighted national average carbon content was calculated using the average carbon contents for each sub-sample of gas that conformed with each individual state's typical cubic foot of natural gas. The result was a weighted national average of 14.47 million metric tons per quadrillion Btu. This was identical to the average carbon coefficient for all samples with more than 1,000 Btu per cubic foot and the average carbon coefficient for all samples with a heat content between 1,025 and 1,050 Btu per cubic foot. Because those samples with a heat content below 1,000 Btu had an unusually high carbon coefficient attributable to large portions of carbon dioxide (not seen in the median sample), they were excluded from the final sample so as not to bias the carbon coefficient upwards.

Selecting a carbon coefficient for flare gas was much more difficult than for pipeline natural gas because of the uncertainty of its composition. Because EIA estimates the heat content of flare gas at 1,130 Btu per cubic foot, the average carbon coefficient for samples with more than 1,100 Btu per cubic foot, 14.92 million metric tons per quadrillion Btu, was adopted as the coefficient for flare gas. It should be noted that the sample data set did not include any samples with more than 1,130 Btu per cubic foot.

Data Sources

Natural gas samples were obtained from a Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States.

Average heat content of natural gas consumed in the U.S. from is EIA, *Monthly Energy Review* (Washington, D.C.), Table A4. www.eia.doe.gov/emeu/mer/contents.html.

Average heat content consumed on a state by state basis is from EIA, *State Energy Data Report* (Washington, D.C.), Table 1 and 2. www.eia.doe.gov/emeu/sedr/contents.html#PDF%20Files.

6.3 Petroleum

There are four critical determinants of the carbon coefficient for a petroleum-based fuel:

1) The density of the fuel (e.g., the weight in kilograms of one barrel of fuel);

2) The fraction by mass of the product that consists of hydrocarbons, and the fraction of non-hydrocarbon impurities;

3) The specific types of 'families' of hydrocarbons that make up the hydrocarbon portion of the fuel; and

4) The heat content of the fuel.

Petroleum products vary between 5.6 degrees API gravity (dense products such as asphalt and road oil) and 247 degrees (ethane).[133] This is a range in density of 60 to 150 kilograms per barrel,

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[133] API gravity is an arbitrary scale expressing the gravity or density of liquid petroleum products, as established by the American Petroleum Institute (API). The measuring scale is calibrated in terms of degrees API. The higher the API gravity, the lighter the compound. Light crude oils generally exceed 38

or ±50 percent. The variation in carbon content, however, is much smaller (±5 to 7 percent): ethane is 80 percent carbon by weight, while petroleum coke is 90 to 92 percent carbon. The tightly bound range of carbon contents can be explained by basic petroleum chemistry.

6.3.1 Petroleum Chemistry

Crude oil and petroleum products are typically mixtures of several hundred distinct compounds, predominantly hydrocarbons. All hydrocarbons contain hydrogen and carbon in various proportions. When crude oil is distilled into petroleum products, it is sorted into fractions by the boiling temperature of these hundreds of organic compounds. Boiling temperature is strongly correlated with the number of carbon atoms in each molecule. Petroleum products consisting of relatively simple molecules and few carbon atoms have low boiling temperatures and, larger molecules with more carbon atoms have higher boiling temperatures.

Products that boil off at higher temperatures are usually more dense, which implies greater carbon content as well. Petroleum products with higher carbon contents, in general, have lower energy content per unit mass and higher energy content per unit volume than products with a lower carbon content. Empirical research led to the establishment of a set of quantitative relationships between density, energy content per unit weight and volume, and carbon and hydrogen content. Figure 6-1 compares carbon coefficients calculated on the basis of the derived formula with fuel sample-based carbon coefficients for a range of crude oils, fuel oils, petroleum products, and pure hydrocarbons. The actual fuel samples were drawn from the sources described below in the discussions of individual petroleum products.

The derived empirical relationship between carbon content per unit heat and density is based on the types of hydrocarbons most frequently encountered. Actual petroleum fuels can vary from this relationship due to non-hydrocarbon impurities and variations in molecular structure among classes of hydrocarbons. In the absence of more exact information, this empirical relationship offers a good indication of carbon content.

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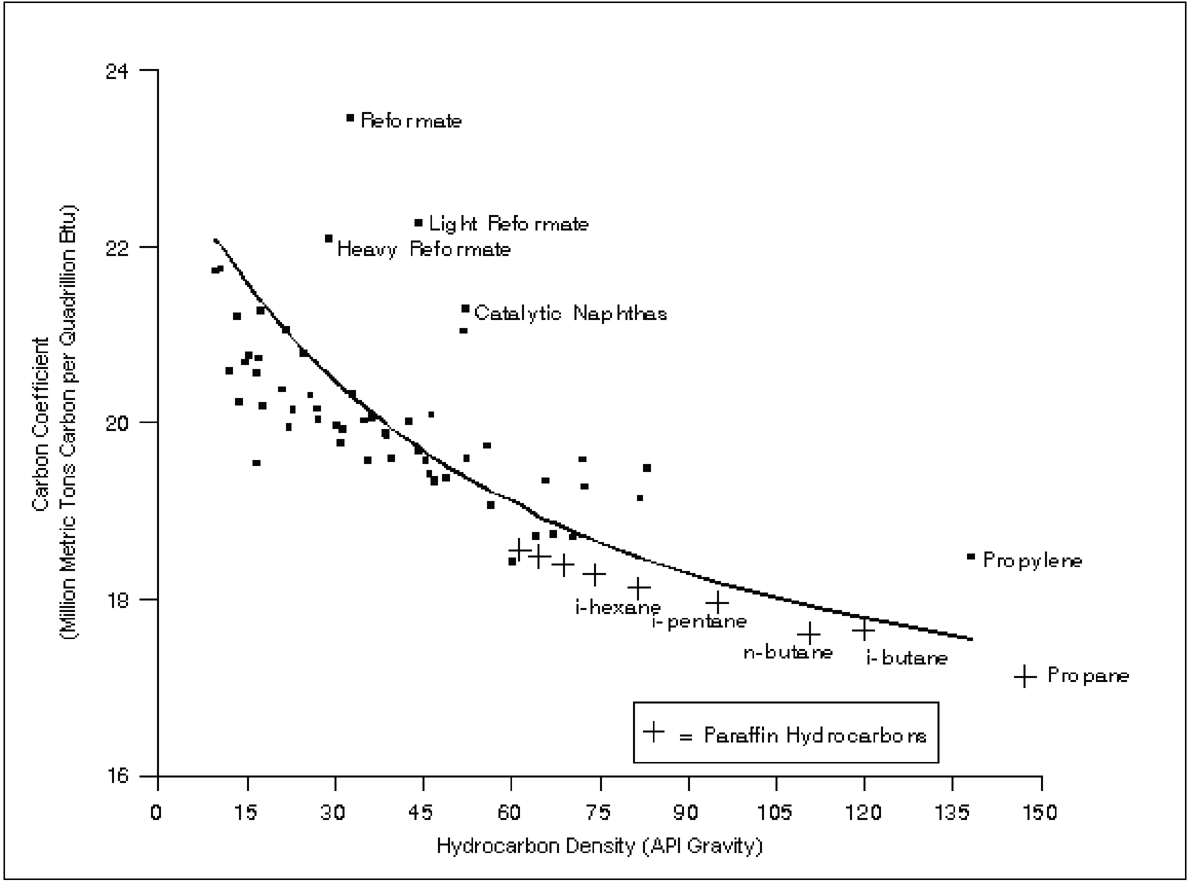
degrees API and heavy crude oils are all crude oils with an API gravity of 22 degrees or below. Intermediate crude oils fall in the range of 22 degrees to 38 degrees API gravity. API gravity can by calculated with the following formula Degrees API = (141.5/Specific Gravity) – 131.5. Specific gravity is the density of a material relative to that of water. At standard temperature and pressure, there are 62.36 pounds of water per cubic foot, or 8.337 pounds water per gallon.

Figure 6-1. Estimated and Actual Relationships between Petroleum Carbon Coefficients and Hydrocarbon Density



Source: Carbon content factors for paraffins are calculated based on the properties of hydrocarbons in V. Guthrie (ed.), *Petroleum Products Handbook* (New York: McGraw Hill, 1960) p. 33. Carbon content factors from other petroleum products are drawn from sources described below. Relationship between density and emission factors based on the relationship between density and energy content in U.S. Department of Commerce, National Bureau of Standards, *Thermal Properties of Petroleum Products*, Miscellaneous Publication, No. 97 (Washington, D.C., 1929), pp.16-21, and relationship between energy content and fuel composition in S. Ringen, J. Lanum, and F.P. Miknis, “Calculating Heating Values from the Elemental Composition of Fossil Fuels,’ *Fuel,* Vol. 58 (January 1979), p.69.

Non-hydrocarbon Impurities

Most fuels contain a certain share of non-hydrocarbon material. This is also primarily true of crude oils and fuel oils. The most common impurity is sulfur, which typically accounts for between 0.5 and 4 percent of the mass of most crude oils, and can form an even higher percentage of heavy fuel oils. Some crude oils and fuel oils also contain appreciable quantities of oxygen and nitrogen, typically in the form of asphaltenes or various acids. The nitrogen and oxygen content of crude oils can range from near zero to a few percent by weight. Lighter petroleum products have much lower levels of impurities, because the refining process tends to concentrate all of the non-hydrocarbons in the residual oil fraction. Light products usually contain less than 0.5 percent non-hydrocarbons by mass. Thus, the carbon content of heavy fuel oils can often be several percent lower than that of lighter fuels, due entirely to the presence of non-hydrocarbons.

Variations in Hydrocarbon Classes

Hydrocarbons can be divided into five general categories, each with a distinctive relationship between density and carbon content and physical properties. Refiners tend to control the mix of hydrocarbon types in particular products in order to give petroleum products distinct properties. The main classes of hydrocarbons are described below.

Paraffins. Paraffins are the most common constituents of crude oil, usually comprising 60 percent by mass. Paraffins are straight-chain hydrocarbons with the general formula C_nH_{2n+2}. Paraffins include ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and octane (C_8H_{18}). As the chemical formula suggests, the carbon content of the paraffins increases with their carbon number: ethane is 80 percent carbon by weight, octane 84 percent. As the size of paraffin molecules increases, the carbon content approaches the limiting value of 85.7 percent asymptotically. (See Figure 6-2.)

Cycloparaffins. Cycloparaffins are similar to paraffins, except that the carbon molecules form ring structures rather than straight chains, and consequently require two fewer hydrogen molecules than paraffins. Cycloparaffins always have the general formula C_nH_{2n} and are 85.7 percent carbon by mass, regardless of molecular size.

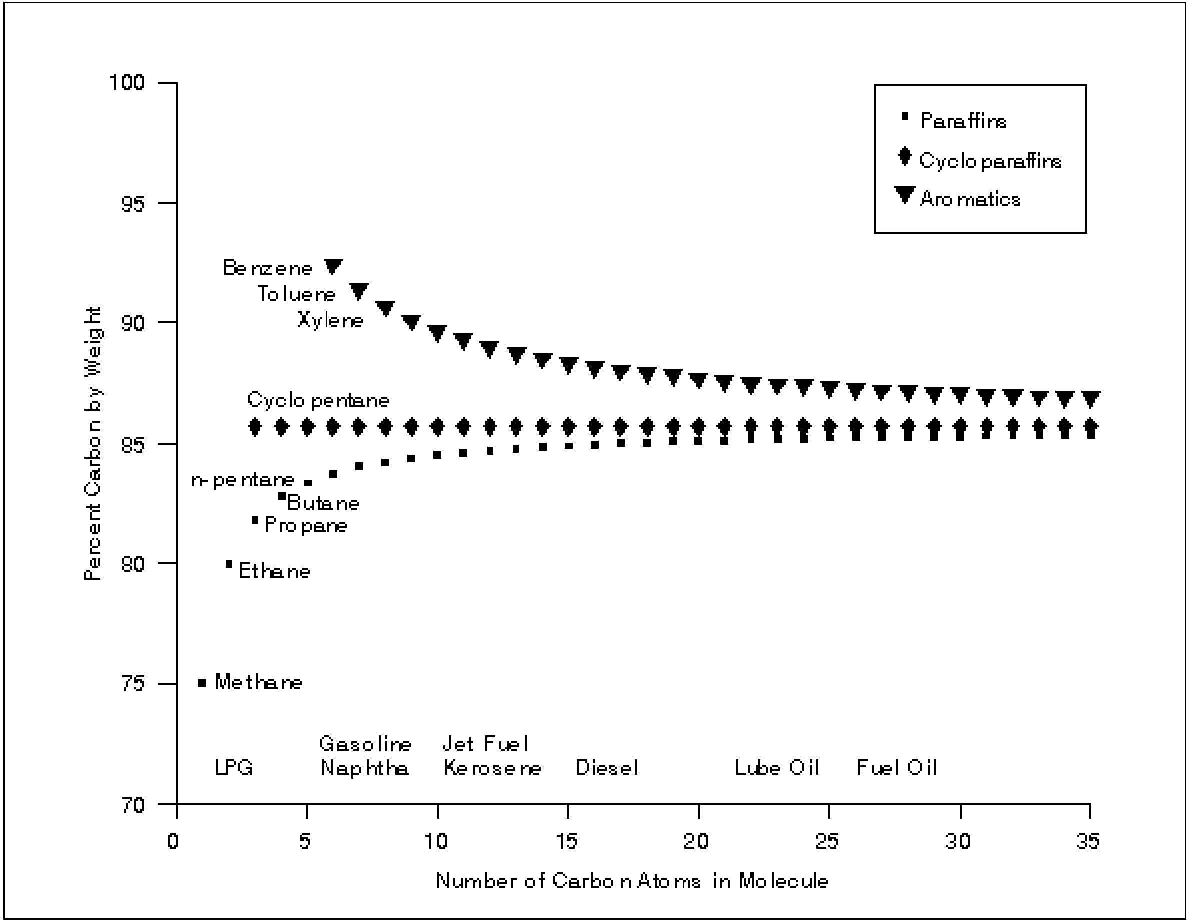
Olefins. Olefins are a reactive and unstable form of paraffin: a straight chain with the two hydrogen atoms at each end of the chain missing. They are never found in crude oil but are created in moderate quantities by the refining process. Thus, gasoline, for example, may contain 2 percent olefins. They also have the general formula C_nH_{2n}, and hence are also always 85.7 percent carbon by weight. Propylene (C_3H_6), a common intermediate petrochemical product, is an olefin.

Aromatics. Aromatics are very reactive hydrocarbons that are relatively uncommon in crude oil (10 percent or less). Light aromatics increase the octane level in gasoline, and consequently are deliberately created by steam reforming of naphtha. Aromatics also take the form of ring structures with some double bonds between carbon atoms. The most common aromatics are benzene (C_6H_6), toluene (C_7H_8), and xylene (C_8H_{10}). The general formula for aromatics is C_nH_{2n-6}. Benzene is 92 percent carbon by mass, while xylene is 90.6 percent carbon by mass. Unlike the other hydrocarbon families, the carbon content of aromatics declines asymptotically toward 85.7 percent with increasing carbon number and density. (See Figure 6-2.)

Polynuclear Aromatics. Polynuclear aromatics are large molecules with a multiple ring structure and few hydrogen atoms, such as naphthalene ($C_{10}H_2$ and 94.4 percent carbon by mass) and anthracene ($C_{14}H_4$ and 97.7 percent carbon). They are relatively rare but do appear in heavier petroleum products.

Figure 6-2 illustrates the share of carbon by weight for each class of hydrocarbon. Hydrocarbon molecules containing 2 to 4 carbon atoms are all natural gas liquids; hydrocarbons with 5 to 10 carbon atoms are predominantly found in naphtha and gasoline; and hydrocarbon compounds with 12 to 20 carbons comprise “middle distillates,” which are used to make diesel fuel, kerosene and jet fuel. Larger molecules are generally used as lubricants, waxes, and residual fuel oil.

Figure 6-2. Carbon Content of Pure Hydrocarbons as a Function of Carbon Number



Source: J.M. Hunt, *Petroleum Geochemistry and Geology* (San Francisco, CA, W.H. Freeman and Company, 1979), pp. 31-37.

If one knows nothing about the composition of a particular petroleum product, assuming that it is 85.7 percent carbon by mass is not an unreasonable first approximation. Since denser products have higher carbon numbers, this guess would be most likely to be correct for crude oils and fuel oils. The carbon content of lighter products is more affected by the shares of paraffins and aromatics in the blend.

6.3.2 Energy Content of Petroleum Products

The exact energy content (gross heat of combustion) of petroleum products is not generally known. EIA estimates energy consumption in Btu on the basis of a set of industry-standard conversion factors. These conversion factors are generally accurate to within 3 to 5 percent.

Individual Petroleum Products

The U.S. maintains data on the consumption of more than 20 separate petroleum products and product categories. The carbon contents, heat contents, and density for each product are provided below in Table 6-5. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table 6-5. Carbon Coefficients and Underlying Data for Petroleum Products

Fuel	2005 Carbon Content (MMTC/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.33	5.253	59.1	86.60
LPG	17.00	*	*	*
Jet Fuel	19.33	5.670	42.0	86.30
Distillate Fuel	19.95	5.825	35.5	86.34
Residual Fuel	21.49	6.287	11.0	85.68
Asphalt and Road Oil	20.62	6.636	5.6	83.47
Lubricants	20.24	6.065	25.6	85.80
Petrochemical Feedstocks	19.37	5.248[a]	67.1 [a]	84.11 [a]
Aviation Gas	18.87	5.048	69.0	85.00
Kerosene	19.72	5.670	41.4	86.01
Petroleum Coke	27.85	6.024	-	92.28
Special Naphtha	19.86	5.248	51.2	84.76
Petroleum Waxes	19.81	5.537	43.3	85.29
Still Gas	17.51	6.000	-	-
Crude Oil	20.30	5.800	30.5	84.8
Unfinished Oils	20.29	5.825	30.5	85.49
Miscellaneous Products	20.29	5.796	30.5	85.49
Pentanes Plus	18.24	4.620	81.7	83.70
Natural Gasoline	18.24	4.620	81.7	83.70

Note: All coefficients based on Higher Heating (Gross Calorific) Value and assume 100 percent combustion.
[a]Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Petrochemical feedstocks with higher boiling points are assumed to have the same characteristics as distillate fuel.
* LPG is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and carbon content. (See table 6-9.)
-(No sample data available)

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573 (Washington, D.C., November 1994).

