

Emissions of Greenhouse Gases in the United States 1998

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Preface

Title XVI, Section 1605(a) of the Energy Policy Act of 1992 (enacted October 24, 1992) provides:

Not later than one year after the date of the enactment of this Act, the Secretary, through the Energy Information Administration, shall develop, based on data available to, and obtained by, the Energy Information Administration, an inventory of the national aggregate emissions of each greenhouse gas for each calendar year of the baseline period of 1987 through 1990. The Administrator of the Energy

Information Administration shall annually update and analyze such inventory using available data. This subsection does not provide any new data collection authority.

The first report in this series, *Emissions of Greenhouse Gases 1985-1990*, was published in September 1993. This report—the seventh annual report, as required by law—presents the Energy Information Administration’s latest estimates of emissions for carbon dioxide, methane, nitrous oxide, and other greenhouse gases.

Contents

	Page
Executive Summary	ix
1. U.S. Emissions of Greenhouse Gases in Perspective	1
About This Report	1
The Greenhouse Effect and Global Climate Change	1
Global Sources of Greenhouse Gases	4
Relative Forcing Effects of Various Gases	6
Global Climate Change Policy Developments	8
From the Framework Convention to the Kyoto Protocol	8
The Kyoto Protocol	9
The Kyoto Protocol and the United States	10
Beyond the Kyoto Protocol	10
2. Carbon Dioxide Emissions	13
Overview	13
Energy Consumption	14
Residential Sector	14
Commercial Sector	15
Transportation Sector	15
Industrial Sector	15
Electric Utilities	16
Energy Intensity Versus Carbon Intensity in Emissions Trends	18
Weather-Adjusted Carbon Dioxide Emissions	19
Adjustments to Energy Consumption	19
U.S. Territories	19
International Bunker Fuels	19
Other Carbon Dioxide Emissions	20
Energy Production	20
Industrial Process Emissions	20
3. Methane Emissions	27
Overview	27
Energy Sources	28
Coal Mining	28
Oil and Gas Production, Processing, and Distribution	29
Stationary Combustion	29
Mobile Combustion	30
Waste Management	30
Landfills	31
Domestic and Commercial Wastewater Treatment	31
Agricultural Sources	32
Enteric Fermentation in Domesticated Animals	32
Solid Waste of Domesticated Animals	33
Rice Cultivation	33
Burning of Crop Residues	33
Industrial Sources	34
Chemical Production	34
Iron and Steel Production	34

Contents

4. Nitrous Oxide Emissions	41
Overview	41
Energy Use	42
Mobile Combustion	42
Stationary Combustion	43
Agriculture	43
Nitrogen Fertilization of Agricultural Soils	43
Crop Residue Burning	44
Solid Waste of Domesticated Animals	44
Waste Management	44
Waste Combustion	45
Human Sewage in Wastewater	45
Industrial Processes	45
Adipic Acid Production	46
Nitric Acid Production	46
5. Halocarbons and Other Gases	51
Overview	51
Hydrofluorocarbons (HFCs)	52
HFC-23	52
1,2,2,2-Tetrafluoroethane (HFC-134a)	52
1,1-Difluoroethane (HFC-152a)	53
Other HFCs	53
Perfluorocarbons (PFCs)	54
Sulfur Hexafluoride	55
Ozone-Depleting Substances	55
Chlorofluorocarbons (CFCs)	55
Hydrochlorofluorocarbons (HCFCs)	56
Bromofluorocarbons (Halons)	56
Other Chemicals	56
Criteria Pollutants That Affect Climate	57
Overview	57
Carbon Monoxide	58
Nitrogen Oxides	58
Nonmethane Volatile Organic Compounds	58
6. Land Use Issues	65
Overview	65
Land Use and the Kyoto Protocol	65
Land Use Data Issues	68
Appendixes	
A. Estimation Methods	71
Carbon Dioxide	71
Methane	83
Nitrous Oxide	95
Halocarbons and Other Gases	100
B. Carbon Coefficients Used in This Report	103
C. Uncertainty in Emissions Estimates	109
D. Emissions Sources Excluded	125
E. Emissions of Energy-Related Carbon Dioxide in the United States, 1949-1998	131
F. Common Conversion Factors	135
References	137
Glossary	147