Motor Gasoline and Motor Gasoline Blending Components

Motor gasoline is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines.[134] "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline; but excludes aviation gasoline.

Gasoline is the most widely used petroleum product in the United States, and its combustion accounts for nearly 20 percent of all U.S. carbon dioxide emissions. EIA collects consumption data (i.e., "petroleum products supplied" by wholesalers) for several types of gasoline: leaded regular, unleaded regular, and unleaded high octane. The American Society for Testing and Materials (ASTM) standards permit a broad range of densities for gasoline, ranging from 50 to 70 degrees API gravity, which implies a range of possible carbon and energy contents per barrel.

The density of motor gasoline increased across all grades through 1994, partly as a result of the leaded gasoline phase-out. In order to maintain the "anti-knock" quality and octane ratings of gasoline in the absence of lead, the portion of aromatic hydrocarbons used in gasoline increased. As discussed above, aromatic hydrocarbons have a lower ratio of hydrogen to carbon than other hydrocarbons typically found in gasoline, and therefore increase fuel density.

The trend in gasoline density was reversed beginning in 1996 with the development of fuel additives that raised oxygen content. In 1995, a requirement for reformulated gasoline in non-attainment areas implemented under the Clean Air Act Amendments further changed the composition of gasoline consumed in the United States. In reformulated gasoline, methyl tertiary butyl ether (MTBE) and tertiary amyl methyl ether (TAME) are often added to standard gasoline to boost it oxygen content. The increased oxygen reduces the emissions of carbon monoxide and unburned hydrocarbons. These oxygen-rich blending components are also much lower in carbon than standard gasoline. The average gallon of reformulated gasoline consumed in a recent year for example (2004) contained 9.1 percent MTBE and 0.4 percent TAME. The characteristics of reformulated fuel additives appear in Table 6-6.

Table 6-6. Characteristics of Major Reformulated Fuel Additives

Additive	Density (Degrees API)	Carbon Share (Percent)	Carbon Content (MMTC/QBtu)
MTBE	59.1	68.2	16.92
ETBE	59.1	70.5	17.07
TAME	52.8	70.5	17.00

Source: American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components, API 4261.

Estimation Methods

U.S. gasoline consumption was divided by product grade and season for both standard gasoline and reformulated gasoline. Carbon coefficients for each grade and type are derived from three parameters: gasoline density, share of the gasoline mixture that is carbon; and the energy content

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[134] Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 degrees to 158 degrees Fahrenheit at the 10-percent recovery point to 365 degrees to 374 degrees Fahrenheit at the 90-percent recovery point.

of a gallon of gasoline. Carbon coefficients for reformulated fuels were calculated by applying the carbon coefficient for the fuel additives listed in Table 6-6 to the increased share of reformulated gasoline represented by these additives (standard gasoline contains small amounts of MTBE and TAME) and weighting the gasoline carbon content accordingly. The carbon content for each grade and type of fuel is multiplied by the share of overall consumption that the grade and fuel type represent. Individual coefficients are then summed to yield an overall carbon content coefficient.

The carbon coefficient for motor gasoline varies annually based on the density of and proportion of additives in a representative sample of motor gasoline examined each year. However, in 1997 EIA began incorporating the effects of the introduction of reformulated gasoline into its estimate of carbon coefficients for motor gasoline. This change resulted in a downward step function in carbon coefficients for gasoline of approximately 0.3 percent beginning in 1995.

Data Sources

The density of motor gasoline is drawn from the National Institute for Petroleum and Energy Research, *Motor Gasolines, Summer* (various years) and the National Institute for Petroleum and Energy Research, *Motor Gasolines, Winter* (various years).

The characteristics of reformulated gasoline additives are taken from American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components, API 4261.

The carbon content of motor gasoline is found in Mark DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity,* Volume 2, ANL/ESD/TM-22, Vol. 2 (Chicago, IL: Argonne National Laboratory, November 1993), Appendix C, pp. C-1 to C-8 and ultimate analyses of one sample of shale-oil derived gasoline from Applied Systems Corp., *Compilation of Oil Shale Test Results* (Submitted to the Office of Naval Research, April 1976), p. 3-2, three varieties of gasoline from C.C. Ward, “Petroleum and Other liquid Fuels,” in *Marks’ Standard Handbook for Mechanical Engineers* (New York, NY: McGraw-Hill, 1978), pp. 7-14, and one sample of gasoline from J.W. Rose and J.R. Cooper, *Technical Data on Fuel*, The British National Committee, World Energy Conference, London, England (1977).

Standard heat contents for motor gasoline of 5.253 million Btu per barrel conventional gasoline and 5.150 million Btu per barrel reformulated gasoline were adopted from EIA, *Annual Energy Review 2000* Appendix A (Washington, D.C., July 2001). www.eia.doe.gov/emeu/aer/contents.html.

Jet Fuel

Jet fuel is a refined petroleum product used in jet aircraft engines. There are two classes of jet fuel used in the U.S.: “naphtha-based” jet fuels and “kerosene-based” jet fuels. In 1989, 13 percent of U.S. consumption was naphtha-based fuel, with the remainder kerosene-based jet fuel. In 1993, the U.S. Department of Defense began a conversion from naphtha-based JP-4 jet fuel to kerosene-based jet fuel, because of the possibility of increased demand for reformulated motor gasoline limiting refinery production of naphtha-based jet fuel. By 1996, naphtha-based jet fuel represented less than one-half of one percent of all jet fuel consumption. The carbon coefficient for jet fuel used represents a consumption-weighted combination of the naphtha-based and kerosene-based coefficients.

Estimation Methods

Because naphtha-based jet fuel is used on a limited basis in the United States, sample data on its characteristics are limited. The density of naphtha-based jet fuel (49 degrees) was estimated as the central point of the acceptable API gravity range published by ASTM. The heat content of the fuel was assumed to be 5.355 million Btu per barrel based on EIA industry standards. The carbon fraction was derived from an estimated hydrogen content of 14.1 percent and an estimated content of sulfur and other non-hydrocarbons of 0.1 percent.[135]

The density and carbon share of kerosene-based jet fuels was based on the average composition of 39 fuel samples taken by Boeing Corporation (the leading U.S. commercial airline manufacturer) in 1989. EIA's standard heat content of 5.67 million Btu per barrel was adopted for kerosene-based jet fuel.

The carbon content for each jet fuel type is multiplied by the share of overall consumption of that fuel type. Individual coefficients are then summed to yield an overall carbon coefficient.

Between 1994 and 1995, the carbon coefficient for kerosene-based jet fuel was revised downward from 19.71 million metric tons per quadrillion Btu to 19.33 million metric tons per quadrillion Btu. This downward revision was the result of a shift in the sample set used from one collected between 1959 and 1972 and reported on by Martel and Angello in 1977 to one collected by Boeing in 1989 and published by Hadaller and Momenthy in 1990. The latter set of fuel samples have a decreased density and slightly lower carbon share than the earlier samples. However, the assumed heat content is unchanged because it is based on an EIA standard and thus, probably yields a downward bias in the revised carbon coefficient.

Data Sources

The carbon content of naphtha-based jet fuel is from C.R. Martel and L.C. Angello, "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels," in *Current Research in Petroleum Fuels*, Volume I (New York, NY: MSS Information Company, 1977), p. 116.

The density of naphtha-based jet fuel is from the American Society for Testing and Materials**,** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985), p. 60

A standard heat content for naphtha-based jet fuel was adopted from EIA, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001), www.eia.doe.gov/emeu/aer/contents.html.

Carbon content and density for kerosene-based jet fuels is drawn from O.J. Hadaller and A.M. Momenthy, *The Characteristics of Future Fuels*, Part 1, "Conventional Heat Fuels" (Seattle, WA: Boeing Corp., September 1990), pp. 46-50

A standard heat content for kerosene-based jet fuel was adopted from EIA, *Annual Energy Review 2000* Appendix A (Washington, D.C., July 2001). www.eia.doe.gov/emeu/aer/contents.html.

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[135] Martel, C.R., and Angelo, L.C., "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels," *Current Research in Petroleum Fuels*, Vol. I. New York, NY: MSS Information Corporation (1977).

Distillate Fuel

Distillate fuel is a general classification for diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. No. 1, No. 2, and No. 4 fuel oils are also used for space heating and electric power generation.

Estimation Methods

For the purposes of this report, the carbon content of No. 2 fuel oil is assumed to typify the carbon content of distillate fuel generally. The carbon share in No. 2 fuel oil was estimated based on the average of 11 ultimate analyses. This carbon share was combined with EIA's standard heat content of 5.825 million Btu per barrel and the density of distillate assumed to be 35.5 degrees API, in accord with its heat content.

Data Sources

Carbon content and density were derived from the following:

Four samples of distillate from C. T. Hare and R.L. Bradow, "Characterization of Heavy-Duty Diesel Gaseous and Particulate Emissions, and the Effects of Fuel Composition," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 128;

Three samples from E.F. Funkenbush, D.G. Leddy, and J.H. Johnson, "The Organization of the Soluble Organic Fraction of Diesel Particulate Matter," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979) p. 128;

One sample from R.L. Mason, "Developing Prediction Equations for Fuels and Lubricants," SAE Paper 811218, p.34;

One sample from C.T. Hare, K.J. Springer, and R.L. Bradow, "Fuel and Additive Effects on Diesel Particulate- Development and Demonstration of Methodology," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 179; and

One Sample from F. Black and L. High, "Methodology for Determining Particulate and Gaseous Diesel Emissions," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 128.

A standard heat content was adopted from EIA, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). www.eia.doe.gov/emeu/aer/contents.html.

Residual Fuel

Residual fuel is a general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Residual fuel conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO

Symbol F-770). It is used in steam-powered vessels in government service and inshore power plants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

In the United States, electric utilities purchase about a third of the residual oil consumed. A somewhat larger share is used for vessel bunkering, and the balance is used in the commercial and industrial sectors. The residual oil (defined as No.6 fuel oil) consumed by electric utilities has an energy content of 6.287 million Btu per barrel and an average sulfur content of 1 percent.[136] This implies a density of about 17 degrees API.

Estimation Methods

For this report, residual fuel was defined as No.6 fuel oil. The National Institute of Petroleum and Energy Research, Fuel Oil Survey shows an average density for fuel oil of 11.3 API gravity and anecdotal evidence suggests that marine residual fuel is also very dense, with typical gravity of 10.5 to 11.5 degrees API.[137] Because the largest share of fuel oil consumption is for marine vessels, a density of 11 degrees API was adopted when developing the carbon coefficient for this report. An average share of carbon in residual fuel of 85.67 percent by mass was used based on ultimate analyses of a dozen samples.

Data Sources

The carbon content of residual fuel oil is based on the following:

Three samples of residual fuel from the Middle East and one sample from Texas in F. Mosby, G.B. Hoekstra, T.A. Kleinhenz, and J.M. Sokra, "Pilot Plant Proves Resid Process," in *Chemistry of Petroleum Processing and Extraction* (MSS Information Corporation, 1976), p.227;

Three samples of heavy fuel oils from J.P. Longwell, "Interface Between Fuels and Combustion," in *Fossil Fuel Combustion: A Sourcebook* (New York, NY: John Wiley & Sons, 1991);

Three samples of heavy fuel oils from C.C. Ward, "Petroleum and Other Liquid Fuels," in *Marks' Standard Handbook for Mechanical Engineers* (New York, NY: McGraw-Hill, 1978), pp. 7-14;

Two samples of heavy fuel oils from, D.A. Vorum, "Fuel and Synthesis Gases from Gaseous and Liquid Hydrocarbons," in American Gas Association, *Gas Engineer's Handbook* (New York, NY: Industrial Press, 1974), p. 3/71; and

One sample of heavy fuel oil from W. Rose and J.R. Cooper, *Technical Data on Fuel*, The British National Committee, World Energy Conference, London, England (1977).

The density of residual fuel consumed for electric power generation was from EIA, *Cost and Quality of Fuels* (Washington, D.C.). www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html.

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[136] U. S. Energy Information Administration, *Cost and Quality of Fuels*, DOE/EIA-0191 (Washington, D.C.), www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html.

[137] U. S. Energy Information Administration, Petroleum Supply Division, *Btu Tax on Finished Petroleum Products*, (unpublished manuscript, April 1993).

Density of residual fuel consumed in marine vessels was from EIA, Petroleum Supply Division, *Btu Tax on Finished Petroleum Products,* (unpublished manuscript, April 1993) and the National Institute for Petroleum and Energy Research, *Fuel Oil Surveys* (Bartlesville, OK, 1992).

A standard heat content was adopted from EIA, *Annual Energy Review* Various years), Appendix A (Washington, D.C., various years), www.eia.doe.gov/emeu/aer/contents.html.

Liquefied Petroleum Gases (LPG)

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and n-butane. Because each of these compounds is a pure paraffinic hydrocarbon, their carbon shares are easily derived by taking into account the atomic weight of carbon (12) and the atomic weight of hydrogen (1). Thus, for example, the carbon share of propane, C_3H_8, is 81.8 percent. The densities and heat content of the compounds are also well known allowing carbon coefficients to be calculated directly. Table 6-7 summarizes the physical characteristic of LPG.

Table 6-7. Physical Characteristics of Liquefied Petroleum Gases

Compound	Chemical Formula	Density (Barrels Per Metric Ton)	Carbon Content (Percent)	Energy Content (MMBtu/Barrel)	Carbon Coefficient (MMTC/QBtu)
Ethane	C_2H_6	16.88	80.0	2.916	16.25
Propane	C_3H_8	12.44	81.8	3.824	17.20
Isobutane	C_4H_{10}	11.20	82.8	4.162	17.75
n-butane	C_4H_{10}	10.79	82.8	4.328	17.72

Note: All coefficients based on Higher Heating (Gross Calorific) Value and assume 100 percent combustion

Source: V.B. Guthrie (ed.), *Characteristics of Compounds*, Petroleum Products Handbook, (New York, NY: Mcgraw-Hill, 1960), p.3-3.

Estimation Methods

Based on their known physical characteristics, a carbon coefficient is assigned to each compound contained in the U.S. energy statistics category, Liquefied Petroleum Gases. A weighted carbon coefficient for LPG used as fuel is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics. The mix of LPG consumed for non-fuel use differs significantly from the mix of LPG that is combusted. While the preponderance of LPG consumed for fuel use is propane, the largest single LPG used for non-fuel applications is ethane. A carbon coefficient for LPG used for non-fuel applications is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics.

The carbon coefficient of LPG is updated annually to reflect changes in the consumption mix of the underlying compounds: ethane; propane; isobutane; and normal butane. In 1994, EIA included pentanes plus – assumed to have the characteristics of hexane – in the mix of compounds broadly described as LPG. In 1995, EIA removed pentanes plus from this fuel category. Because pentanes plus is relatively rich in carbon per unit of energy, its removal from the consumption mix lowered the carbon coefficient for LPG from 17.26 million metric tons per quadrillion Btu to 17.02 million metric tons per quadrillion Btu. In 1998, EIA began separating LPG consumption into two categories: energy use; and non-fuel use and providing individual coefficients for each. Because LPG for fuel use typically contains higher proportions of propane than LPG for non-fuel use, the carbon coefficient for fuel use is about 2 percent higher than the coefficient for non-fuel use.

Data Sources

Carbon share, density and heat content of liquefied petroleum gases from V.B. Guthrie (ed.), Characteristics of Compounds, Petroleum Products Handbook, (New York, NY: Mcgraw-Hill, 1960), p.3-3.

LPG consumption was from EIA, *Petroleum Supply Annual* (Washington, D.C.) various years. www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html.

Non-fuel use of LPG is derived from American Petroleum Institute, *Natural Gas Liquids and Liquefied Refinery Gas Survey*, various years.

Aviation Gasoline

Aviation gasoline is used in piston-powered airplane engines. It is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D 910 and Military Specification MIL-G-5572. Aviation gas is a relatively minor contributor to greenhouse gas emissions compared to other petroleum products, representing approximately 0.1 percent of all consumption.

The ASTM standards for boiling and freezing points in aviation gasoline effectively limit the aromatics content to a maximum of 25 percent (ASTM D910). Because weight is critical in the operation of an airplane, aviation gas must have as many Btu per pound (implying a lower density) as possible, given other requirements of piston engines such as high anti-knock quality.

Estimation Methods

A carbon coefficient for aviation gasoline was calculated on the basis of the EIA standard heat content of 5.048 million Btu per barrel. This implies a density of approximately 69 degrees API gravity or 5.884 pounds per gallon. To estimate the share of carbon in the fuel, it was assumed that aviation gasoline is 87.5 percent iso-octane, 9.0 percent toluene, and 3.5 percent xylene. The maximum allowable sulfur content in aviation gasoline is 0.05 percent, and the maximum allowable lead content is 0.1 percent. These amounts were judged negligible and excluded for the purposes of this analysis. This yielded a carbon share of 85 percent and a carbon coefficient of 18.87 million metric tons per quadrillion Btu.

Data Sources

Fuel characteristics were taken from the American Society for Testing and Materials, ASTM and Other Specifications for Petroleum Products and Lubricants (Philadelphia, PA, 1985).

A standard heat content for aviation gas was adopted from EIA, *Annual Energy Review (various years)*, Appendix A (Washington, D.C., various years) www.eia.doe.gov/emeu/aer/contents.html.

Still Gas

Still gas, or refinery gas is composed of light hydrocarbon gases that are released as petroleum is processed in a refinery. The composition of still gas is highly variable, depending primarily on the nature of the refining process and secondarily on the composition of the product being processed. Petroleum refineries produce still gas from many different processes. Still gas can be used as a fuel or feedstock within the refinery, sold as a petrochemical feedstock, or purified and sold as pipeline-quality natural gas. In general, still gas tends to include large amounts of free hydrogen and methane, as well as smaller amounts of heavier hydrocarbons. Because different refinery operations result in different gaseous byproducts, it is difficult to determine what represents typical still gas.

Estimation Methods

EIA obtained data on four samples of still gas. Table 6-8 below shows the composition of those samples.

Table 6-8. Composition, Energy Content, and Carbon Coefficient for Four Samples of Still Gas

Sample	Hydrogen (percent)	Methane (percent)	Ethane (percent)	Propane (percent)	Btu Per Cubic Foot	Carbon Coefficient (MMTC/QBtu)
One	12.7	28.1	17.1	11.9	1,388	17.51
Two	34.7	20.5	20.5	6.7	1,143	14.33
Three	72.0	12.8	10.3	3.8	672	10.23
Four	17.0	31.0	16.2	2.4	1,100	15.99

Note: All coefficients based on Higher Heating (Gross Calorific) Value and assume 100 percent combustion.

Because gas streams with a large free hydrogen content are likely to be used as refinery or chemical feedstocks, EIA selected the carbon coefficient from the sample with the lowest hydrogen content as the representative value for still gas.

Data Sources

One still gas sample was drawn from American Gas Association, *Gas Engineer's Handbook,* (New York, NY: Industrial Press, 1974), pp. 3.71, and three still gas samples came from C.R. Guerra, K. Kelton, and D.C. Nielsen, Natural Gas Supplementation with Refinery Gases and Hydrogen," in Institute of Gas Technology, *New Fuels and Advances in Combustion Technologies* (Chicago, IL, June 1979).

Asphalt

Asphalt is used to pave roads. Because most of its carbon is retained in those roads, it is not a source of emissions. It is derived from a class of hydrocarbons called "asphaltenes," abundant in some crude oils but not in others. Asphaltenes have oxygen and nitrogen atoms bound into their molecular structure, so that they tend to have lower carbon contents than other hydrocarbons.

Estimation Methods

Ultimate analyses of twelve samples of asphalts showed an average carbon content of 83.5 percent. The EIA standard heat content for asphalt of 6.636 million Btu per barrel was assumed. The ASTM petroleum measurement tables show a density of 5.6 degrees API or 8.605 pounds per gallon for asphalt. Together, these variables generate a carbon coefficient of 20.62 million metric tons per quadrillion Btu.

Data Sources

A standard heat content for asphalt was adopted from EIA, *Annual Energy Review (various years)*, Appendix A (Washington, D.C., various years) www.eia.doe.gov/emeu/aer/contents.html.

The density of asphalt is from American Society for Testing and Materials**,** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

Lubricants

Lubricants are substances used to reduce friction between bearing surfaces, or incorporated into processing materials used in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases. Lubricant consumption is dominated by motor oil for automobiles, but there is a large range of product compositions and end uses within this category.

Estimation Methods

The ASTM Petroleum Measurement Tables give the density of lubricants at 25.6 degrees API. Ultimate analysis of a single sample of motor oil yielded a carbon content of 85.8 percent. A standard heat content of 6.065 million Btu per barrel was adopted. These factors produce a carbon coefficient of 20.24 million metric tons per quadrillion Btu.

Data Sources

A standard heat content was adopted from EIA, *Annual Energy Review (various years)*, Appendix A (Washington, D.C., various years) www.eia.doe.gov/emeu/aer/contents.html.

The density of asphalt was adopted from American Society for Testing and Materials**,** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

Petrochemical Feedstocks

U.S. energy statistics distinguish between two different kinds of petrochemical feedstocks: those with a boiling temperature below 400 degrees Fahrenheit, generally called “naphtha,” and those with a boiling temperature 400 degrees Fahrenheit and above.

Estimation Methods

Because reformed naphtha is used to make motor gasoline (hydrogen is released to raise aromatics content and octane rating), “straight-run” naphtha is assumed to be used as a petrochemical feedstock. Ultimate analyses of five samples of naphtha were examined and showed an average carbon share of 84.11 percent and an average density of 67.1 degrees API gravity. The standard EIA heat content of 5.248 million Btu per barrel is used to estimate a carbon coefficient of 18.14 million metric tons per quadrillion Btu.

Petrochemical feedstocks with a boiling temperature greater than 401 degrees Fahrenheit are part of the "middle distillate" fraction in the refining process, and EIA estimates that these petrochemical feedstocks have the same heat content as distillate fuel. Thus, the carbon coefficient of 19.95 million metric tons per quadrillion Btu used for distillate fuel is also adopted for this portion of petrochemical feedstocks. The weighted average of the two carbon coefficients for petroleum feedstocks equals 19.37 million metric tons per quadrillion Btu.

Data Sources

The carbon content and density of naphthas is estimated based on G.H. Unzelman, "A Sticky Point for Refiners: FCC Gasoline and the Complex Model," *Fuel Reformulation* (July/August 1992), p. 29.

A standard heat content for petrochemical feedstock was adopted from EIA, *Annual Energy Review (various years)*, Appendix A (Washington, D.C., various years) www.eia.doe.gov/emeu/aer/contents.html.

Kerosene

A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps, kerosene is drawn from the same petroleum fraction as jet fuel. Kerosene is generally comparable to No.1 fuel oil.

Estimation Methods

The average density of 41.4 degrees API and average carbon share of 86.01 percent found in five ultimate analyses of No. 1 fuel oil samples were applied to a standard heat content of 5.67 million Btu per barrel to yield a carbon coefficient of 19.72 million metric tons per quadrillion Btu.

Data Sources

A standard heat content was adopted from EIA, *Annual Energy Review (various years)*, Appendix A (Washington, D.C., various years) www.eia.doe.gov/emeu/aer/contents.html.

Petroleum Coke

Petroleum coke is the solid residue of the extensive processing of crude oil. It is a coal-like solid, usually with a carbon content greater than 90 percent, which is used as a boiler fuel and industrial raw material.

Estimation Methods

Ultimate analyses of two samples of petroleum coke showed an average carbon share of 92.3 percent. The ASTM standard density of 9.543 pounds per gallon was adopted and the EIA standard energy content of 6.024 million Btu per barrel assumed. Together, these factors produced an estimated carbon coefficient of 27.85 million metric tons per quadrillion Btu.

Data Sources

Carbon content for petroleum coke was estimated from two samples from S. W. Martin, "Petroleum Coke," in Virgil Guthrie (ed.), *Petroleum Processing Handbook* (New York, NY: McGraw-Hill, 1960), pp. 14-15. Density of petroleum coke adopted from American Society for Testing and Materials**,** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985). A standard heat content was adopted from EIA, *Annual Energy Review (various years)*, Appendix A (Washington, D.C., various years) www.eia.doe.gov/emeu/aer/contents.html.

Special Naphtha

Special naphtha is defined as a light petroleum product to be used for solvent applications, including commercial hexane and four classes of solvent: stoddard solvent, used in dry cleaning; high flash point solvent, used as an industrial paint because of its slow evaporative characteristics; odorless solvent, most often used for residential paints; and high solvency mineral spirits, used for architectural finishes. These products differ in both density and carbon percentage, requiring the development of multiple coefficients.

Estimation Methods

Hexane is a pure paraffin containing 6 carbon atoms and 14 hydrogen atoms. Thus, it is 83.7 percent carbon. Its density is 76.6 degrees API or 5.649 pounds per gallon and its derived carbon coefficient is 17.17 million metric tons per quadrillion Btu. The other hydrocarbon compounds in special naphthas are assumed to be either paraffinic or aromatic. (See discussion above.) The portion of aromatics in odorless solvents is estimated at less than 1 percent, Stoddard and high flash point solvents contain 15 percent aromatics and high solvency mineral spirits contain 30 percent aromatics (Boldt and Hall, 1985). These assumptions, when combined with the relevant densities, yield the carbon coefficients contained in Table 6-9 below.

Table 6-9. Characteristics of Non-hexane Special Naphthas

Special Naphtha	Aromatic Content (Percent)	Density (Degrees API)	Carbon Content (Percent)	Carbon Coefficient (MMTC/QBtu)
Odorless Solvent	1	55.0	84.51	19.41
Stoddard Solvent	15	47.9	84.44	20.11
High Flash Point	15	47.6	84.70	20.17
Mineral Spirits	30	43.6	85.83	20.99

Note: All coefficients based on Higher Heating (Gross Calorific) Value and assume 100 percent combustion.

EIA reports only a single consumption figure for special naphtha. The carbon coefficients of the five special naphthas are weighted according to the following formula: approximately 10 percent of all special naphtha consumed is hexane and the remaining 90 percent is assumed to be distributed evenly among the four other solvents. The resulting emission coefficient for special naphthas is 19.86 million metric tons carbon per quadrillion Btu.

Data Sources

A standard heat content for special naphtha was adopted from EIA, *Annual Energy Review*, Appendix A (Washington, D.C., July 2001), www.eia.doe.gov/emeu/aer/contents.html.

Density and aromatic contents for special naphthas are from K. Boldt and B.R. Hall, *Significance of Tests for Petroleum Products* (Philadelphia, PA: American Society for Testing and Materials), p. 30.

Petroleum Waxes

The ASTM standards define petroleum wax as a product separated from petroleum that is solid or semi-solid at 77 degrees Fahrenheit (25 degrees Celsius). The two classes of petroleum wax are paraffin waxes and microcrystalline waxes. They differ in the number of carbon atoms and the type of hydrocarbon compounds. Microcrystalline waxes have longer carbon chains and more variation in their chemical bonds than paraffin waxes.

Estimation Methods

For the purposes of this analysis, paraffin waxes are assumed to be composed of 100 percent paraffinic compounds with a chain of 25 carbon atoms. The resulting carbon share for paraffinic wax is 85.23 percent and the density is estimated at 45 degrees API or 6.684 pounds per gallon.

Microcrystalline waxes are assumed to consist of 50 percent paraffinic and 50 percent cycloparaffinic compounds with a chain of 40 carbon atoms, yielding a carbon share of 85.56 percent. The density of microcrystalline waxes is estimated at 36.7 degrees API, based on a sample of 10 microcrystalline waxes found in the *Petroleum Products Handbook*.

A weighted average density and carbon coefficient was calculated for petroleum waxes, assuming that wax consumption is 80 percent paraffin wax and 20 percent microcrystalline wax. The weighted average carbon content is 85.29 percent, and the weighted average density is 6.75 pounds per gallon. EIA’s standard heat content for waxes is 5.537 million Btu per barrel. These inputs yield a carbon coefficient for petroleum waxes of 19.81 million metric tons per quadrillion Btu.

Data Sources

The density of paraffin wax is from American Society for Testing and Materials**,** *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985). The density of microcrystalline waxes is based on 10 samples found in V. Guthrie (ed.), *Petroleum Products Handbook* (New York, NY: McGraw-Hill, 1960).

A standard heat content for petroleum waxes was adopted from EIA, *Annual Energy Review (various years)*, Appendix A (Washington, D.C., various years) www.eia.doe.gov/emeu/aer/contents.html.

Crude Oil, Unfinished Oils, and Miscellaneous

U.S. energy statistics include several categories of petroleum products designed to ensure that reported refinery accounts “balance” and cover any “loopholes” in the taxonomy of petroleum products. These categories include crude oil, unfinished oils, and miscellaneous products. Crude oil is rarely consumed directly, miscellaneous products account for less than one percent of oil consumption and unfinished oils are a balancing item that may show negative consumption. For carbon accounting purposes, it was assumed that all these products have the same carbon content as crude oil.

Estimation Methods

EIA reports on the average density and sulfur content of U.S. crude oil purchased by refineries. To develop a method of estimating carbon content based on this information, ultimate analyses of 182 crude oil samples were collected. Within the sample set, carbon content ranged from 82 to 88 percent carbon, but almost all samples fell between 84 percent and 86 percent carbon. The density and sulfur content of the crude oil data were regressed on the carbon content, producing the following equation:

$$\text{Percent Carbon} = 76.99 + (10.19 * \text{Specific Gravity}) + (-0.76 * \text{Sulfur Content})$$

Absent the term representing sulfur content, the equation had an R-squared of only 0.35.[138] When carbon content was adjusted to exclude sulfur, the R-squared rose to 0.65. While sulfur is the most important nonhydrocarbon impurity, nitrogen and oxygen can also be significant, but they do not seem to be correlated with either density or sulfur content. Restating these results, density accounts for about 35 percent of the variation in carbon content, impurities account for about 30 percent of the variation, and the remaining 35 percent is accounted for by other factors, including (presumably) the degree to which aromatics and polynuclear aromatics are present in the crude oil. Applying this equation to the 2002 crude oil quality data (30.42 degrees API and 1.41 percent sulfur) produces an estimated carbon content of 84.8 percent. Applying the density and carbon content to the EIA standard energy content for crude oil of 5.8 million Btu per barrel produces an emission coefficient of 20.29 million metric tons per quadrillion Btu.

Data Sources

The carbon content for crude oil was developed from an equation based on 182 crude oil samples, including 150 samples from U.S. National Research Council, *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology* (New York, NY: McGraw-Hill, 1927).

A standard heat content for crude oil was adopted from EIA, *Annual Energy Review*, Appendix A (Washington, D.C., various years), www.eia.doe.gov/emeu/aer/contents.html.

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[138] R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

7. Global Warming Potentials

7.1 Introduction

Global warming potentials (GWPs) are indices used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative forcing effects[139] (heat-absorbing ability) of each gas relative to that of carbon dioxide (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO_2. The GWP for a gas provides a construct for converting emissions of each GHG into a common measure, which allows analysts to aggregate and compare the radiative impacts of various greenhouse gases into a uniform measure denominated in carbon dioxide equivalents (CO_2e). Thus, applying the appropriate GWP to a greenhouse gas will yield the CO_2e of the greenhouse gas being measured. GWPs can also serve as an important quantitative tool for governments and policymakers seeking consensus in formulating an effective climate policy.

In preparing the estimations of emissions provided in *Emissions of Greenhouse Gases in the United States*, EIA seeks to employ the most current data sources. In doing so, EIA has generally relied on the GWPs published in assessment reports by the IPCC prepared every five years. Over the past decade, the IPCC has conducted an extensive research program aimed at determining the sources and effects of various greenhouse gases and their effect on the climate system. The results of that work were originally released in 1995 in an the IPCC first assessment report, *Climate Change 1994*,[140] and subsequently updated in their second assessment report (SAR) *Climate Change 1995*[141] and third assessment report (TAR) *Climate Change 2001*.[142]

There has been some discussion about which GWPs to use when preparing estimates of greenhouse gas emissions, largely stemming from the different stages of publication and formal approval of the IPCC SAR, published in 1996, and the TAR, published in 2001. The United Nations Framework Convention on Climate Change (UNFCCC) requirements for developing national inventories—provided under the *Revised 1996 IPCC Guidelines* for National Greenhouse Gas Inventories and the UNFCCC's Guidelines on Reporting and Review[143] for national inventories—were developed prior to the publication of the TAR. Both documents continue to require national inventories to be based on the GWPs in the IPCC SAR,[144] and the UNFCCC negotiating body, called the Conference of Parties (COP)[145], has yet to adopt decisions

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[139] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in Watts per square meter (Wm^2).

[140] Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

[141] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

[142] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

[143] Conference of Parties, Fifth Session, United Nations Framework Convention on Climate Change (UNFCCC) Guidelines on Reporting and Review, FCCC/CP/1999/7 (16 February 2000).

[144] *Revised Guidelines for the Preparation of National Communications by Parties included in Annex I to the Convention*, FCCC/CP/1996/15/Add.1 (1996).

[145] Soon to be joined by the meeting of the parties (MOP) to the Kyoto Protocol, upon entry into force in February 2005. The MOP will not include the United States.

to approve the TAR.[146] As a result, the U.S. EPA and a number of national governmental bodies responsible for publishing and submitting national emissions inventories to the UNFCCC utilize the GWPs published in the SAR.

In contrast, EIA's *Emissions of Greenhouse Gases* has relied on the likelihood that the TAR, as published, will be adopted and approved by the COP/MOP in the future, and that there is little reason not to use the TAR GWP values but for the fact that the COP has yet to formally adopt the TAR. The section below addresses the differences between the GWPs presented in the SAR and TAR, and explains the rationale for applying the GWPs from the TAR.

7.2 Understanding Global Warming Potentials

A global warming potential (GWP) is defined as the cumulative radiative forcing—both in terms of direct effects and indirect effects (such as resulting from chemical transformations)—over a period of time, relative to a reference gas.[147] GWP values are derived from laboratory experiments on molecular attributes of greenhouse gases and data modeling of the gases' radiative transfer properties.[148] While any time period can be selected, the IPCC recommends using 100-year GWPs. According to the IPCC, the direct GWPs for gases with distinguished lifetimes have an estimated uncertainty within ±35 percent, but the indirect GWPs are less certain, particularly those for which lifetimes are not yet understood.[149] Table 7-1 illustrates the differences in estimated GWP values as a factor of time horizons.

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[146] Decision 2/CP.3 of the UNFCCC.