Tables

ES1. U.S. Emissions of Greenhouse Gases by Gas, 1990-1998	ix
ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-1998	x
1. Global Atmospheric Concentrations of Selected Greenhouse Gases	3
2. Global Natural and Anthropogenic Sources and Absorption of Greenhouse Gases, 1992	4
3. Numerical Estimates of Global Warming Potentials Compared With Carbon Dioxide	8
4. U.S. Carbon Dioxide Emissions from Energy and Industry, 1990-1998	22
5. U.S. Carbon Dioxide Emissions from Energy Consumption by End-Use Sector, 1990-1998	22
6. U.S. Carbon Sequestered by Nonfuel Use of Energy, 1990-1998	23
7. U.S. Carbon Dioxide Emissions from Energy Use in the Industrial Sector, 1990-1998	23
8. U.S. Carbon Dioxide Emissions from Energy Use in the Transportation Sector, 1990-1998	24
9. U.S. Carbon Dioxide Emissions from Energy Use in the Residential Sector, 1990-1998	24
10. U.S. Carbon Dioxide Emissions from Energy Use in the Commercial Sector, 1990-1998	25
11. U.S. Carbon Dioxide Emissions from Electric Utilities, 1990-1998	25
12. U.S. Carbon Dioxide Emissions from Industrial Processes, 1990-1998	26
13. U.S. Methane Emissions from Anthropogenic Sources, 1990-1998	35
14. U.S. Methane Emissions from Coal Mining and Post-Mining Activities, 1990-1998	36
15. U.S. Methane Emissions from Oil and Gas Operations, 1990-1998	36
16. U.S. Methane Emissions from Stationary Combustion Sources, 1990-1998	37
17. U.S. Methane Emissions from Mobile Sources, 1990-1998	38
18. U.S. Methane Emissions from Landfills, 1990-1998	38
19. U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-1998	39
20. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1990-1998	39
21. U.S. Methane Emissions from Industrial Processes, 1990-1998	40
22. Estimated U.S. Emissions of Nitrous Oxide, 1990-1998	47
23. U.S. Nitrous Oxide Emissions from Mobile Sources, 1990-1998	47
24. U.S. Nitrous Oxide Emissions from Stationary Combustion Sources, 1990-1998	48
25. U.S. Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils, 1990-1998	49
26. U.S. Nitrous Oxide Emissions from Solid Waste of Domesticated Animals, 1990-1998	50
27. U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-1998	50
28. U.S. Emissions of Halocarbons and Miscellaneous Greenhouse Gases, 1990-1998	59
29. GWP-Weighted U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-1998	60
30. U.S. Carbon Monoxide Emissions, 1990-1998	61
31. U.S. Nitrogen Oxide Emissions, 1990-1998	62
32. U.S. Emissions of Nonmethane Volatile Organic Compounds, 1990-1998	63
33. Net Carbon Flux from Land Use Change and Forestry, 1990-1997	66
34. Comparison of Components of Forestry and Land Use Change Included in the Kyoto Protocol and IPCC Guidelines	67
A1. U.S. Fossil Fuel Consumption for Nonfuel Use, 1990-1998	74
A2. Rates of Sequestration for U.S. Fossil Fuel Consumption	75
A3. Energy Consumption in U.S. Territories, 1990-1998	78
A4. Carbon Emissions from International Bunker Fuels Supplied in the United States, 1990-1998	79
A5. Production Data for Industrial Sources of Carbon Dioxide, 1990-1998	80
A6. Methane Emissions Factors for Gassy Underground Coal Mines, 1990-1998	86
A7. U.S. Coal Production by Type of Mining and Basin for Mines With Annual Production Exceeding 10,000 Tons, 1990-1998	86
A8. EMCON Methane Generation Model Parameters	90
A9. Estimates of U.S. Waste Generated and Landfilled, 1990-1998	90
A10. Average Pre-Slaughter Live Weights for U.S. Cattle and Calves, 1990-1998	92
A11. Factors Used To Estimate Methane and Nitrous Oxide Emissions from Burning of Crop Residues	94
A12. Methane Emissions Factors for Industrial Processes	95

Tables (Continued)

B1. Carbon Emissions Coefficients at Full Combustion, 1990-1998	104
B2. Changes in Motor Gasoline Density, 1990-1998	105
B3. Characteristics of Major Reformulated Fuel Additives	106
B4. U.S. Crude Oil Characteristics, 1990-1998	107
B5. Emissions Coefficients for Liquefied Petroleum Gases, 1990-1998	108
C1. Reliability of Emissions Estimates in This Report	110
D1. Estimated U.S. Carbon Dioxide Emissions from Biofuels, 1990-1998	125
D2. Estimated Carbon Emissions from U.S. Military Operations Abroad, 1990-1998	126
E1. Energy-Related Carbon Dioxide Emissions from the Residential and Commercial Sectors, 1949-1998	132
E2. Energy-Related Carbon Dioxide Emissions from the Industrial and Transportation Sectors, 1949-1998	133
E3. Energy-Related Carbon Dioxide Emissions from the Electricity Generation Sector, and Total Energy-Related Carbon Dioxide Emissions by End-Use Sector, 1949-1998	134

Figures

ES1. U.S. Greenhouse Gas Emissions by Gas, 1998	x
ES2. Emissions Intensity of U.S. Gross Domestic Product, Population, and Electricity Production, 1980-1998	x
ES3. U.S. Carbon Dioxide Emissions by Sector, 1980-1998	xi
ES4. U.S. Methane Emissions by Source, 1980-1998	xii
ES5. U.S. Nitrous Oxide Emissions by Source, 1980-1998	xiii
1. Annual Change in U.S. Carbon Dioxide Emissions, 1990-1998	13
2. Industrial Output Growth, 1996-1998	16
3. Changes in U.S. Energy Intensity and Carbon Intensity, 1980-1998	18
4. Change in Actual and Weather-Normalized Carbon Emissions by Fuel, 1997-1998	19
5. U.S. Methane Emissions by Source, 1990 and 1998	28
6. U.S. Solid Waste Generated and Landfilled, 1990-1998	31
7. U.S. Emissions of Nitrous Oxide by Source, 1990-1998	41

Executive Summary

Introduction

Total U.S. emissions of greenhouse gases in 1998 increased by 0.2 percent from their 1997 level, below the average growth rate of the 1990s (1.2 percent). During 1998, crude oil prices dropped by one-third and the U.S. economy expanded at a 3.9-percent annual rate. The slowing of growth in emissions resulted in part from a much warmer-than-usual winter in 1998 and in part from lower emissions from the industrial sector.

Overall, 1998 U.S. greenhouse gas emissions were about 10 percent higher than 1990 emissions. Since 1990, U.S. emissions have increased at an annual rate of 1.2 percent, slightly faster than population (1.1 percent) but more slowly than energy consumption (1.4 percent), electricity consumption (2.2 percent), or gross domestic product (GDP) (2.6 percent).