[147] U.S. Environmental Protection Agency, *Greenhouse Gases and Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002, http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html. Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

[148] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001) Section 6.12.

[149] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001) Section 6, Executive Summary.

Table 7-1. Numerical Estimates of Global Warming Potentials Compared With Carbon Dioxide (Kilogram of Gas per Kilogram of Carbon Dioxide)

Gas	Lifetime (Years)	Direct Effect for Time Horizons of		
		20 Years	100 Years	500 Years
Carbon Dioxide	5 - 200[a]	1	1	1
Methane	12	62	23	7
Nitrous Oxide	114	275	296	156
HFCs, PFCs, and SF_6				
HFC-23	260	9,400	12,000	10,000
HFC-125	29	5,900	3,400	1,100
HFC-134a	13.8	3,300	1,300	400
HFC-152a	1.4	410	120	37
HFC-227ea	33	5,600	3,500	1,100
Perfluoromethane (CF_4)	50,000	3,900	5,700	8,900
Perfluoroethane (C_2F_6)	10,000	8,000	11,900	18,000
Sulfur Hexafluoride (SF_6)	3,200	15,100	22,200	32,400

[a] No single lifetime can be defined for carbon dioxide due to different rates of uptake by different removal processes.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), pp. 38 and 388-389.

Greenhouse gases with relatively long atmospheric lifetimes (e.g., carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. Short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, and other ambient air pollutants (e.g., nitrogen oxide, and non methane volatile organic compounds), and tropospheric aerosols (e.g., sulfur dioxide products and black carbon), however, are present in very different quantities spatially around the world, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially heterogeneous in the atmosphere.[150]

7.3 Changes between the Second and Third Assessment Reports

More than two decades of research have provided a progressively improved understanding of the interaction between anthropogenic emissions of greenhouse gases and their potential to alter the

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[150] U.S. Environmental Protection Agency, *Greenhouse Gases and Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, (Washington, D.C., April 2002), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Earth's atmosphere. In the five years between the publication of the SAR in 1996 and the TAR in 2001, considerable progress was achieved in reducing the scientific uncertainty associated with the direct and indirect relationship of atmospheric responses to various external influences.

The IPCC TAR includes GWP estimates for several gases that have been modified from the SAR, as well as new GWPs for a more complete set of gases. In keeping with IPCC protocol, the use of all GWPs continues to be based on the effect of that greenhouse gas over a 100-year time period. Included among the new gases are certain ozone-depleting substances (ODSs), originally considered only to be harmful to stratospheric ozone but now recognized as potent greenhouse gases. In addition, the TAR includes new categories for ethers and halogenated ethers.

In general, the TAR served to confirm and reinforce the conclusions put forth in the SAR. Table 7-2 provides a comparison of 100-year GWP estimates from the SAR and TAR. The bulk of changes to the GWPs, as described below, have also shown to have little overall impact on the quantification of total greenhouse gases emitted at the U.S. national level. Table 7-2 illustrates the effect SAR and TAR 100-year GWPs have on U.S. emissions estimates.

Table 7-2. Comparison of 100-Year GWP Estimates from the Intergovernmental Panel on Climate Change (IPCC) Second (SAR) and Third (TAR) Assessment Reports

Gas	GWP		Absolute Change	Percentage Change
	SAR	TAR		
Carbon Dioxide	1	1	No Change	No Change
Methane	21	23	2	10%
Nitrous Oxide	310	296	-14	-5%
Hydrofluorocarbons				
HFC-23	11,700	12,000	300	3%
HFC-32	650	550	-100	-15%
HFC-41	150	97	-53	-35%
HFC-125	2,800	3,400	600	21%
HFC-134	1,100	1,100	100	10%
HFC-134a	1,300	1,300	No Change	No Change
HFC-143	300	330	30	10%
HFC-143a	3,800	4,300	500	13%
HFC-152	NA	43	NA	NA
HFC-152a	140	120	-20	-14%
HFC-161	NA	12	NA	NA
HFC-227ea	2,900	3,500	600	21%
HFC-236cb	NA	1,300	NA	NA
HFC-236ea	NA	1,200	NA	NA
HFC-236fa	6,300	9,400	3,100	49%
HFC-245ca	560	640	80	14%
HFC-245fa	NA	950	NA	NA
HFC-365mfc	NA	950	NA	NA
HFC-4310mee	1,300	1,500	200	15%
Iodocarbons				
FIC-1311	<1	1	No Change	No Change
Fully Fluorinated Species				
SF_6	23,900	22,000	-1,900	-8%
CF_4	6,500	5,700	-800	-12%
C_2F_6	9,200	11,900	2,700	29%
C_3F_8	7,000	8,600	1,600	23%
C_4F_{10}	7,000	8,600	1,600	23%
c-C_4F_8	8,700	10,000	1,300	15%
C_5F_{12}	7,500	8,900	1,400	19%
C_6F_{14}	7,400	9,000	1,600	22%

Sources: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

7.4 Improvements to GWP Estimates in the Third Assessment Report

Improvements to the IPCC GWP values in the TAR were a result of an improved calculation of CO_2 radiative forcing, an improved CO_2 response function, and recalculations of some atmospheric lifetimes. GWPs presented in the TAR are drawn from the SAR and the World Meteorological Organization (WMO),[151] and include specific updates drawn from new published cases of laboratory or radiative transfer results.

As stated in the TAR:

> The direct GWPs have been calculated relative to CO_2 using an improved calculation of the CO_2 radiative forcing, the SAR response function for a CO_2 pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons. [TAR 2001]

To determine the direct radiative forcings (ppbv or parts per billion volume), the IPCC “derived from infrared radiative transfer models based on laboratory measurements of the molecular properties of each substance and considering the molecular weights.”[152] The radiative forcing of CO_2 was found to be about 12 percent lower than that reported in the SAR. For example, the improved formula, for fixed changes in gas concentrations, decreased CO_2 and N_2O radiative forcing by 15 percent, increased CFC-11 and CFC-12 radiative forcing by 10 to 15 percent, and yielded no change in the case of CH_4. As a consequence of changes in the radiative forcing for CO_2 and CFC-11, the revised GWPs are typically 20 percent higher than listed in the SAR.[153]

The response function for a CO_2 pulse can be explained in simple terms as the response from adding an additional ton of CO_2 to the atmosphere, and the function specifies the proportion of CO_2 that remains in the atmosphere after a designated amount of time (an average of single exponential decay functions). The GWP of any substance therefore expresses the integrated forcing of a pulse (of given small mass) of that substance relative to the integrated forcing of a pulse (of the same mass) of the reference gas over some time horizon.

Many atmospheric lifetimes were recalculated in the TAR. The lifetimes of non-CO_2 greenhouse gases are dependent largely on atmospheric photochemistry, which controls photolysis and related removal processes. When the lifetime of the gas in question differs substantially from the response time of the reference gas (CO_2), the GWP becomes sensitive to the choice of time horizon. For example, for longer time horizons (greater than 100 years), those gases that decay more rapidly than the CO_2 display decreasing GWPs; and conversely those gases with lifetimes much longer than that of the CO_2 display increasing GWPs. Table 7-3 provides a comparison of the lifetimes and GWPs for the greenhouse gases provided in the SAR and TAR, showing a range of between a 15 decrease and 49 percent increase in GWP values.

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[151] World Meteorological Organization, *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project-Report No. 44*, Geneva, Switzerland (1999).

[152] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), Section 6.12.1.

[153] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

Table 7-3. Comparison of GWPs and Lifetimes Used in the SAR and the TAR

Gas	Lifetime (years)		GWP (100 year)		Absolute Change	Percent Change
	SAR	TAR	SAR	TAR		
Carbon Dioxide	50-200	5-200[a]	1	1	NC	NC
Methane[b]	12±3	8.4/12[c]	21	23	2	10%
Nitrous Oxide	120	120/114[c]	310	296	(14)	-5%
Hydrofluorocarbons						
HFC-23	264	260	11,700	12,000	300	3%
HFC-32	5.6	5.0	650	550	(100)	-15%
HFC-41	3.7	2.6	150	97	(53)	-35%
HFC-125	32.6	29	2,800	3,400	600	21%
HFC-134	10.6	9.6	1,000	1,100	100	10%
HFC-134a	14.6	13.8	1,300	1,300	NC	NC
HFC-143	3.8	3.4	300	330	30	10%
HFC-143a	48.3	52	3,800	4,300	500	13%
HFC-152	NA	0.5	NA	43	NA	NA
HFC-152a	1.5	1.4	140	120	(20)	-14%
HFC-161	NA	0.3	NA	12	NA	NA
HFC-227ea	36.5	33.0	2,900	3,500	600	21%
HFC-236cb	NA	13.2	NA	1,300	NA	NA
HFC-236ea	NA	10	NA	1,200	NA	NA
HFC-236fa	209	220	6,300	9,400	3,100	49%
HFC-245ca	6.6	5.9	560	640	80	14%
HFC-245fa	NA	7.2	NA	950	NA	NA
HFC-365mfc	NA	9.9	NA	890	NA	NA
HFC-4310mee	17.1	15	1,300	1,500	200	15%
Iodocarbons						
FIC-1311	<0.005	0.005	<1	1	NC	NC
Fully Fluorinated Species						
SF_6	3,200	3,200	23,900	22,000	(1,900)	-8%
CF_4	50,000	50,000	6,500	5,700	(800)	-12%
C_2F_6	10,000	10,000	9,200	11,900	2,700	29%
C_3F_8	2,600	2,600	7,000	8,600	1,600	23%
C_4F_{10}	2,600	2,600	7,000	8,600	1,600	23%
$c\text{-}C_4F_8$	3,200	3,200	8,700	10,000	1,300	15%
C_5F_{12}	4,100	4,100	7,500	8,900	1,400	19%
C_6F_{14}	3,200	3,200	7,400	9,000	1,600	22%
Ethers & Halogenated Ethers						
CH3OCH3	NA	0.015	NA	1	NA	NA
(CF3)2CFOCH3	NA	3.4	NA	330	NA	NA
(CF3)CH2OH	NA	0.5	NA	57	NA	NA
CF3CF2CH2OH	NA	0.4	NA	40	NA	NA
(CF3)2CHOH	NA	1.8	NA	190	NA	NA
HFE-125	NA	150	NA	14,900	NA	NA
HFE-134	NA	26.2	NA	6,100	NA	NA
HFE-143a	NA	4.4	NA	750	NA	NA
HCFE-235da2	NA	2.6	NA	340	NA	NA
HFE-245cb2	NA	4.3	NA	580	NA	NA
HFE-245fa2	NA	4.4	NA	570	NA	NA

Table 7-3. Comparison of GWPs and Lifetimes Used in the SAR and the TAR

Gas	Lifetime (years)		GWP (100 year)		Absolute Change	Percent Change
	SAR	TAR	SAR	TAR		
HFE-254cb2	NA	0.22	NA	30	NA	NA
HFE-347mcc3	NA	4.5	NA	480	NA	NA
HFE-356pcf3	NA	3.2	NA	430	NA	NA
HFE-374pcf2	NA	5.0	NA	540	NA	NA
HFE-7100	NA	5.0	NA	390	NA	NA
HFE-7200	NA	0.77	NA	55	NA	NA
H-Galden 1040x	NA	6.3	NA	1,800	NA	NA
HG-10	NA	12.1	NA	2,700	NA	NA
HG-01	NA	6.2	NA	1,500	NA	NA
Others[d]						
NF3	NA	740	NA	10,800	NA	NA
SF5CF3	NA	>1,000	NA	>17,500	NA	NA
c-C3F6	NA	>1,000	NA	>16,800	NA	NA
HFE-227ea	NA	11	NA	1,500	NA	NA
HFE-236ea2	NA	5.8	NA	960	NA	NA
HFE-236fa	NA	3.7	NA	470	NA	NA
HFE-245fa1	NA	2.2	NA	280	NA	NA
HFE-263fb2	NA	0.1	NA	11	NA	NA
HFE-329mcc2	NA	6.8	NA	890	NA	NA
HFE-338mcf2	NA	4.3	NA	540	NA	NA
HFE-347-mcf2	NA	2.8	NA	360	NA	NA
HFE-356mec3	NA	0.94	NA	98	NA	NA
HFE-356pcc3	NA	0.93	NA	110	NA	NA
HFE-356pcf2	NA	2.0	NA	260	NA	NA
HFE-365mcf3	NA	0.11	NA	11	NA	NA
(CF3)2CHOCHF2	NA	3.1	NA	370	NA	NA
(CF3)2CHOCH3	NA	0.25	NA	26	NA	NA
(CF2)4CH(OH)-	NA	0.85	NA	70	NA	NA

[a] No single lifetime can be determined for carbon dioxide. See Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), http://www.grida.no/climate/ipcc_tar/wg1/.

[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.

[c] Methane and nitrous oxide have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT).

[d] Gases whose lifetime has been determined only via indirect means of for whom there is uncertainty over the loss process.

Notes: NC (No Change); NA (Not Applicable)

Sources: U.S. Environmental Protection Agency, Greenhouse Gases And Global Warming Potential Values: Excerpt from the *Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000* (Washington, D.C., April 2002) http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html; Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), http://www.grida.no/climate/ipcc_tar/wg1/.

As a result of the adjustments to the radiative forcing of CO_2 and the recalculation of atmospheric lifelines of several gases, the GWPs of the other gases, relative to CO_2, have generally increased. Other variables, such as the radiative efficiency or chemical lifetime, have also altered the GWP values.[154] Because much detailed laboratory data are not yet available, however, some of the GWPs have larger uncertainties than others. As mentioned above, the IPCC estimates that GWPs generally have an uncertainty of ±35 percent.

Because GWP values are based on the concept of radiative forcing, and these forcings do not appear to stay constant over time, the values for GWPs also will continue to fluctuate, particularly if the amounts and composition of the various gases in the atmosphere change. In some cases, where concentrations of a greenhouse gas are low, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, the marginal effects of additional emissions may not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or CO_2, tends to be less than that of a rare gas, such as sulfur hexafluoride (SF_6). This “diminishing return” effect implies that increasing concentrations of a particular gas reduces the impact of additional quantities of that gas. Thus, the relative impacts of various gases will change as their relative concentrations in the atmosphere change.

Figure 7-1 shows the comparative global and annual mean radiative forcing of a range of gases from 1750 to the late 1990s. Note that greenhouse gases are provided in the left-most bar in the graphic. The IPCC notes that, all the forcings shown have distinct spatial and seasonal features such that the global, annual means appearing on this plot do not yield a complete picture of the radiative perturbation. They are only intended to give, in a relative sense, a first-order perspective on a global, annual mean scale, and cannot be readily employed to obtain the climate response to the total natural and/or anthropogenic forcings. As in the SAR, it is emphasized that the positive and negative global mean forcings cannot be added up and viewed a priori as providing offsets in terms of the complete global climate impact.

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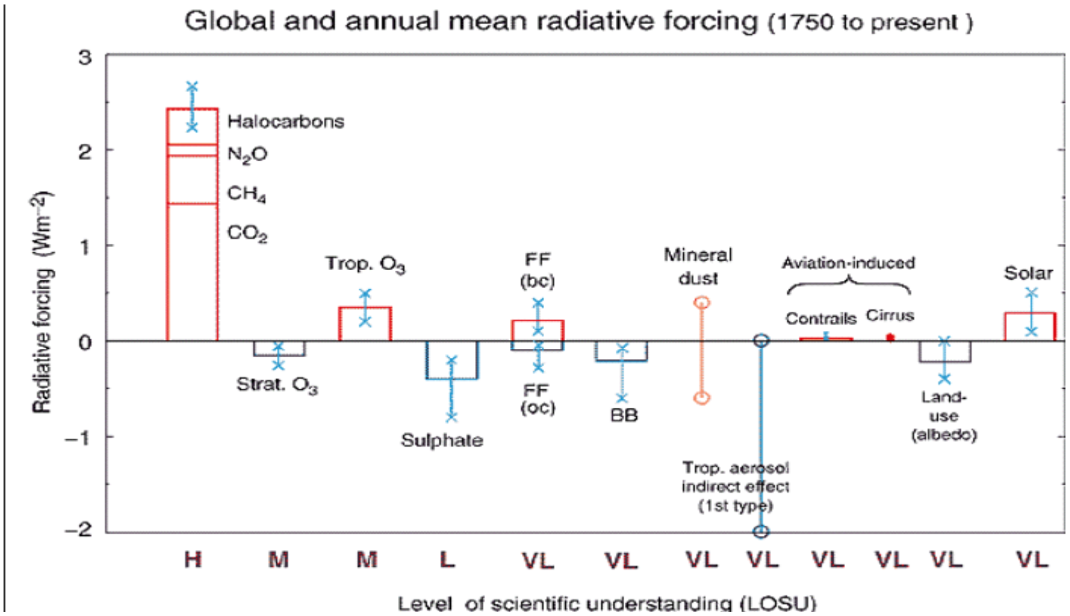
[154] U.S. Environmental Protection Agency, *Greenhouse Gases and Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000* (April 2002), http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html.