Table ES1 shows trends in emissions of the principal greenhouse gases, measured in million metric tons of gas. In Table ES2, the value shown for each gas is weighted by its global warming potential (GWP), which is a measure of “radiative forcing.” This concept, developed by the Intergovernmental Panel on Climate Change (IPCC), provides a comparative measure of the impacts of different greenhouse gases on global warming, with the effect of carbon dioxide being equal to one.¹

During 1998, some 81 percent of U.S. greenhouse gas emissions resulted from the combustion of fossil fuels such as coal, petroleum, and natural gas. Consequently, U.S. emissions trends are largely caused by trends in energy consumption. In recent years, national energy consumption, like emissions, has grown relatively slowly, with year-to-year fluctuations caused by weather-related phenomena, business cycle fluctuations,

Table ES1. U.S. Emissions of Greenhouse Gases by Gas, 1990-1998
(Million Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Carbon Dioxide	4,939.0	4,886.0	4,972.9	5,091.5	5,169.7	5,220.5	5,395.6	5,464.9	5,483.4
Methane	30.2	30.5	30.6	29.9	30.0	30.2	29.3	29.3	28.8
Nitrous Oxide	1.2	1.2	1.2	1.2	1.3	1.3	1.2	1.2	1.2
Halocarbons and Other Gases									
CFC-11, CFC-12, CFC-113	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0
HCFC-22	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HFCs, PFCs, and SF ₆	*	*	*	*	*	*	*	*	*
Methyl Chloroform	0.2	0.2	0.1	0.1	0.1	*	*	*	*
Criteria Pollutants That Affect Climate									
Carbon Monoxide	86.8	88.6	85.5	85.6	89.5	80.7	82.3	79.2	NA
Nitrogen Oxides	21.2	21.3	21.6	21.8	22.1	21.5	21.3	21.4	NA
Nonmethane VOCs	18.9	19.0	18.6	18.8	19.4	18.6	17.4	17.3	NA

*Less than 50,000 metric tons of gas.

P = preliminary data. NA = not available.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Sources: **Carbon dioxide, methane, nitrous oxide emissions:** EIA estimates described in Chapters 2, 3, and 4 of this report. **Halocarbons and other gases:** U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. ES-2, web site www.epa.gov/globalwarming/inventory/1999-inv.html. **Criteria pollutants:** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends Update, 1900-1997*, EPA-454-R-98-007 (Research Triangle Park, NC, December 1998), Tables A-1–A-3, pp. A-2–A-18, web site www.epa.gov/ttn/chief/trends97/emtmd.html.

¹See “Units for Measuring Greenhouse Gases” on page 3, and Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

Executive Summary

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-1998

(Million Metric Tons of Carbon or Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Carbon Dioxide	1,347	1,333	1,356	1,389	1,410	1,424	1,472	1,490	1,495
Methane	173	174	175	171	172	173	168	168	165
Nitrous Oxide	99	101	103	103	111	106	105	104	103
HFCs, PFCs, and SF ₆	22	22	23	24	26	32	36	38	40
Total	1,641	1,629	1,657	1,686	1,719	1,735	1,780	1,800	1,803

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Sources: EIA estimates documented in this report.

and developments in domestic and international energy markets.

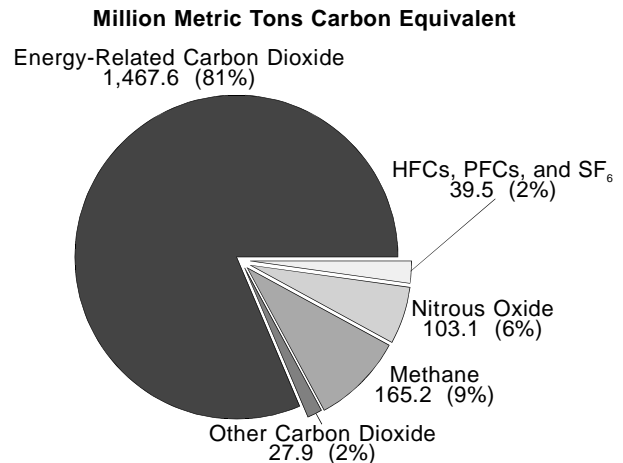
Other 1998 U.S. emissions include carbon dioxide from noncombustion sources (2 percent of total U.S. greenhouse gas emissions), methane (9 percent), nitrous oxide (6 percent), and other gases (2 percent) (Figure ES1). Methane and nitrous oxide emissions are caused by the biological decomposition of various waste streams and fertilizer, fugitive emissions from chemical processes, fossil fuel production and combustion, and many smaller sources. The other gases include hydrofluorocarbons (HFCs), used primarily as refrigerants, perfluorocarbons (PFCs), released as fugitive emissions from aluminum smelting and also used in semiconductor manufacture, and sulfur hexafluoride (SF₆), used as an insulator in utility-scale electrical equipment.

The Kyoto Protocol, drafted in December 1997, raised the public profile of climate change issues in the United States in general, and of emissions estimates in particular. Emissions inventories are the yardstick by which success or failure in complying with the Kyoto Protocol and the Framework Convention on Climate Change would be measured. This report, required by Section 1605(a) of the Energy Policy Act of 1992, provides estimates of U.S. emissions of greenhouse gases, as well as information on the methods used to develop the estimates.

Carbon Dioxide

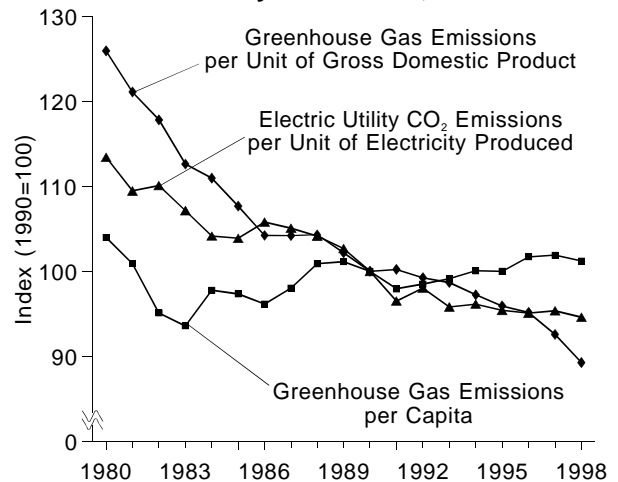
Carbon dioxide accounts for 83 percent of 1998 U.S. greenhouse gas emissions. In 1998, carbon dioxide emissions increased by 0.3 percent, compared with 1997. Figure ES2 illustrates some recent U.S. trends in emissions and energy consumption. Emissions per dollar of GDP and emissions per capita are approximate measures of the carbon intensity of the use of energy services. U.S. emissions per capita, which

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 1998



Source: EIA estimates documented in this report.

Figure ES2. Emissions Intensity of U.S. Gross Domestic Product, Population, and Electricity Production, 1980-1998

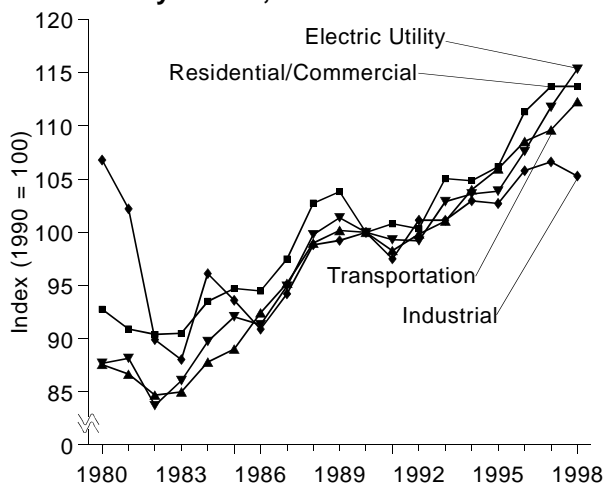


Sources: EIA estimates documented in this report.

declined in the early 1980s, have risen in the 1990s, although at a relatively low rate. Emissions per dollar of GDP have declined almost every year. During the early 1990s, several unrelated factors combined to lower the carbon intensity of power generation, including improved nuclear power plant operating rates and the expansion of natural-gas-fired generation caused by relatively low natural gas prices. However, nuclear output has stabilized since 1995, and fossil fuels have supplied most of the incremental growth in generation.

Figure ES3 illustrates trends in carbon dioxide emissions by energy consumption sector. Emissions from the industrial sector dropped by 12 percent between 1980 and 1985 as higher energy prices and a severe recession reduced output and induced industry to adopt energy-efficient technologies. Emissions from other sectors also declined in the early 1980s. In the late 1980s, however, emissions rose consistently as energy prices declined in the wake of the 1986 disintegration of OPEC's oil pricing regime. Higher oil prices in 1990, caused by the invasion of Kuwait and a subsequent recession, reduced national emissions by 1.1 percent in 1991. Industrial sector carbon dioxide emissions, which are relatively sensitive to economic fluctuations, declined by 2.5 percent in 1991. During 1991-1997, emissions grew consistently in most sectors, with the largest increases in the transportation and electric utility sectors.

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1980-1998



Source: EIA estimates documented in Chapter 2 of this report.

²As of 1994, the most recent year for which information is available. Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), web site www.eia.doe.gov/emeu/mecs/contents.html.

³Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1999* (Washington, DC, August 1999), and American Iron and Steel Institute, *Iron & Steel Industry Annual Statistical Report 1999* (Washington, DC, 1999). Both associations conduct proprietary surveys of their members' energy use. There are, however, steel and chemical companies which are not members of the industry trade associations and whose energy consumption is consequently not included in the surveys.

In 1998, emissions from the electric utility sector grew somewhat more rapidly (3.2 percent) than the 1991-1997 average (2.0 percent), particularly in the residential and commercial sectors (3.7 percent). Summer air conditioning usage was stimulated by weather that was 14 percent warmer than average and 22 percent warmer than in 1997. Also, very low oil prices stimulated large-scale fuel switching in the electric utility sector from natural gas to residual oil. Oil consumption in the electric utility sector expanded by 42 percent in 1998, raising the average carbon intensity of electricity generation.

Warmer winter weather (13 percent warmer than in 1997) reduced consumption of winter heating fuels, particularly natural gas. Overall, carbon dioxide emissions in the residential and commercial sectors (which account for about 35 percent of total emissions) in 1998 remained at their 1997 level.

In the industrial sector, energy-related carbon dioxide emissions declined by 1.3 percent in 1998 compared with 1997. Industrial energy consumption historically has been more sensitive to economic growth than to the weather, and 1998 was a year of rapid economic growth. Industrial energy consumption and emissions are concentrated in a few industries, however, and their performance may have more influence on emissions than does the performance of the industrial sector as a whole. Two industrial groupings, chemicals and petroleum refining, account for 54 percent of manufacturing energy consumption. Four more groupings (food, primary metals, stone clay, and glass, pulp and paper) account for another 34 percent of manufacturing energy consumption.² Trade association data suggest that direct fuel use in the steel and chemical industries declined.³ U.S. automobile production also declined in 1998, largely because of a strike at General Motors.