Figure 7-1. Global and Annual Mean Radiative Forcing (1750 to Present)



This figure illustrates the global, annual mean radiative forcings (Wm^{-2}) due to a number of agents for the period from pre-industrial (1750) to the late 1990s (about 2000). The height of the rectangular bar denotes a central or best estimate value while its absence denotes no best estimate is possible. The vertical line about the rectangular bar with "x" delimiters indicates an estimate of the uncertainty range, guided by the spread in the published values of the forcing and physical understanding. A vertical line without a rectangular bar and with "o" delimiters denotes a forcing for which no central estimate can be given owing to large uncertainties. The uncertainty range specified here has no statistical basis and therefore differs from the use of the term elsewhere in this document. A "level of scientific understanding" (LOSU) index is accorded to each forcing, with H, M, L and VL denoting high, medium, low and very low levels, respectively. This represents our subjective judgment about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of our knowledge of the physical/chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing. The well-mixed greenhouse gases are grouped together into a single rectangular bar with the individual mean contributions due to CO_2, CH_4, N_2O, and halocarbons shown; halocarbons refers to all halogen-containing compounds listed in "FF" denotes fossil fuel burning while "BB" denotes biomass burning aerosol. Fossil fuel burning is separated into the "black carbon" (bc) and "organic carbon" (oc) components with its separate best estimate and range. The sign of the effects due to mineral dust is itself an uncertainty. Only the first type of indirect effect due to aerosols as applicable in the context of liquid clouds is considered here.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

7.5 Effect of Using TAR GWPs for Greenhouse Gas Emissions Estimations

As Table 7-4 indicates, the values calculated with the TAR GWPs are 0.7 percent higher than the estimate calculated with SAR GWPs when applied to the 1990 base year estimate. When applying the TAR GWPs, the greatest overall difference to the SAR estimates, in terms of having a significant effect on the atmosphere, can be seen in a 9.5 percent increase in carbon-equivalent methane emissions and a 4.5 percent decrease in carbon-equivalent nitrous oxide emissions. Carbon equivalent emissions of HFCs, PFCs, and SF_6 have varied over the years depending on the relative share of the gases, but in 1990 the difference was a 4 percent decrease. Taken as a whole, however, the differences in GWPs between the SAR and TAR do not prove a significant effect on U.S. emissions trends.

Table 7-4. GWP Effects on U.S. Greenhouse Gas Emissions for 1990

	IPCC GWP		Annual GWP-Weighted Emissions, 1990 (Million Metric Tons Carbon Dioxide Equivalent)		
			1990		
Gas	**1996**	**2001**	**1996 GWP**	**2001 GWP**	**% Change**
Carbon dioxide	1	1	5,002	5,002	0.0%
Methane	21	23	659	721	9.5%
Nitrous oxide	310	296	353	337	-4.5%
HFCs, PFCs, and SF_6	M	M	92	88	-4.0%
Total	–	–	6,106	6,149	0.7%

M=mixture of gases

Sources: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2003* (December 2004); Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), http://www.ipcc.ch/pub/reports.htm; and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), http://www.grida.no/climate/ipcc_tar/wg1/.

7.6 Conclusions

In the five years between the publication of the SAR in 1996 and the TAR in 2001, progress was achieved in reducing the scientific uncertainty associated with the direct and indirect relationship of atmospheric responses to various external influences. Improvements have been made to the GWP values published in the TAR, and these are may be adopted and approved by the UNFCCC COP/MOP. While participating countries are still required to apply the GWPs published in the SAR according to the most recently adopted requirements for the development of national GHG inventories submitted to the UNFCCC, the TAR has been recognized as providing the most scientifically accurate GWPs to date, and has been adopted by EIA in the completion of this report.

Part III

Uncertainty in Emission Estimates

8. Uncertainty in Emission Estimates

8.1 Overview

The *Revised 1996 IPCC Guidelines*,[155] as established at the UNFCCC 4th Conference of the Parties in Kyoto, Japan in December 1997, recommend that nations carry out analyses to estimate the uncertainty in their national greenhouse gas emissions inventories. According to the guidelines, nations should construct 95 percent confidence intervals for their greenhouse gas emission estimates using classical sampling techniques, Monte Carlo techniques, or assessments by national experts. The UNFCCC subsequently requested that the Intergovernmental Panel on Climate Change complete its work on uncertainty and prepare a report on good practice in inventory management. In 2000, the IPCC issued its report *Good Practice Guidance*.[156] The report established Tier 1 and Tier 2 methods of estimating uncertainty in greenhouse gas inventories.

8.1.1 Good Practice Guidance on Uncertainty Management in National Greenhouse Gas Inventories

Tier 1 Analysis

In 1998, EIA carried out an uncertainty analysis of U.S. greenhouse gas emissions. This analysis included emissions of carbon dioxide, methane, nitrous oxide, and other gases. The results of this analysis can be found in Table 8-1 below. The analysis provides a "weighted uncertainty" for each source calculated as the squared root of the sum of the squared activity data and emission factor errors multiplied by the point estimate of the share of total emissions for the source. This approach was later described as a Tier 1 analysis under the IPCC *Good Practice Guidance*. The Tier 1 approach, however, as pointed out by the Intergovernmental Panel on Climate Change, may be inappropriate when combining non-normal distributions, as may be the case with some of the distributions for emission factors and activity data. The uncertainty analysis found in Table 8-1 excludes estimates for emissions and sequestration from land use changes and forestry. The Tier 1 analysis concluded that U.S. national greenhouse gas emissions, taken as a group, may differ by as much as 13 percent from the estimates published in the earlier edition of this report. Much of the uncertainty in national emissions was attributable to estimates of nitrous oxide emissions. If nitrous oxide emissions were excluded, the range of uncertainty for the total estimate was calculated to be on the order of 10 percent.

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[155] Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines* (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[156] Intergovernmental Panel on Climate Change, *Good Practice Guidance* (Montreal, May 2000), http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

Table 8-1. Estimate of the Reliability of 1999 U.S. Emissions Estimates (Tier 1 Method)

Greenhouse Gas Source	Share of Total Emissions	Activity Data			Emission factor			Weighted by Total Emissions	
		Bias		Random	Bias		Random		
		Min	Max		Min	Max		Min	Max
	Percent of Source							Percent of Total	
Carbon Dioxide									
Petroleum	35.2%	2.1%	2.4%	0.5%	1.7%	1.7%	0.5%	1.0%	1.1%
Coal	29.9%	0.6%	4.3%	0.6%	1.0%	1.0%	0.5%	0.4%	1.4%
Natural Gas	17.2%	0.5%	2.8%	0.5%	0.0%	0.0%	0.4%	0.1%	0.5%
Other	0.6%	-9.3%	7.8%	11.1%	23.3%	23.3%	4.4%	0.2%	0.2%
Missing Sources	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%
Total	82.9%	1.1%	3.7%	0.6%	1.2%	1.2%	0.5%	1.7%	3.5%
Methane									
Energy-Related	3.2%	13.2%	14.0%	4.9%	20.8%	25.0%	4.5%	0.8%	0.9%
Agricultural	2.8%	3.1%	5.0%	3.0%	36.4%	36.4%	10.6%	1.1%	1.1%
Industrial & Waste	3.2%	9.7%	29.4%	5.0%	50.5%	13.8%	10.1%	1.6%	1.1%
Missing Sources	0.0%	0.0%	4.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	9.2%	8.9%	20.6%	4.3%	35.9%	24.6%	8.3%	3.5%	3.1%
Nitrous Oxide									
Energy-Related	1.3%	0.5%	2.8%	0.5%	55.0%	200.0%	10.0%	0.7%	2.5%
Agricultural	4.1%	4.0%	5.0%	4.5%	90.0%	100.0%	10.0%	3.7%	4.1%
Industrial & Waste	0.4%	2.8%	5.0%	3.5%	55.0%	200.0%	10.0%	0.1%	0.5%
Missing Sources	0.0%	0.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.5%
Total	5.7%	3.1%	19.5%	3.5%	80.0%	128.5%	10.0%	6.5%	7.5%
HFCs, PFCs, SF_6									
HFCs, PFCs, SF_6	2.2%	4.5%	2.4%	0.9%	13.8%	15.5%	2.5%	0.5%	0.6%
Missing Sources	0%	0.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Total	2.2%	4.5%	12.4%	0.9%	13.8%	15.5%	2.5%	0.5%	0.6%
Total-All Sources	100.0%	2.0%	6.4%	1.1%	9.2%	11.0%	1.8%	13.2%	12.9%

Notes: The “low” and “high” bias errors provide a subjective estimate of the largest bias error lower or higher than the current point estimate that would be consistent with current understanding of the nature of the activity or emissions mechanism. Each value is calculated as the weighted average of the uncertainties associated with a group of sources in each category. It is calculated as a percentage of the point estimate of emissions from that source. “Random error” is a subjective estimate of the largest random error that is consistent with current understanding of the nature of the activity or emissions estimate. “Weighted uncertainty” is calculated as the square root of the sum of the squared activity factor and emission factor errors and then multiplied by the point estimate of the share of total emissions for the source. It is calculated as a percentage of the point estimate of total 1997 U.S. emissions.
Source: Estimates prepared for *Emissions of Greenhouse Gases In the United States 1997.*

Tier 2 Analysis

EIA later undertook a Tier 2 uncertainty analysis of U.S. carbon dioxide, methane and nitrous oxide emission estimates for 1999. The Tier 2 uncertainty analysis involves Monte Carlo simulations that facilitate the combination of various types of probability density functions. As a point of comparison, the Tier 2 analysis estimated total uncertainty about a simulated mean of total carbon dioxide, methane and nitrous oxide emissions[157] for 1999 to be -4.4 percent to 4.6 percent. When expressed as a percentage of total estimated 1999 emissions,[158] the uncertainty becomes -0.4 to 9.0 percent.

The principle of Monte Carlo analysis is to select random values of activity data and emission factors from within their individual probability density functions, and to calculate the corresponding emission values. This procedure is repeated many times, using a computer, and the results of each calculation run build up to the overall emission probability density function. Monte Carlo analysis can be performed at the source category level, for aggregations of source categories or for the inventory as a whole.

Like all methods, Monte Carlo analysis only provides satisfactory results if it is properly implemented. This requires the analyst to have scientific and technical understanding of the inventory. Of course, the results will only be valid to the extent that the input data, including any expert judgments, are sound.[159]

8.1.2 Sources of Uncertainty

The uncertainties in the estimates presented in this report come from the following sources:

Evolving Definitions

In general, this report attempts to measure “anthropogenic” (human-caused) emissions and sequestration of greenhouse gases in the United States, excluding carbon emissions of biological origin. Although in most cases it is obvious whether emissions from a particular source fall within this definition, there are a number of ambiguous cases, and the range of accepted definitions has shifted over time. Since the first edition of this report, sulfur hexafluoride has been added to the generally accepted definition of “greenhouse gases.” Emissions from bunker fuel are now excluded from the definition of “U.S. emissions.” Definitional changes tend to raise or lower emission estimates systematically.

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[157] It is important to point out that the Tier 1 analysis includes all UNFCCC greenhouse gases while the Tier 2 analysis does not include HFCs, PFCs and SF_6 emissions in its simulation. The inclusion of these gases, which represent approximately 2.5 percent of total U.S. greenhouse gases, would have increased the uncertainty band in the Tier 2 analysis.

[158] Total 1999 emissions of carbon dioxide, methane and nitrous oxide as estimated in U. S. Energy Information Administration, Emissions of Greenhouse Gases in the United States 1999, DOE/EIA-0573 (99) (October 2000).

[159] Intergovernmental Panel on Climate Change, *Good Practice Guidance*, (Montreal, May 2000) pp. 6.18-6.19, http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

Emissions Sources Excluded from the Report

An estimate that excludes some sources will be biased downward by the amount of the excluded source. Of course, if the existence or magnitude of the excluded emissions were known, they would be included. It is probable that there are still sources that have not yet been identified and escape inclusion in both the estimates and the list of sources excluded.

Incorrect Models of Emissions Processes

An estimate based on a belief that emissions are caused by (or can be estimated from) a particular activity or process can produce large, systematically biased errors if the emissions are actually caused by some other process. The incorrect method can produce estimates that are considerably higher or lower than actual emissions and that have different time-series properties.

Errors in Emission factors

Errors in emission factors can have diverse causes, the most common of which are definitional errors, sampling errors, and measurement errors. These errors can be either random or systematic.

Errors in Activity Data

Activity data are also subject to definitional errors, frame errors, sampling errors, and measurement errors, which can be either random or systematic.

Computational Errors

Computational errors can exist in the estimation of emission factors by EIA, in the calculation of emissions by EIA, or in the computation of the underlying activity data by the source organization. Although any single computational error will usually produce a systematic error, computational errors as a group tend to produce very small (about 0.1 percent) random errors in the estimate.[160]

8.1.3 Bias and Random Error

The different sources of error, as noted above, can produce random or systematic ("bias") errors. Random errors have the appearance of "noise" in the estimate, causing random year-to-year changes in the estimate as compared with (unobservable) actual emissions. Random errors might be caused by data collection and computation errors, the inherent imprecision of metering and measurement, and timing problems. Thus, it should be difficult to distinguish the "signal" of growing or declining emissions until the magnitude of the trend exceeds the "noise" from the random fluctuations. Since, in the case of U.S. energy data, rather small trends in the underlying data can be detected, it is likely that the aggregate magnitude of random errors in U.S. energy data is small, and, in particular, smaller than bias errors.

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[160] Every year, as this report is prepared for publication, a number of computational errors that have crept into the report are detected and fixed. Sometimes, the detected errors have been present for more than one year. The errors that have been detected are typically very small (about 0.01 to 0.1 percent of emissions) and subtle, and they tend to both raise and lower estimated emissions. The U. S. Energy Information Administration is not aware of any remaining computational errors, but it is assumed that any undetected errors generally are similar to, or smaller than, the errors that have been detected.

Bias errors will produce an error of approximately the same magnitude every year. If bias errors are small, they are not likely to affect the estimates of trends. Excluded sources and changes in definition produce bias errors. “Double counting” in activity data surveys will produce upwardly biased estimates of the activity; frame errors or other forms of undercounting will produce estimates that are biased downward. Because EIA, like other statistical agencies, produces data by approximately the same methods every year, double counting and undercounting errors are likely to persist over time.

There is no reason to believe that the distribution of bias errors is symmetrical around the point estimate of the value. In fact, a priori or independently gathered information may indicate that the potential size and probability of the existence of bias errors may be skewed: for example, in EIA data it is likely that essentially all the transactions reported to EIA actually occurred; however, it is possible that some transactions were never reported. Thus, EIA energy data are more likely to underestimate than to overestimate actual energy consumption. Further, because there are multiple surveys of energy production and consumption, undertaken for multiple purposes, the results of the surveys can help put bounds on the extent of possible bias errors.

Bias errors can be hard to detect, and it is difficult to prove either the presence or absence of bias errors. The best ways of detecting them are to use multiple methods of estimating the source series and compare the results, or to determine the range of possible values from a priori information. Comparison methods usually can establish “ceilings” and “floors” for bias errors: that is, it is possible to demonstrate that if the bias error exceeded a certain percent, then a separate, independently collected series must also have a bias error of the same sign. An investigation of how the data are collected may also uncover information about the magnitude or scale of potential bias errors.

The reliability of emissions data varies by category and by source. In general, estimates of carbon dioxide emissions are more reliable than estimates for other gases. It is likely that the estimate of carbon dioxide emissions is accurate to within 5 percent. Estimates of methane emissions are much more uncertain. The level of uncertainty may exceed 30 percent. Estimates of methane emissions are also likely to understate actual emissions, as a result of the exclusion of sources that are unknown or difficult to quantify such as abandoned coal mines or industrial wastewater. Nitrous oxide emissions estimates are much more unreliable than carbon dioxide or methane emissions estimates, in part because nitrous oxide emissions have been studied far less than emissions from other sources and in part because the largest apparent sources of nitrous oxide emissions are area sources that result from biological activity, which makes for emissions that are highly variable and hard to measure or characterize. The uncertainty for nitrous oxide emissions may exceed 100 percent.

8.2 Methods for Determining Uncertainties

8.2.1 Good Practice Guidance for Selecting a Probability Density Function (PDF)

The Intergovernmental Panel on Climate Change *good practice* guidelines state the following: “Where there is sufficient information to define the underlying probability distribution for conventional statistical analysis, a 95 per cent confidence interval should be calculated as a definition of the range.” As part of its earlier Tier 1 uncertainty analysis, EIA assigned relative uncertainties to each sector. Those figures served as a basis for building the PDFs for the Monte Carlo simulations, or Tier 2 analysis.

The chief purpose of using statistical inference is to develop a compact representation of a data set. The following summary statistics represent an efficient approach to measure the variability that occurs when multiple determinations are made of a quantity that is an input to the inventory:

***Arithmetic Mean* -** The statistical definition of the arithmetic mean is the sum of the values divided by the number of values.

***Variance* -** The statistical definition of variance is a parameter of a PDF, which expresses the variability of the population, i.e., the total number of items under consideration.

***Skewness (Asymmetry of the Distribution)* -** The statistical definition of skewness is a measure of asymmetry of a PDF. It is a simple function of two moments[161] of the PDF.

***Kurtosis (Peakedness of the Distribution)* -** The statistical definition of kurtosis is a measure of the flatness of a PDF. It also is a simple function of two moments of the PDF.

Choosing a PDF

Because uncertainty often exists as to which of the data points are representative of the real situation, however, it is common to estimate the value of that measure by using a distribution. The PDF encompasses the range of possible outcomes within a percentage interval (e.g. 95 percent) that is likely to capture the actual outcome. Introducing the concept of a probability around the point estimate reflects both the uncertain and variable nature of the expected value.

Based on the results of EIA’s Tier 1 analysis, the numbers reported in the activity data can be characterized as lying between a maximum and a minimum value. Accuracy around the reported value was an important issue and discussions about a sufficient confidence-level led EIA to select a uniform distribution. The uniform distribution is useful for representing subjective judgment about uncertainty when an expert is only seeking to estimate an upper and lower limit for a quantity because it is the maximum entropy distribution in the case. This assumes that there is an equal probability for the two limits to occur. An example of a uniform PDF is illustrated in Figure 8-1 below.

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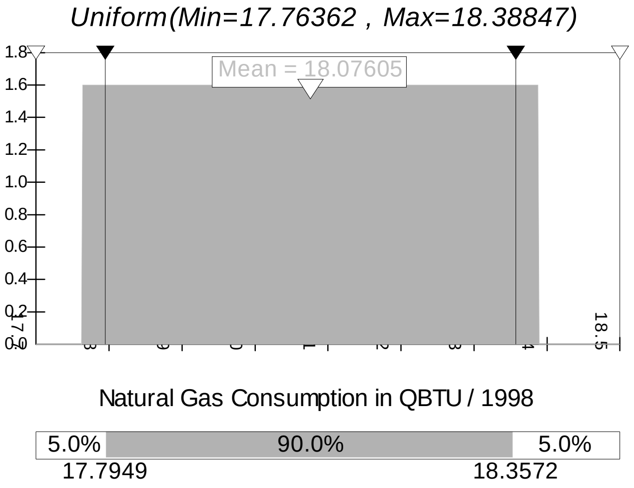
[161] Calculations are usually based upon the moments of the PDF rather than the PDF itself. The most commonly encountered moments are the mean and the variance.

Figure 8-1. **Probability Density Function of Natural Gas Consumption by RCIT Sectors in the United States for the Year 1998 – (Variability)**

Properties

Minimum	17.76362
Maximum	18.38847
Mean	18.07605
Std. Dev	0.18038
Variance	0.032537
Skewness	0.0000
Kurtosis	1.8000
Left X	17.7949
Left P	5.00%
Right X	18.3572
Right P	95.00%
Diff. X	0.5624
Diff. P	90.00%



Note: R, C, I, T: are Residential, Commercial, Industrial and Transportation

In addition to systematic error, the numbers derived from EIA's collected data also contained errors due to human mistakes and instrumental errors. A random error was considered based on the recommendation of inventory experts at EIA, and was represented by a normal or bell shaped distribution. Figure 8-2 provides an example of the data implementation.

The same approach was also applied to emission factors as EIA assigned bias and random errors accordingly. Variability and uncertainty were introduced in the input data for each year from 1990 through 1999 for all sectors.

In the absence of sample data, and given a particular set of parameters, the principle of maximum entropy inference was applied in order to choose a PDF consistent with the available information. For example:

Given a mean value and a standard deviation, it is appropriate to define the variable as a normal distribution or bell shaped function, $N_{(\mu,\sigma)}$;

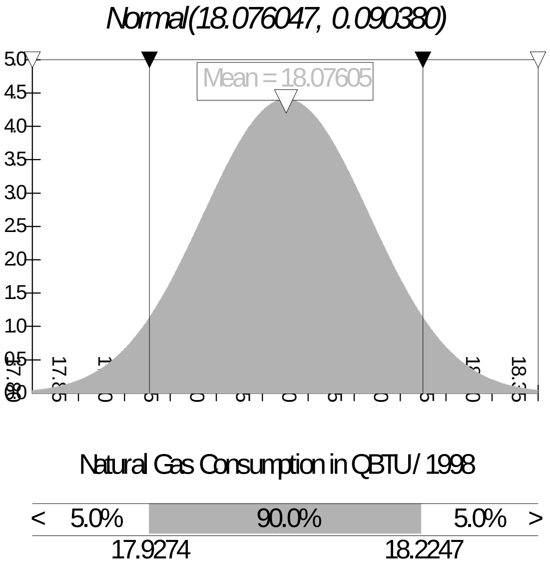
Given an upper and lower value of the quantity, a uniform distribution function will be the least biased, $U_{(a,b)}$;

Given that a real minimum, a real maximum and a most likely value exist, a triangular distribution function will be suitable, $T_{(a,m,b)}$;

Given estimates of the lower and upper bounds, mean and standard deviation, a beta distribution function is the most unbiased PDF to use, $B_{(\alpha 1,\alpha 2)}$.

Figure 8-2. Probability Density Function of Natural Gas Consumption by RCIT Sectors in the United States for the Year 1998 –(Variability Plus Uncertainty)

Properties	
Minimum	-Infinity
Maximum	+Infinity
Mean	18.076047
Mode	18.076047
Median	18.076047
Std. Dev	0.090380
Variance	0.0081686
Skewness	0.0000
Kurtosis	3.0000
Left X	17.9274
Left P	5.00%
Right X	18.2247
Right P	95.00%
Diff. X	0.2973
Diff. P	90.00%



Note: R, C, I, T: are Residential, Commercial, Industrial and Transportation

8.3 Method for Aggregating Uncertainties

Monte Carlo simulations were performed on 1999 emission estimates based on basic statistical considerations and the nature of the parameters related to the uncertainties. Relative uncertainties were assigned to consumption data and emission factors by sector and category. Density functions were then built to reflect those uncertainties. The modeling procedure was implemented for each input variable for random sampling. Simulations were run at 10,000 iterations, to reach results stabilization.

All input figures were represented by PDFs according to their individual variability and uncertainty, and then combined through Monte Carlo sampling. Carbon dioxide emissions are the result of multiplication between activity or consumption data and the appropriate emission coefficients.

For methane and nitrous oxide, estimates were derived from a less straightforward calculation. The data offered an opportunity for a detailed investigation. However, due to limited time and resources, EIA decided to keep the same level of granularity for all gases. In order to accomplish the objective of this effort, a methodology similar to that for carbon dioxide was used and one element of aggregated activity was selected as the indicator for each source category. Applicable aggregated emission factors were used in conjunction with this activity data. The source of activity data was carefully selected to provide a similar calculation method to the one used for carbon dioxide.

8.3.1 Monte Carlo Technique

In order to carry out a Monte Carlo analysis, estimates of minimum, maximum and random bias in emission factors and activity data were established. Table 8-2 shows the estimated bias and random uncertainties in activity data and emission factors for carbon dioxide, methane and nitrous oxide delineated by fuel type and activity that were used in the Monte Carlo analysis. For petroleum, the activity data are divided into the following sectors: residential, commercial, and transportation; industrial; electric utility; and non-fuel use. For coal emissions, the division is between electric utility and other sectors (industrial combined with residential, commercial, and transportation). For natural gas emissions, the division is the same as those for coal with the addition of flared gas. Methane and nitrous oxide emissions are divided by source categories. For each source category, bias and random errors were combined by assuming an aggregate emission factor and a single scaling factor for activity data.

Table 8-2. Random and Bias Uncertainties Associated with 1999 Inventory Data						
Source Category	Activity Data Uncertainty			Emission Factor Uncertainty		
	BIAS (Uniform)		Random	BIAS (Uniform)		Random
	Min[a]	Max[b]		Min[a]	Max[b]	
Carbon Dioxide						
Natural gas						
Other Sectors (R,C,I,T)	0.5%	3.0%	0.5%	0.0%	0.0%	0.4%
Electric Utility	0.5%	2.0%	0.5%	0.0%	0.0%	0.4%
Flared	10.0%	25.0%	2.0%	10.0%	10.0%	5.0%
Coal						
Other Sectors (R,C,I,T)	1.00%	7%	0.70%	1%	1%	0.5%
Electric Utility	0.50%	4%	0.60%	1%	1%	0.5%
Petroleum						
R,C,T Sectors	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
Industrial	2.0%	3.0%	0.6%	4.0%	4.0%	0.6%
Electric Utility [Heavy Oil, Light Oil, Petroleum Coke]	0.5%	2.0%	0.5%	3.0%	3.0%	0.6%
Non-Fuel Use	1.0%	4.0%	0.6%	3.0%	3.0%	0.6%
U.S. Territories	5.0%	10.0%	5.0%	1.0%	1.0%	0.5%
CO_2 in Natural Gas	5.0%	5.0%	5.0%	30.0%	30.0%	5.0%
Bunkers	10.0%	10.0%	0.2%	1.0%	1.0%	2.0%
Cement	2.0%	4.0%	1.0%	3.0%	3.0%	1.0%
Others Industrial Sources	5.0%	10.0%	3.0%	5.0%	5.0%	5.0%
Methane						
Coal						
Underground Coal Mines-Very Gassy	5.0%	10.0%	20.0%	0.0%	0.0%	0.0%
Degasification & Underground Mines	5.0%	10.0%	20.0%	35.0%	25.0%	5.0%
Surface Mines & Post-mining Emissions	10.0%	10.0%	10.0%	40.0%	100.0%	10.0%
Oil and Gas Systems						
Natural Gas Systems	3%	5%	3%	40%	40%	5%
Petroleum Systems	3%	5%	3%	50.0%	60.0%	5.0%
Combustion						
R&C Wood	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary & Mobile Combustion	0.5%	2.8%	0.5%	30.0%	30.0%	15.0%
Waste Handling						
Landfills - Recovery Systems (Modeled)	5.0%	20.0%	10.0%	25.0%	25.0%	10.0%

Table 8-2. Random and Bias Uncertainties Associated with 1999 Inventory Data

Source Category	Activity Data Uncertainty			Emission Factor Uncertainty		
	BIAS (Uniform)		Random	BIAS (Uniform)		Random
	Min[a]	Max[b]		Min[a]	Max[b]	
Landfills - Recovery Systems in Place (1992)	10.0%	10.0%	7.0%	0.0%	0.0%	0.0%
Landfills no Recovery Systems	10.0%	30.0%	5.0%	50.0%	10.0%	10.0%
Wastewater Systems	0.0%	3.0%	5.0%	55.0%	200.0%	10.0%
Agricultural Sources						
Livestock - Enteric Fermentation	3.0%	5.0%	3.0%	10.0%	10.0%	10.0%
Livestock Waste	3.0%	5.0%	3.0%	30.0%	40.0%	10.0%
Rice	5.0%	5.0%	3.0%	60.0%	60.0%	20.0%
Crop Residues	5.0%	5.0%	3.0%	60.0%	60.0%	20.0%
Industrial Processes						
Chemicals and Steel & Iron	3.00%	5%	3.00%	60%	60%	10.0%
Nitrous Oxide						
Agricultural Sources						
Nitrogen Fertilization	5.0%	10.0%	5.0%	90.0%	200.0%	10.0%
Animal Waste	3.0%	5.0%	3.0%	90.0%	100.0%	10.0%
Crop Residues	5.0%	10.0%	3.0%	60.0%	60.0%	20.0%
Energy Combustion						
R&C Wood	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary Combustion	0.5%	2.8%	0.5%	55.0%	200.0%	10.0%
Waste Combustion	30.0%	30.0%	10.0%	90.0%	200.0%	15.0%
Mobile Sources	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
Waste Management	2.0%	5.0%	5.0%	55.0%	200.0%	10.0%
Industrial Processes	10.0%	10.0%	3.0%	55.0%	200.0%	10.0%

a: The minimum bias is the relative change below the mean value.
b: The maximum bias is the relative change above the mean value.
Key: R,C,T, I: Residential, Commercial, Transportation, and Industrial; GHG: Greenhouse Gases.

Source: Energy Information Administration, Emissions of Greenhouse Gases in the United States 2001, Appendix C, DOE/EIA-0573 (2001)(Washington, DC, December 2002)

Because the underlying data were obtained from various EIA surveys, they possessed different levels of associated uncertainty. For example, the maximum bias error for coal activity associated with electric utilities was estimated to be 4 percent, whereas the maximum bias error for coal activity associated with the other sectors was estimated to be 7 percent. This is because fuel use among the reporting electric power generators is relatively well known, but for the other sectors (especially residential and commercial) the data are less reliable.

Monte Carlo simulations were carried out for each greenhouse gas separately, as well as all greenhouse gases as a group. As such, each column of Table 8-3 denotes a separate simulation. Uncertainty about the simulated mean varies by type of gas. There is less uncertainty around the carbon dioxide simulated mean (-1.4 percent to 1.3 percent) than methane (-15.6 percent to 16 percent) or nitrous oxide (-53.5 percent to 54.2 percent). If uncertainty is expressed as a percentage of estimated 1999 emissions, the uncertainty becomes more skewed in the positive direction. This follows from the bias error assumptions above that generally assume that emissions are underestimated. Denominating uncertainty as a percentage of estimated 1999 emissions yields the following uncertainty bands: carbon dioxide (-0.7 percent to 2.0 percent), methane (-2.8 percent to 33.7 percent) and nitrous oxide (-35.1 percent to 115.3 percent). If these uncertainty bands are expressed as a percentage of total estimated 1999 emissions (EIA, October 2000), the following uncertainty bands are derived: carbon dioxide (-0.6 percent to 1.7 percent), methane (-0.3 percent to 3.4 percent) and nitrous oxide (-1.9 percent to 6.3 percent). The final column in the table shows the Monte Carlo results when all the gases are simulated together. The simulation shows that total uncertainty about the simulated mean is –4.4 percent to 4.6 percent. Expressed as a percentage of total emissions, the uncertainty is –0.4 to 9.0 percent.

Table 8-3. Preliminary Results of the Tier 2 Monte Carlo Uncertainty Analysis of EIA's Reported Greenhouse Gas Inventory Data, 1999 (Based on 1999 Data) (Million Metric Tons of Carbon Equivalent, MMTCe)

	Carbon Dioxide	Methane	Nitrous Oxide	Total
Estimated 1999 Value	1,526.8	180.7	98.8	1,806.3
Monte Carlo Simulated 1999 Mean	1,536.4	208.2	138.0	1,882.2
5th Percentile	1,515.5	175.6	64.2	1,799.5
95th Percentile	1,556.8	241.5	212.8	1,969.6
Total Uncertainty Around Simulated Mean	41.3	65.9	148.6	170.1
Uncertainty as Percent of Simulated Mean	-1.4% to 1.3%	-15.6% to 16.0%	-53.5% to 54.2%	-4.4% to 4.6%
Uncertainty as Percent of Estimated Value	-0.7% to 2.0%	-2.6% to 33.7%	-35.1% to 115.3%	-0.4% to 9.0%
Uncertainty as Percent of Total Estimated Emissions	-0.6% to 1.7%	-0.3% to 3.4%	-1.9% to 6.3%	-0.4% to 9.0%

[a] Estimated 1999 emissions from Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99), October 2000.

[b] Monte Carlo simulations using 1999 Energy Information Administration data from Science Applications International Corporation, prepared for Energy Information Administration, *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emissions and Related Support Work* (Washington, D.C., May 2001).

[c] Expressed as a percentage of total carbon dioxide, methane and nitrous oxide emissions in 1999. Note, that this excludes HFC, PFC and SF_6 emissions, as these were not included in the uncertainty analysis.

[d] Note that, with the exception of estimated 1999 values, rows will not sum to total because each individual row denotes a separate simulation. Monte Carlo simulations were carried out for each pollutant separately, as well as a group.

8.4 Identifying Areas Requiring Further Research and Observations

The bulk of the potential uncertainty in the overall national estimate takes the form of bias errors, which are likely to persist from one year to the next and, thus, have relatively little influence on trends, rather than random errors, which would increase the difficulty of determining whether or not a trend exists. Estimates of energy-related carbon dioxide are probably accurate to within 10 percent of estimated emissions, and energy-related carbon dioxide accounts for 81 percent of national emissions of greenhouse gases. There are much larger uncertainties for methane and, particularly, for nitrous oxide emissions, but the present evidence suggests that emissions from these sources accounts for only a small portion of total emissions.

8.4.1 Sensitivity Analyses

EIA conducted a sensitivity analysis in an effort to determine the areas of greatest impact on the total emission estimates. A sensitivity analysis is only a first step in the prioritization of future research and information gathering. Priority should be given to those sources that influence the overall uncertainty most. Sources expected to have a major impact are:

CO_2 Emissions: Total carbon dioxide emissions appear to be primarily affected by residential, commercial and transportation activities associated with the use of petroleum, and with electric-utility consumption of coal. Petroleum and coal emission coefficients for the same sectors had the next greatest effect.

CH_4 Emissions: Total methane emissions seem to be principally effected by landfills without recovery systems. Natural gas systems had the next greatest impact.

N_2O Emissions: Total nitrous dioxide emissions are primarily affected by nitrogen fertilization associated with agricultural activities. The source with the next greatest effect was that of animal waste.

8.4.2 Uncertainty of Carbon Coefficients Used in This Report

Because carbon dioxide emissions are such a large component of total greenhouse gas emissions, EIA has undertaken a review and update of the carbon coefficients for fossil fuels that when combined with combustion factors produce the emission factor for that fuel. A discussion of the uncertainty inherent in those factors is presented below.

Coal

Carbon coefficients for coal vary considerably by rank and state. The large number of samples and the low variability within the sample set of the states that represent the predominant source of supply for U.S. coals suggest that the uncertainty in this factor is very low, on the order of ±1.0 percent. Bituminous coal production and sub-bituminous coal production represented 53.4 percent and 38.1 percent of total U.S. supply in 2000, respectively. Carbon coefficients for bituminous coal vary from a low of 200.5 pounds carbon dioxide per million Btu in Kansas to a high of 232.0 pounds carbon dioxide per million Btu in Montana. In 2000, however, just 200 tons of bituminous coal were produced in Kansas and none were produced in Montana. In 2000, more than 60 percent of bituminous coal was produced in three states: West Virginia, Kentucky and Pennsylvania, and this share has remained fairly constant since 1990. These three states show a variation in carbon content for bituminous coals of ±0.7 percent that is based on more than 2,000 samples. (See Table 8-4.)