Emissions in the transportation sector expanded by 2.4 percent in 1998 compared with 1997. Gasoline consumption, which accounted for 63 percent of transportation sector emissions, grew by 2.8 percent. Emissions from jet fuel grew more slowly (1.5 percent), and reported emissions from residual fuel (used mostly by oceangoing ships) actually declined by 3.8 percent. Emissions from distillate use increased by 3.7 percent, as a healthy U.S. economy led to greater consumption of diesel fuel by freight trucks.

Methane

U.S. methane emissions declined by 1.4 percent in 1998 compared with 1997, to 28.8 million metric tons of methane (165 million metric tons of carbon equivalent). The decline resulted from an increase in landfill gas recovery operations, spurred in part by the implementation of controls in response to U.S. Environmental Protection Agency (EPA) regulations. In addition, operators were trying to meet a legal deadline for receiving tax credits for landfill methane recovery projects.⁴ Because methane accounts for 9.2 percent of U.S. GWP-weighted greenhouse gas emissions, a 1.8-percent decline in methane emissions is equivalent to a 0.2-percent decline in total emissions.

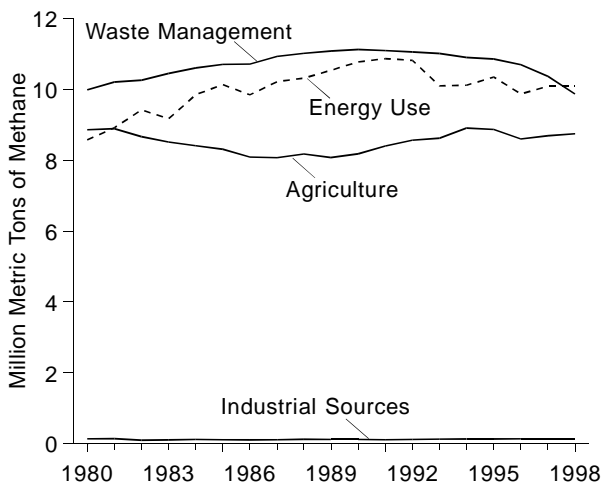
Methane emissions come from four categories of sources, three major and one minor. The major sources are energy, waste management, and agriculture, and the minor source is industrial processes. The three major sources accounted for 35, 34, and 31 percent, respectively, of total 1998 U.S. emissions of methane, or approximately 3 percent of the Nation's total greenhouse gas emissions. The largest of the three major sources was energy, followed by waste management (Figure ES4). Emissions from the anaerobic decomposition of municipal solid waste in landfills, part of the waste management source category, had been declining slowly before 1998 as a consequence of a reduction in the volume of waste landfilled and a gradual increase

in the volumes of landfill gas captured. Emissions of methane resulting from waste management declined by 4.9 percent in 1998.

Methane is also emitted as a byproduct of fossil energy production and transport. Methane can leak from natural gas production and distribution systems and is also emitted during coal production. Energy-related methane emissions were virtually unchanged in 1998. Agricultural emissions have several sources but are dominated by emissions from domestic livestock, including the animals themselves and the anaerobic decomposition of their waste. Agricultural emissions increased by about 0.6 percent in 1998.

Methane emissions estimates are more uncertain than those for carbon dioxide. U.S. methane emissions do not necessarily increase with growth in energy consumption or the economy. Energy-related methane emissions are strongly influenced by coal production from a relatively restricted number of mines; agricultural emissions are influenced in part by the public's consumption of milk and beef and in part by animal husbandry practices; and livestock and municipal waste emissions are influenced by husbandry and waste management practices.

Figure ES4. U.S. Methane Emissions by Source, 1980-1998



Source: EIA estimates documented in Chapter 3 of this report.

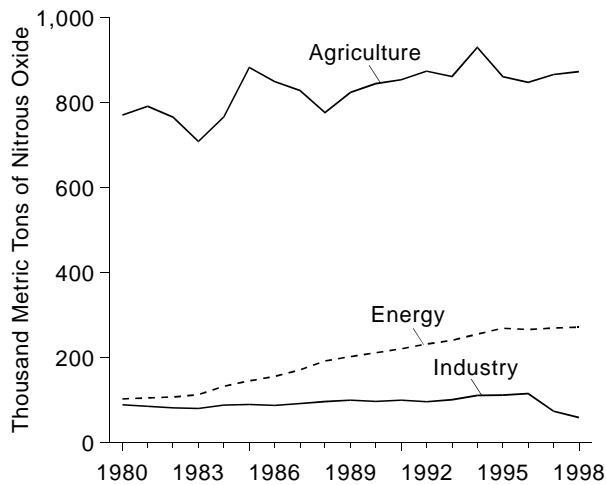
Nitrous Oxide

U.S. nitrous oxide emissions declined by 0.5 percent in 1998 compared with 1997, from 104 million metric tons carbon equivalent to 103 million. Nitrous oxide accounts for 6 percent of U.S. GWP-weighted greenhouse gas emissions. Emissions estimates for nitrous oxide are more uncertain than those for either carbon dioxide or methane. The nitrous oxide emissions estimates appearing in this report have been revised upward from last year's report by about 21 percent following the complete implementation of changes in estimation methods recommended by the 1996 revised guidelines of the Intergovernmental Panel on Climate Change.