Table 8-4. Variability in Carbon Content Coefficients by Rank Across States (pounds Carbon Dioxide per Million Btu)

State	Number of Samples	Bituminous	Sub-bituminous	Anthracite	Lignite
Alabama	946	204.7	-	-	218.5
Alaska	90	216.8	216.3	-	217.5
Arizona	11	-	215.0	-	-
Arkansas	70	212.8	-	-	209.4
Colorado	292	208.1	212.7	-	212.7
Georgia	35	209.5	-	-	-
Idaho	1	-	209.2	-	-
Illinois	16	205.8	-	-	-
Indiana	125	204.3	-	-	-
Iowa	89	202.7	-	-	-
Kansas	28	200.5	-	-	-
Kentucky	870	204.1	-	-	-
Louisiana	1	-	-	-	211.7
Maryland	46	208.0	-	-	-
Massachusetts	3	-	-	253.1	-
Michigan	3	204.7	-	-	-
Mississippi	8	-	-	-	216.5
Missouri	91	202.5	-	-	-
Montana	301	232.0	215.5	228.4	219.1
Nevada	2	208.1	-	-	220.1
New Mexico	167	210.0	209.2	229.1	-
North Dakota	186	-	-	-	219.5
Ohio	646	202.5	-	-	-
Oklahoma	46	204.3	-	-	-
Pennsylvania	739	205.9	-	228.5	-
Tennessee	58	204.6	-	-	-
Texas	48	-	-	-	208.9
Utah	152	211.8	201.3	-	-
Virginia	456	206.2	-	217.2	-
Washington	14	210.3	217.5	226.0	234.9
West Virginia	566	207.0	-	-	-
Wyoming	476	208.7	214.3	-	-

- (No Sample Data Available)
Note: All coefficients based on Higher Heating (Gross Calorific) Value and assume 100 percent combustion.

Source: U.S. Geological Survey, CoalQual Database Version 2.0 (1998) and analysis prepared by Science Applications International Corporation (SAIC) for the U.S. Environmental Protection Agency, Office of Air and Radiation, Market Policies Branch, October 2002.

Similarly, the carbon coefficients for sub-bituminous coals range from 201.3 pounds carbon dioxide per million Btu in Utah to 217.5 pounds carbon dioxide per million Btu in Washington. Utah showed no sub-bituminous production in 2000 and Washington just 4,000 tons. Wyoming, however, has represented between 75 percent and 82 percent of total sub-bituminous coal production in the United States since 1990. Thus, the carbon content coefficient for Wyoming, based on 435 samples, dominates. The interquartile range of carbon content coefficients among samples of sub-bituminous coal in Wyoming was ±1.5 percent from the mean. Similarly this range among samples of bituminous coal from West Virginia, Kentucky, and Pennsylvania was ±1.0 percent or less for each State.

Natural Gas

Pipeline-Quality

EIA examined the composition of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 States. Figure 8-3 shows the relationship between the calculated carbon coefficient for each natural gas sample and its energy content. This figure illustrates the relatively restricted range of variation in both the energy content (which varies by about 6 percent from average) and the carbon coefficient of natural gas (which varies by about 5 percent). Thus, the knowledge that gas has been sold via pipeline to an end use consumer allows us to predict its carbon coefficient with an accuracy of ±5.0 percent.

Natural gas suppliers may achieve the same energy contents with a wide variety of methane, higher hydrocarbon, and non-hydrocarbon gas combinations. Thus, the plot reveals large variations in carbon content for a single Btu value. In fact, the variation in carbon content for a single Btu value may be nearly as great as the variation for the whole sample. As a result, while energy content has some predictive value, the specific energy content does not substantially improve the accuracy of an estimated carbon content coefficient beyond the ±5.0 percent offered with the knowledge that it is of pipeline-quality.

The plot of carbon content also reveals other interesting anomalies. The samples with the lowest emission coefficients tend to have energy contents of about 1,000 Btu per cubic foot. They are composed of almost pure methane. Samples with a greater proportion of natural gas liquids (NGLs) (e.g., ethane, propane, and butane) tend to have energy contents greater than 1,000 Btu per cubic foot, along with higher emission coefficients. Samples with a greater proportion of inert gases tend to have lower energy content, but they usually contain carbon dioxide as one of the inert gases and, consequently, also tend to have higher emission coefficients. (See Figure 8-3.)

For the full sample (N=6,743), the average carbon content of a cubic foot of gas was 14.51 million metric tons per quadrillion Btu. However, this average was raised by both the samples with less than 1,000 Btu per cubic foot that contained large amounts of inert carbon dioxide and those samples with more than 1,050 Btu per cubic foot that contain an unusually large amount of NGLs. Because typical gas consumed in the U.S. does not contain such a large amount of carbon dioxide or natural gas liquids, a weighted national average of 14.47 million metric tons per quadrillion Btu that represents fuels more typically consumed is used.[162]

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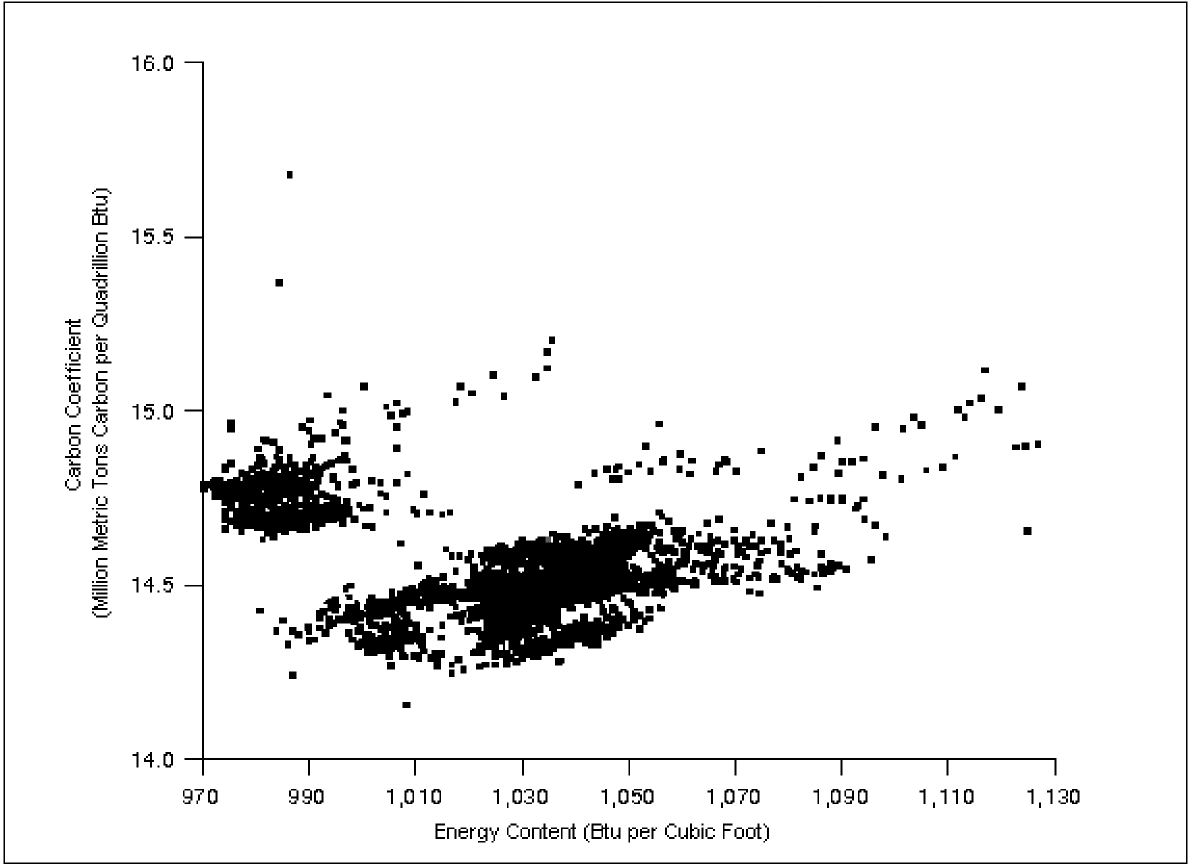
[162] The national average was weighted by applying the carbon content associated with the average heat content of natural gas consumed in each state by the portion of national natural gas consumption represented by that state.

Figure 8-3. Carbon Content for Samples of Pipeline-Quality Natural Gas Included in the Gas Technology Institute (Formerly Gas Research Institute) Database



Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*,) DOE/EIA 0573, Appendix A (Washington, D.C., November, 1994).

Flare Gas

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

There may be no market for some natural gas associated with oil wells, as the amount may be too small or too variable, or the quality might be too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of carbon dioxide). All natural gas flared for these reasons is probably "rich" associated gas, with relatively high energy content, high NGL content, and a high carbon content.

Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

Data on the energy content of flare gas, as reported by states to EIA, indicates an energy content of 1,130 Btu per standard cubic foot. Flare gas may have a higher energy content than reported by EIA because rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot. Rich associated gas will have a much higher proportion of natural gas liquids than pipeline natural gas. The most common NGLs are ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and, to a lesser extent, pentane (C_5H_{12}) and hexane (C_6H_{14}). Because the NGLs have more carbon atoms than methane (which has only one) their presence increases the overall carbon content of natural gas. Hexane is 83.7 percent carbon compared to the 75 percent carbon share found in methane.

Another important source of uncertainty associated with the carbon coefficient for flare gas is the definition of flare gas as reported to EIA by the States. EIA collects data on natural gas vented and flared without a clear distinction between gas flared and gas vented. For the purposes of this report all gas reported to EIA as vented or flared is assumed to be flared. Further, States may report a broad array of gases under the vented and flared category, some of which, such as hydrogen sulfide, are quite different in composition from the natural gas samples used for deriving the carbon coefficient adopted for this report. In some States, carbon dioxide that is vented is reported as vented and flared and its contribution to overall national emissions is not accurately reflected by treating it as combusted natural gas. Thus, there is a wide band of uncertainty associated with the carbon coefficient for flared natural gas.

Petroleum

Motor Gasoline and Motor gasoline Blending Components

There are two primary contributors to the uncertainty of carbon coefficients for motor gasoline. The first is the small number of motor gasoline samples and ultimate analyses from the work by Mark DeLuchi.[163] However, the amount of variation in carbon content of gasoline is restricted by the compounds in the fuel to ±4 percent. The second primary contributor to uncertainty is the assumed heat content. The heat contents are industry standards established many years ago. The heat contents are standard conversion factors used by EIA to convert volumetric energy data to energy units. Because the heat contents of fuels change over time, without necessarily and directly altering their volume, the conversion of known volumetric data to energy units may introduce bias. Thus, a more precise approach to estimating emission factors would be to calculate carbon content per unit of volume, rather than per unit of energy. Adopting this approach, however, makes it difficult to compare U.S. carbon coefficients with those of other nations. The changes in density of motor gasoline over the last decade suggest that the heat content of the fuels is also changing. However, that change within any season grade has been less than 1 percent over the decade. Of greater concern is the use of a standardized heat content across grades, which show a variation in density of ±1.5 percent.

Jet Fuel

Variability in jet fuel is relatively small with the average carbon share of kerosene-based jet fuel varying by less than ±1 percent and the density varying by ±1 percent. This is because jet fuel is used to transport passengers long distances on commercial airliners. The ratio of fuel mass to useful energy must be tightly bounded to maximize safety and range. There is more uncertainty associated with the density and carbon share of naphtha-based jet fuel because sample data were unavailable and default values were used. This uncertainty has only a small impact on the overall uncertainty of the carbon coefficient for jet fuels, however, because naphtha-based jet fuel represents a small and declining share of total jet fuel consumption in the United States.

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[163] DeLuchi, Mark, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, Volume 2, ANL/ESD/TM-22, Vol. 2 (Chicago, IL: Argonne National Laboratory, November 1993).

Distillate Fuel

The primary source of uncertainty for the estimated carbon coefficient of distillate fuel is the selection of No.2 fuel oil as the typical distillate fuel. No.2 fuel oil is generally consumed for home heating. No.1 fuel oil is generally less dense and if it is consumed in large portions for mobile sources, the carbon content estimated for this report is likely to be too high. The five No.1 fuel oil samples obtained by EIA contained an average of 86.01 percent carbon compared to the 86.34 percent contained in samples of No.2 fuel oil. A carbon coefficient based on No.1 fuel oil would equal 19.72 million metric tons per quadrillion Btu rather than the 19.95 million metric tons per quadrillion Btu for No.2 fuel oil. There is also small uncertainty in the share of carbon based on the limited sample size of ±1 percent.

Residual Fuel

The largest source of uncertainty for estimating the carbon coefficient of residual fuel centers on the estimates of density, which differ from power generation to marine vessel fuels. The difference between the density implied by the energy content of electric power sector fuels and the density observed in the NIPER surveys is probably due to nonsulfur impurities, which reduce the energy content without greatly affecting the density of the product. Impurities of several percent are commonly observed in residual oil. The presence of these impurities also affects the share of the fuel that is carbon. Overall, the uncertainty associated with the carbon coefficient of residual fuel is probably ± 1 percent.

Liquefied Petroleum Gases

Because LPG consists of pure paraffinic compounds whose density, heat content and carbon share are physical constants, there is limited uncertainty associated with the carbon coefficient for this petroleum product. Overall uncertainty is derived mainly from the collection of consumption data and non-fuel data in U.S. energy statistics. This uncertainty is probably less than ±3 percent.

Aviation Gasoline

The uncertainty associated with the carbon coefficient for aviation gasoline is larger than that for other liquid petroleum products examined because no ultimate analyses of samples were conducted. However, given the requirements for safe operation of piston-powered aircraft, the composition of aviation gas is well bounded and the uncertainty of the carbon coefficient is likely to be ±5 percent.

Still Gas

Because the composition of still gas is highly heterogeneous, the carbon coefficient for this product is highly uncertain, with an accuracy of ±33 percent. The carbon coefficient used for this report is probably at the high end of the plausible range.

Asphalt

The share of carbon in asphalts ranges somewhat broadly from 79 percent to 88 percent by weight, with the remainder of the mixture also being variable; hydrogen shares vary by weight from seven to 13 percent and sulfur shares vary from trace levels to eight percent. Because carbon share and total heat content in asphalts do vary systematically, the overall carbon coefficient is likely to be accurate to ±5 percent.

Lubricants

Uncertainty in the estimated carbon coefficient for lubricants is driven by the large range of product compositions and end uses in this category combined with an inability to establish the shares of the various products captured under this category in U.S. energy statistics. Because lubricants may be produced from either the distillate or residual fractions during refining, the possible carbon coefficients range from just under 20.0 million metric tons per quadrillion Btu to about 21.5 million metric tons per quadrillion Btu, or an uncertainty band from – 1 percent to +6 percent of the estimated value.

Petrochemical Feedstocks

Petrochemical feedstocks are not so much distinguished on the basis of chemical composition as on the identity of the purchaser, who may be presumed to be a chemical company or petrochemical unit co-located on the refinery grounds. This produces a considerable degree of uncertainty about the exact composition of petrochemical feedstocks. Since the carbon coefficient for petrochemical feedstocks is a weighted average of the coefficients for naphtha and some class of middle distillates, the accurate coefficient is likely bounded by the two individual coefficients suggesting an uncertainty of ±6 percent.

Kerosene

Uncertainty in the estimated carbon coefficient for kerosene is driven by the selection of No. 1 fuel oil as a proxy for kerosene. If kerosene is more like kerosene-based jet fuel, the true carbon coefficient is likely to be some 2 percent lower. If kerosene is more aptly compared to No. 2 fuel oil, then the true carbon content coefficient is likely to be about 1 percent higher.

Petroleum Coke

The uncertainty associated with the estimated carbon coefficient of petroleum coke can be traced to two factors: the use of only two samples to establish carbon contents and a standard heat content which may be too low. Together, these uncertainties are likely to bias the carbon coefficient upwards by as much as 6 percent.

Special Naphtha

The principal uncertainty associated with the estimated carbon coefficient for special naphtha is the allocation of overall consumption across individual solvents. The overall uncertainty is bounded on the low end by the carbon content of hexane and on the upper end by the carbon content of high solvency mineral spirits. This implies an uncertainty band of –15 percent to + 6 percent.

Petroleum Waxes

Although there is considerable qualitative uncertainty associated with the allocation of petroleum waxes and microcrystalline waxes, the quantitative variation in the carbon contents for all waxes is limited to ±1 percent because of the nearly uniform relationship between carbon and other elements in petroleum waxes broadly defined.

Crude Oil, Unfinished Oils and Miscellaneous

The uncertainty of the estimated carbon content for crude oil centers on the 35 percent of variation that cannot be explained by density and sulfur content. However, as crude is not currently directly consumed in the United States this does not add to the overall uncertainty of the U.S. emissions estimate. Because unfinished oils and miscellaneous products are difficult to define, the uncertainty of applying a crude oil carbon content is likely to be bounded by the range of petroleum products described in this chapter at ±10 percent. This has a larger implication for the overall uncertainty of the emissions estimate than does crude oil directly. Miscellaneous products have been relatively stable in recent years with consumption in the range of 100 to 120 trillion Btu. However, in 2001, the volume of unfinished oils was estimated to contain an energy value of 69 trillion Btu, a value that is subtracted from the total supply disposition in order to avoid double counting with finished products. In 2000 this value was about 401 trillion Btu. Because this is a negative number in the energy consumption total, this fluctuation effectively added about one-third a quad of energy to the balance – or 22 million metric tons of carbon dioxide equivalent from 2000 to 2001. Therefore, the uncertainty associated with emission coefficients for unfinished oils could contribute to the overall uncertainty of the emissions estimate to a measurable degree.

9. Emissions Excluded

Certain sources of emissions of greenhouse and related gases are not included in the estimates presented in this report. The omissions have been made on the basis of lack of essential data, highly speculative emission methods, ambiguity of overall climate effect, or classification as "natural" sources. A number of the sources of excluded emissions for carbon dioxide, methane, and nitrous oxide are described below.

9.1 Carbon Dioxide Emissions Excluded

The following processes or sources generate carbon dioxide emissions that are not included in the estimates presented in this report (additional discussion of these excluded sources is presented below):

1)Biofuel combustion;

2) Enhanced oil recovery;

3) "Off spec" gases;

4) Forest Fires;

5) Unaccounted for natural gas;

6) Fermentation; and

7) Lead Smelting.

9.1.1 Carbon Dioxide Emissions from Biofuel Combustion

Biofuels consist of wood, wood waste, alcohol fuels, biogenic municipal solid waste, and other biomass that are burned for energy. The carbon found in biofuels is the result of the natural process of atmospheric uptake of carbon dioxide by plants. During the combustion of biofuels and the biogenic components of municipal solid waste, there is an immediate release of the carbon in the form of carbon dioxide. Biofuels are assumed to be produced as renewable resources, and the carbon released through burning is assumed to be reabsorbed over time as part of the natural carbon cycle.

Because emissions from biofuel combustion produce no net change in the overall carbon budget, such emissions are not included in this report. If the initial flux had been counted, carbon dioxide emissions from biofuel combustion in 2001 were estimated to have been approximately 65 million metric tons.

Emissions are estimated by multiplying EIA energy consumption data for biofuels by the applicable emission factors. Emission factors for wood and wood waste are 3,120 pounds carbon dioxide per short ton and 195.0 pounds carbon dioxide per million Btu.[164] The emission coefficient for alcohol fuels, 17.99 million metric tons of carbon per quadrillion Btu, was derived specifically for use in this report.

9.1.2 Carbon Dioxide Emissions from Enhanced Oil Recovery

Enhanced oil recovery is the process used by oil producers of injecting anthropogenic or naturally occurring carbon dioxide into petroleum reservoirs for the purpose of retrieving previously unrecoverable oil. Over time, the carbon dioxide seeps into the producing well, contributing to a mixture of oil, natural gas, and carbon dioxide. If the energy content is sufficiently high, the gaseous portion of this mix may be sent to a gas plant. If the energy content is low, the gas may be reinjected, vented, or flared. At this time, there is no basis for EIA to estimate the quantity of added carbon dioxide that is vented or flared. EIA believes that most of the carbon dioxide recovered with the oil is re-injected at that site or recovered for reuse at another site, so that annual emissions are a fraction of the carbon dioxide recovered. The annual amount of carbon dioxide used for enhanced oil recovery is probably on the order of 8 million metric tons,[165] and emissions would be some fraction of that figure. Emissions from this source may be included in future reports if more data become available.

9.1.3 Carbon Dioxide Emissions from “Off Spec” Gases

Off spec gases are those gases that fail to meet Btu content or other specifications for commercial use as combustible fuel. Some flared methane, for example, is too diluted with carbon dioxide to be marketable. Combustion of “off spec” gases and fuels is not covered as a separate line item in this report, but a significant portion of the emissions from this source may be included in the “flaring” category, addressed in Chapter 1, above, or as industrial consumption of “still gas” by refineries.

9.1.4 Carbon Dioxide Emissions from Forest Fires

Forest fires are known to create greenhouse gas fluxes within the atmosphere over extensive time periods. Specifically, forest fires produce carbon dioxide, methane, and nitrous oxide. Considering that carbon uptake occurs with subsequent regrowth (assumed to balance out the initial carbon flux), and because emissions from natural forest fires cannot be distinguished from those from human-induced fires, estimates from this source are not included in this report.

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[164] U. S. Energy Information Administration, *Instructions for Form EIA-1605 Voluntary Reporting of Greenhouse Gases* (March 2003), Appendix B. Fuel and Energy Source Codes and Emission Coefficients, p.48. Wood and wood waste contain “biogenic” carbon. Under international greenhouse gas accounting methods developed by the IPCC, biogenic carbon is considered to be part of the natural carbon balance and does not add to atmospheric concentrations of carbon dioxide. Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines*, (Paris, France, 1997), http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[165] The U.S. Department of Commerce reports total sales of industrial carbon dioxide in 2000 were approximately 13 million metric tons annually, while past Freedonia Group, Inc. reports have reported that approximately 5 million metric tons are used for purposes other than enhanced oil recovery.

9.1.5 Carbon Dioxide Emissions from Unaccounted-for Natural Gas

The editions of *Emissions of Greenhouse Gases in the United States* published by EIA before 1997 included an emissions category called "unmetered natural gas" that includes trace amounts of carbon dioxide. In those years, U.S. natural gas producers consistently reported selling about 3 percent more natural gas than U.S. consumers reported buying. In EIA natural gas statistics, this "missing" gas is described as "the balancing item" or "unaccounted-for gas." The balancing item can be viewed as the sum of leakage, measurement errors, data collection problems, and undetected over- and underreporting, as well as undetected nonreporting. Only a fraction of this amount can credibly be attributed to leakage from gas transmission systems.

Estimates of carbon dioxide emissions from this source were included in early reports, on the grounds that there was an element of systematic underreporting of consumption in the balancing item. In recent years, however, the balancing item has fluctuated between positive and negative values, thus reducing the credibility of the undercounting theory. The balancing item changed to a positive value in 1996 and 1997, and back to negative, increasing values in 1998, 1999 and 2000. Consequently, this report no longer carries "unmetered natural gas" consumption as a source of emissions. The balancing item does serve as a basis for understanding the uncertainty inherent in natural gas combustion emissions estimates. (See chapter 8, which describes the uncertainty analysis.) It should be noted that if this amount were included, U.S. emissions for 2000 would contribute an additional 12 MMTCE.

9.1.6 Carbon Dioxide Emissions from Fermentation

During the fermentation process, such as in the production of beer, wine, and other foods, complex organic compounds are decomposed through a variety of chemical reactions. The most common is the anaerobic conversion of sugar into carbon dioxide and alcohol. Fermentation does not create a net flux of emissions, however, because the carbon dioxide produced is of biological origin.

9.1.7 Carbon Dioxide Emissions from Lead Smelting

Smelting of lead includes a stage in which limestone undergoes calcination. As described in Chapter 1 of the report, carbon dioxide is released as a byproduct of the calcination reaction. Emissions estimates cannot be calculated for this report because there are no known statistics regarding the amount of limestone used in lead smelting. EIA is currently researching alternative data sources in an effort to include estimates of these emissions in future reports.

9.2 Methane Emissions Excluded

9.2.1 Methane Emissions from Industrial Wastewater Treatment

When wastewater that includes large amounts of organic material is treated through anaerobic decomposition, methane is emitted. The most effective method for estimating the magnitude of those emissions is a systematic measurement of all point sources. The number and diversity of industrial wastewater sources in the U.S. make such an approach unaffordable and impractical. Alternatively, methane emissions from industrial wastewater treatment may be calculated using the equation:

$M = P * O * COD * A * EF$

Where:

M = Methane emissions;
P = Product output;
O = Wastewater outflow per unit product produced;
COD = Organic loading in the outflow;
A = Percentage treated anaerobically; and
EF = Emissions factor for portion treated anaerobically.

The IPCC *Good Practice Guidance* provides default data for wastewater generation and COD on an industry specific basis. These defaults are often based on one or two literature sources and are assumed to have an uncertainty range of minus 50 percent to plus 100 percent, although no justification for these ranges is provided. The *Good Practice Guidance* also provides a single default factor of 0.25 kilograms methane per kilogram of COD premised on a general approximation of the theoretical maximum for this emission factor and identifies an uncertainty associated with this estimate of plus or minus 30 percent.

At this time, there is no U.S. specific data to improve on these defaults and the uncertainties make it impossible for EIA to provide a reliable estimate of emissions from this source. However, to the extent that industrial wastewater from industries like meat and poultry processing, pulp and paper manufacturing, and vegetable, fruit and juice processing that is likely to have a high organics content is treated anaerobically, methane emissions will result and the exclusion of this source from U.S. emission totals will, all other things being equal, tend to bias the overall estimate of U.S. methane emissions downwards. The U.S. EPA estimates that this source could be as high as 0.7 million metric tons methane (14.6 million metric tons carbon dioxide equivalent).[b]

9.2.2 Methane Emissions from Abandoned Coal Mines

The U.S. Department of Labor's Mine Safety and Health Administration (MSHA) estimates that since 1980 over 7,500 coal mines have been abandoned. Many of these mines continue to emit methane after they have been abandoned. In an April 2004 report, *Methane Emissions from Abandoned Coal Mines in the United States: Emission Inventory Methodology and 1990-2002 Emission Estimates*, the U.S. EPA estimates methane emission from abandoned coal mines ranged from 130,000 metric tons to 200,000 metric tons in 1990 and 200,000 to 280,000 metric tons in 2002. Because access to abandoned mine sites is very limited and a systematic measurement program at these sites is time intensive and costly, the U.S. EPA study relies upon emissions data from when the abandoned mines were open and assumes a decline function in emissions based on mine and coal seam characteristics.

The most important variable in determining methane emissions from an abandoned mine is the post-mining status of the mine: namely, whether the mine has been sealed, flooded or if it continues to be vented after abandonment. Sealed mines and flooded mines have much lower rates of emissions than vented mines. For operating mines, those defined as gassy (emitting more than 100,000 cubic feet per day) are estimated to emit 98 percent of all coal mine methane. The U.S. EPA assumes that abandoned mines that had been gassy during operation represent a similarly predominant portion of emissions from abandoned mines and thus its study focuses on those abandoned mines that had been gassy prior to closure. Of the 364 gassy mines abandoned since 1972, the U.S. EPA has mine status data for a certain subset of these mines. From this subset, U.S. EPA calculates sample percentage shares by mine status and assumes the sample percentage share also applies to mines with an unknown status.

For those mines that have been vented, U.S. EPA derives an emissions decline curve based on three primary factors: adsorption isotherms by coal basin, coal permeability estimates, and estimates of pressure at abandonment. For mines that are flooded, U.S. EPA assumes a decline curve equation based on measurements taken from eight abandoned mines in two basins. For sealed mines, U.S. EPA treats them as vented mines but adjusts the initial emissions rate and the length of time for overall emissions to account for the slower release from sealed vents. The U.S. EPA sought to calibrate its estimation methodology to field measurements. Limited access to mines precluded measurement at all but seven mines, although the results from those mines suggested the general accuracy of the estimation method.

9.2.3 Methane Emissions from Wetlands

Wetlands are a known source of methane. Environments low in oxygen, combined with abundant organic matter, are conducive to the creation of methane, and wetlands meet both criteria. Wetlands cover approximately 274 million acres of land in the United States and are a potentially important source of atmospheric methane. Because wetlands are a natural source of emissions, human activity that reduces wetlands and their associated methane emissions may be counted as an “anthropogenic” reduction.

The stock of natural wetlands in the United States has diminished considerably over the past two centuries, which should, in principle, have reduced methane emissions from wetlands (EIA is not aware of research proving or disproving this principle). A recent study of wetland losses concluded that the United States had lost approximately 30 percent of its wetlands between colonial times and the mid-1980s. Almost all of the loss has occurred in the lower 48 States, which have lost 53 percent of their original wetlands.[166] Ten States—Arkansas, California, Connecticut, Illinois, Indiana, Iowa, Kentucky, Maryland, Missouri, and Ohio—have lost 70 percent or more of their original wetland acreage. By the mid-1980s, a total of approximately 119 million acres had been lost from the original U.S. total.

An update of the wetlands study indicates that 654,000 acres were converted from wetlands to other uses between 1982 and 1987, and that an additional 431,000 acres were converted between 1987 and 1991.[167] Extrapolating from these data, it is estimated that wetlands in the United States are currently destroyed at a rate of approximately 86,000 acres per year. Wetlands, also known as swamps and marshes, have historically been drained or filled in for agriculture, land development, and mosquito control, although it is currently illegal to drain or fill a wetland without a permit from the U.S. Army Corps of Engineers. It is difficult to find information on the conversion of other land categories to wetlands. It is assumed that the number and extent of wetland creations is small enough to leave the above loss estimates essentially unchanged.

Estimates of global methane fluxes from wetlands suggest that methane emissions from temperate-zone wetlands are typically between 5 and 10 million metric tons of emissions per year

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[166] T. Dahl, U.S. Department of the Interior, Fish and Wildlife Service, *Wetlands Losses in the United States: 1780’s to 1980’s* (Washington, D.C., 1990).

[167] U.S. Department of Agriculture, Soil Conservation Service, *1991 Update of National Resources Inventory Wetlands Data for Non-Federal Rural Lands* (Washington, D.C., not dated), p. 4.

for worldwide temperate-zone wetlands, which include U.S. wetlands.[168] This level of emissions is minimal when compared with estimates of total global wetlands emissions of 115 to 237 million metric tons.[169] The U.S. share of all temperate-zone wetlands is about 57 percent, and temperate-zone wetlands lost during the 1980s accounted for about 0.5 percent of U.S. wetlands at the beginning of the period. Consequently, the reduction in natural methane emissions from wetlands can be approximated as the product of (1) total metric tons of methane emitted in temperate zones, (2) the U.S. share of temperate emissions (percent), and (3) the share of wetlands lost in a decade (percent, using the value for the 1980s). The result is that wetland emissions of methane were reduced by between approximately 14,250 and 28,500 metric tons of methane over the decade.

9.2.4 Methane Removals Resulting from Land Use Changes

Methane removals and nitrous oxide emissions resulting from land use changes are discussed in combination under Section 8.3.2, below.

9.3 Nitrous Oxide Emissions Excluded

9.3.1 Nitrous Oxide Emissions from Industrial Wastewater

Just as industrial wastewater may contain large volumes of organic matter, so, under certain circumstances, industrial wastewater may be a source of nitrogen, leading ultimately to nitrous oxide emissions. However, the problems associated with estimating methane emissions from industrial wastewater are even more difficult with respect to nitrous oxide emissions. This is because the nitrogen content of industrial wastewater is more problematic, and the extent to which bacterial action converts the nitrogen into nitrous oxide (as opposed to molecular nitrogen or nitrogen oxides) is highly uncertain.

9.3.2 Nitrous Oxide Emissions and Methane Removals Resulting from Land Use Changes

The scientific literature suggests that both grasslands and forest lands are natural sinks for methane and natural sources for nitrous oxide, though very minor in both cases. Natural soils apparently serve as methane sinks: well-aerated soils contain a class of bacteria called “methanotrophs” that use methane as food and oxidize it into carbon dioxide. In contrast, experiments indicate that cultivated soils have reduced methane uptake and increased nitrous oxide emissions.

One report indicates that methane uptake in temperate evergreen and deciduous forests in the United States ranges from 0.19 to 3.17 milligrams (measured in carbon units) per square meter per day, equivalent to the uptake of 36.8 to 624.4 metric tons of methane per million acres per year. The range is larger for agricultural lands: 0.2 to 6.3 milligrams per square meter per day.

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[168] E. Matthews and I. Fung, “Methane Emissions from Natural Wetlands: Global Distribution, Area, and Environmental Characteristics,” *Global Biogeochemical Cycles*, Vol. 1, No. 1 (March 1987); and K. Bartlett and R.C. Harriss, “Review and Assessment of Methane Emissions from Wetlands,” *Chemosphere*, Vol. 26, Nos. 1-4 (1993), p. 280.

[169] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.2, p. 250, http://www.grida.no/climate/ipcc_tar/.

Estimates for methane uptake resulting from the abandonment of farmland range from 0.6 to 6.1 milligrams per square meter per day. While all of these ranges are wide, the total amount of methane in question is less than 1 percent of methane emissions from anthropogenic sources.

Of all the greenhouse gases discussed in this report, the least amount of data is available for nitrous oxide. It is known that conversion of forests and grasslands to cropland accelerates nitrogen cycling and increases nitrous oxide emissions from the soil. It is not known with certainty by how much.[170] Some estimates have been made of the difference between fertilized and unfertilized soils. According to one study, unfertilized soils produce emissions of 0.25 to 0.35 milligrams (measured in nitrogen units) per square meter per day, while emissions from fertilized soils range from 0.6 to 1.65 milligrams per square meter per day.[171] Thus, abandoning fertilization should reduce nitrous oxide emissions by 0.35 to 1.3 milligrams per square meter per day—the equivalent of 86 to 321 metric tons of nitrous oxide per million acres per year.

Applying this figure to the 35 million acres of cropland idled between 1982 and 1992 implies a reduction in nitrous oxide emissions ranging from 3,010 to 11,235 metric tons annually. In principle, however, about three-quarters of the reduction in emissions from this source is estimated to be captured by reduced application of nitrogen fertilizers; any emission reductions associated with nitrogen fertilizers would thus already be included in the agriculture statistics in Chapter 3, above.

If such estimates are to be applied to emissions inventories, it is necessary to address a problem of crediting the uptakes. Removing an acre of farmland from production in a particular year creates a permanent annual methane sink that will absorb small additional amounts of methane each year thereafter, or at least until the use of the land changes. It is not currently clear what method should be used to credit such permanent reductions to a particular year.

9.4 Emissions of Ozone-Depleting Substances and Criteria Pollutants

The impact of ozone-depleting substances on global climate is ambiguous, because they have indirect effects that tend to offset their direct warming effects. Furthermore these manufactured substances are being phased out pursuant to the Montreal Protocol. They are not included among the greenhouse gases to be controlled under the Kyoto Protocol. Emissions estimates for chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), bromofluorocarbons (halons), and other ozone-depleting gases are excluded from the main body of this report. Similarly, carbon monoxide, nitrogen oxides, and non-methane volatile organic compounds are excluded from the Kyoto Protocol and from the main body of this report. These gases, termed “criteria pollutants” because they are regulated based on health criteria, have an indirect effect on global climate due to their effect on atmospheric concentrations of greenhouse gases (including carbon dioxide, methane, and ozone).

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[170] A. Mosier, “Nitrous Oxide Emissions from Agricultural Soils,” paper presented at *RIVM International Workshop on Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control* (Amersfoort, The Netherlands, February 3-5, 1993).

[171] A. Mosier and D. Schimel, “Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide,” *Chemistry & Industry*, Vol. 2 (December 1991), p. 875.