U.S. nitrous oxide emissions include one large class of sources and two small classes (Figure ES5). Agricultural sources account for about 71 percent of nitrous oxide emissions. Emissions associated with nitrogen fertilization of soils account for about three-quarters of agricultural emissions. Emissions associated with fossil fuel use account for another 22 percent of nitrous oxide

⁴M. McGuigan and W.G. Vogt, SCS Engineers, "Greenhouse Gas Emission Reductions from U.S. Landfill Gas Utilization Projects: Landfills to the Rescue." Presented at the 22nd Annual Landfill Gas Symposium (Orlando, FL, March 1999). The tax credits are the so-called "Section 29" (of the Internal Revenue Code) tax credits for alternative energy, first enacted in 1981 and extended several times since.

Figure ES5. U.S. Nitrous Oxide Emissions by Source, 1980-1998



Source: EIA estimates documented in Chapter 4 of this report.

emissions, of which about 82 percent comes from mobile sources, principally motor vehicles equipped with catalytic converters. The balance of nitrous oxide emissions are caused by certain chemical manufacturing and wastewater treatment processes.

In 1998, estimated emissions from nitrogen fertilization of soils continued to rise slowly. However, the most striking development has been a 50-percent decline from 1996 levels of industrial emissions of nitrous oxide after the implementation of emissions controls at an adipic acid plant operated by the DuPont Corporation.

Other Gases

The Kyoto Protocol specifies that emissions of several classes of engineered gases—HFCs, PFCs, and sulfur hexafluoride—be limited. Emissions of these three classes of gases account for about 2 percent of U.S. GWP-weighted emissions and are estimated to have increased by about 3 percent in 1998 compared with 1997, a slower rate of growth than in previous years. The slower growth probably is attributable to maturing markets for chlorofluorocarbon substitutes, stagnant markets for key high-GWP gases, and increasing awareness of the potential for recycling these gases.

Emissions of the high-GWP gases specified in the Kyoto Protocol are very small (at most a few thousand metric tons). On the other hand, many of the gases have atmospheric lifetimes measured in the hundreds or thousands of years, and consequently they are potent greenhouse gases with global warming potentials

hundreds or thousands of times higher than that of carbon dioxide per unit of molecular weight.

There are several other categories of chemicals that also qualify as greenhouse gases but are excluded from the Framework Convention on Climate Change and the Kyoto Protocol because they are already controlled under the Montreal Protocol on Ozone-Depleting Substances. They include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and several solvents. This report includes estimates of emissions of these gases for completeness.

In addition, there are several gases that influence climate indirectly because they promote the formation of ozone, which is itself a greenhouse gas. These gases, already regulated in the United States as urban air pollutants, are sometimes called “criteria pollutants.” Criteria pollutants that promote ozone formation are carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds (NMVOCs). Estimates of emissions of these gases, provided by the EPA, are also included for completeness.

Land Use and Forestry

Forest lands in the United States are net absorbers of carbon dioxide from the atmosphere. According to U.S. Forest Service researchers, U.S. forest land absorbs about 209 million metric tons of carbon, equivalent to almost 14 percent of U.S. carbon dioxide emissions. Absorption is enabled by the reversal of the extensive deforestation of the United States that occurred in the late 19th and early 20th centuries. Since then, millions of acres of formerly cultivated land have been abandoned and have returned to forest. The regrowth of forests is sequestering carbon on a large scale. The process is steadily diminishing, however, because the rate at which forests absorb carbon slows as the trees mature.

The extent to which carbon sequestration should be included in emissions inventories generally, and the extent to which sequestration would “count” under the Kyoto Protocol, are still being determined. The Kyoto Protocol specifically limits “countable” effects for countries like the United States to anthropogenic afforestation, deforestation, and reforestation that have occurred “since 1990” and only if they are “measurable and verifiable.” These clauses may tend to limit the applicability of carbon sequestered as a result of land use changes and forestry.

In the past 2 years there has been increasing interest in the United States in carbon sequestration in agricultural

Executive Summary

soils through changes in agricultural practices. Proponents suggest that changes in tillage practices can cause agricultural soils to move from being net sources to net sinks of carbon dioxide, and that the amounts of carbon that might be absorbed by these changes could be significant at the national level. At present, EIA does

not have sufficient information to permit reliable estimation of national-level emissions or sequestration from this source. As more information becomes available, soil carbon estimates will be included in future reports.

1. U.S. Emissions of Greenhouse Gases in Perspective

About This Report

The Energy Information Administration (EIA) is required by the Energy Policy Act of 1992 to prepare a report on aggregate U.S. national emissions of greenhouse gases for the period 1987-1990, with annual updates thereafter. This report is the sixth annual update, covering national emissions over the period 1990-1997, with preliminary estimates of emissions for 1998. The methods used by EIA to estimate national emissions of greenhouse gases are subject to continuing review. As better methods and information become available, EIA revises both current and historical emissions estimates (see "What's New in This Report," page 2). Emissions estimates for carbon dioxide are reported in metric tons of carbon; estimates for other gases are reported in metric tons of gas (see "Units for Measuring Greenhouse Gases," page 3). Total national estimates measured in carbon equivalents are shown in Table ES2.

Chapter 1 of this report briefly summarizes some background information about global climate change and the greenhouse effect and discusses important recent developments in global climate change activities. Chapters 2 through 5 cover emissions of carbon dioxide, methane, nitrous oxide, and halocarbons and related gases, respectively. Chapter 6 describes potential sequestration and emissions of greenhouse gases as a result of land use changes.

Six appendixes are included with this report. Appendix A provides a detailed discussion of emissions sources, estimation methods, and data requirements and sources. Appendix B describes the derivation of the carbon emissions coefficients used for this report. Appendix C describes uncertainties in the emissions estimates. Appendix D describes known emissions sources omitted from the main report because they are not deemed to be "anthropogenic," or because of excessive uncertainty. Appendix E provides a historical time series of U.S. carbon emissions. Appendix F provides some convenient conversion factors.

The Greenhouse Effect and Global Climate Change

The Earth is warmed by radiant energy from the Sun. Over time, the amount of energy transmitted to the Earth's surface is equal to the amount of energy re-radiated back into space in the form of infrared radiation, and the temperature of the Earth's surface stays roughly constant; however, the temperature of the Earth is strongly influenced by the existence, density, and composition of its atmosphere. Many gases in the Earth's atmosphere absorb infrared radiation re-radiated from the surface, trapping heat in the lower atmosphere. Without the natural greenhouse effect, it is likely that the average temperature of the Earth's surface would be on the order of -19° Celsius, rather than the $+15^{\circ}$ Celsius actually observed.¹ The gases that help trap the Sun's heat close to the Earth's surface are referred to as "greenhouse gases." All greenhouse gases absorb infrared radiation (heat) at particular wavelengths.

The most important greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and a host of engineered chemicals, such as hydrofluorocarbons (HFCs). Most greenhouse gases occur naturally. Water vapor is by far the most common, with an atmospheric concentration of nearly 1 percent, compared with less than 0.04 percent for carbon dioxide. Concentrations of other greenhouse gases are a fraction of that for carbon dioxide (Table 1).

Scientists recognized in the early 1960s that concentrations of carbon dioxide in the Earth's atmosphere were increasing every year. Subsequently, they discovered that atmospheric concentrations of methane, nitrous oxide, and many engineered chemicals also were rising. Because current concentrations of greenhouse gases keep the Earth at its present temperature, scientists began to postulate that increasing concentrations of greenhouse gases would make the Earth warmer.

¹Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 57. See also web site www.ipcc.ch.

What's New in This Report

- This year's report contains additional information on the forces that shape year-to-year fluctuations in carbon dioxide emissions, including discussions of weather-adjusted emissions and the interaction between national economic growth and industrial energy emissions.
- International bunker fuel emissions are defined as emissions from fuel consumed by ships and aircraft moving internationally. The guidelines of the International Panel on Climate Change (IPCC) for preparing national emissions inventories specify that bunker fuel emissions be deducted from national emissions totals. This year's bunker fuel emissions estimate uses (for the first time) unpublished data on international marine bunker and international aviation fuel consumption collected by the U.S. Department of Commerce and intended for use as a component in U.S. balance-of-payments statistics. With these data, EIA can for the first time include international aviation bunker emissions from airlines operating in the United States and can replace inferred international marine bunker emissions with actual data. (The U.S. Department of Defense has indicated that it is willing, in principle, to provide estimates of military bunker fuel consumption but has not yet done so as of the date of publication.) The new information increases EIA's estimate of national bunker fuel emissions by about 10 million metric tons of carbon (0.6 percent of emissions), which in turn lower national total emissions by a comparable amount for all years.
- Chapter 4, "Nitrous Oxide Emissions," contains estimates of nitrous oxide emissions from a new source, biological fixation of nitrogen in agricultural soils. The revision increases nitrous oxide emissions by 0.2 million metric tons of gas, or 1 percent of U.S. greenhouse gas emissions in 1998. A text box in Chapter 4 discusses the revision to the estimation method for nitrous oxide emissions and its impact on the estimates for 1990 through 1998 in this report.
- Chapter 4 now includes estimates of nitrous oxide emissions from the consumption of wood in the electric utility, residential, and industrial sectors. This modification to the estimation method results in an average increase of 0.009 million metric tons (20 percent) of nitrous oxide emissions from stationary combustion sources for each year from 1990 through 1998.
- In Chapter 2, "Carbon Dioxide Emissions," consumption of ethanol blended at the pump has been estimated back to 1981, thus slightly reducing emissions for the years before 1993.
- There is a text box in Chapter 2 analyzing the results of EIA's 1994 Manufacturing Energy Consumption Survey in terms of carbon emissions from the largest emitting industries.
- In Chapter 2, estimates of carbon dioxide emissions associated with the consumption of limestone in flue gas desulfurization units have been revised to reflect modifications to the estimation methodology. The modifications were based on a May 1999 report obtained from the U.S. Geological Survey, which characterized limestone utilization in fluidized-bed combustion systems and in flue gas desulfurization units (for details on the revisions to the estimation method, see Appendix A).

In computer-based simulation models, rising concentrations of greenhouse gases nearly always produce an increase in the average temperature of the Earth. Rising temperatures may, in turn, produce changes in weather and in the level of the oceans that might prove disruptive to current patterns of land use and human settlement, as well as to existing ecosystems. To date, it has proved difficult to detect firm evidence of actual temperature changes, in part because the normal temporal and spatial variations in temperature are far larger than the predicted change in the global average temperature. Even when temperature changes are identified, it is not possible to be certain whether they are random fluctuations that will reverse themselves or the beginning of a trend. The possible effects of rising

temperatures on weather patterns are even more uncertain.

The most recent report of the Intergovernmental Panel on Climate Change (IPCC), an international assemblage of scientists commissioned by the United Nations to study this matter, concluded that:

Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitudes and patterns of long-term variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land

Units for Measuring Greenhouse Gases

In this publication, EIA reports information in forms that are most likely to be familiar to users of the document. Therefore, energy and industrial data are reported in their native units. For example, oil production is reported in thousand barrels per day, and energy production and sales are reported in (higher heating value) British thermal units (Btu). Higher heating value Btu can be a relatively intuitive unit for metric users, because a lower heating value exajoule is only 1 to 6 percent larger than a higher heating value quadrillion Btu.

Emissions data are reported in metric units. This report uses the familiar “million metric tons” common in European industry instead of the “gigagrams” favored by the scientific community. Metric tons are also relatively intuitive for users of English units, because a metric ton is only about 10 percent heavier than an English short ton.

Emissions of most greenhouse gases are reported here in terms of the full molecular weight of the gas (as in Table ES1). In Table ES2, however, and subsequently throughout the report, carbon dioxide is reported in carbon units, defined as the weight of the carbon content of carbon dioxide (i.e., just the “C” in CO₂). Carbon dioxide units at full molecular weight can be converted into carbon units by dividing by 44/12, or 3.6667. This approach has been adopted for two reasons:

- Carbon dioxide is most commonly measured in carbon units in the scientific community. Scientists argue that not all carbon from combustion is, in fact, emitted in the form of carbon dioxide. Because combustion is never perfect, some portion of the emissions consists of carbon monoxide, methane, other volatile organic compounds, and particulates. These other gases (particularly carbon monoxide) eventually decay into carbon dioxide, but it is not strictly accurate to talk about “tons of carbon dioxide” emitted.
- Carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration. Because most fossil fuels are 75 percent to 90 percent carbon by weight, it is easy and convenient to compare the weight of carbon emissions (in carbon units) with the weight of the fuel burned. Similarly, carbon sequestration in forests and soils is always measured in tons of carbon, and the use of carbon units makes it simple to compare sequestration with emissions.

While carbon dioxide emissions can be measured in tons of carbon, emissions of other gases (such as methane) can also be measured in “carbon dioxide equivalent” units by multiplying their emissions (in metric tons) by their global warming potentials. For comparability, carbon dioxide equivalent units can be converted to “carbon equivalent” by multiplying by 12/44 (as in Table ES2) to provide a measure of the relative effects of various gases on climate.

Table 1. Global Atmospheric Concentrations of Selected Greenhouse Gases

Item	Carbon Dioxide	Methane	Nitrous Oxide	Sulfur Hexafluoride	Perfluoromethane
	(parts per million)			(parts per trillion)	
Preindustrial Atmospheric Concentration	278	0.700	0.275	0	0
1992 Atmospheric Concentration	356	1.714	0.311	32	70
Average Annual Change, Recent Years	1.6	0.008	0.0008	0.2	1.2
Average Percent Change, Recent Years	0.4	0.6	0.25	0.6	1.7
Atmospheric Lifetime (Years)	50–200	12	120	3,200	50,000

Source: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), pp. 92-93.

surface changes. Nevertheless, the balance of evidence suggests that there is a discernable human influence on global climate.²

While both the existence and consequences of human-induced global climate change remain uncertain, the threat of climate change has put in train an array of efforts by the United States and other governments to find some mechanism for limiting the risk of climate change and ameliorating possible consequences. To date, efforts have focused on identifying levels and sources of emissions of greenhouse gases and on possible mechanisms for reducing emissions or increasing absorption of greenhouse gases.

Global Sources of Greenhouse Gases

Most greenhouse gases have substantial natural sources in addition to human-made sources, and there are powerful natural mechanisms for removing them from the atmosphere. However, the continuing growth in atmospheric concentrations establishes that, for each of the major greenhouse gases, more gas is being emitted than is being absorbed each year: that is, the natural absorption mechanisms are lagging behind. Table 2 illustrates the relationship between anthropogenic (human-made) and natural emissions and absorption of the principal greenhouse gases.

Water Vapor. Water vapor, as noted above, is the most common greenhouse gas present in the atmosphere. It is emitted into the atmosphere in enormous volumes through natural evaporation from oceans, lakes, and soils and is returned to Earth in the form of rain and snow. Water vapor is so plentiful in the atmosphere that additional emissions are unlikely to absorb any significant amount of infrared radiation. It is also likely that the amount of water vapor held in the atmosphere

is generally in equilibrium, and that increasing emissions of water vapor would not increase atmospheric concentrations.³ According to currently available information, anthropogenic water vapor emissions at the Earth’s surface are unlikely to be an important element in either causing or ameliorating climate change.

Carbon Dioxide. Carbon is a common element on the planet, and immense quantities can be found in the atmosphere, in soils, in carbonate rocks, and dissolved in ocean water. All life on Earth participates in the “carbon cycle,” by which carbon dioxide is extracted from the air by plants and decomposed into carbon and oxygen, with the carbon being incorporated into plant biomass and the oxygen released to the atmosphere. Plant biomass, in turn, ultimately decays (oxidizes), releasing carbon dioxide back into the atmosphere or storing organic carbon in soil or rock. There are vast exchanges of carbon dioxide between the ocean and the atmosphere, with the ocean absorbing carbon from the atmosphere and plant life in the ocean absorbing carbon from water, dying, and spreading organic carbon on the sea bottom, where it is eventually incorporated into carbonate rocks such as limestone.

Records from Antarctic ice cores indicate that the carbon cycle has been in a state of imbalance for the past 200 years, with emissions of carbon dioxide to the atmosphere exceeding absorption. Consequently, carbon dioxide concentrations in the atmosphere have been steadily rising.

The most important natural sources of carbon dioxide are releases from the oceans (90 billion metric tons per year), aerobic decay of vegetation (30 billion metric tons), and plant and animal respiration (30 billion metric tons).⁴ Known anthropogenic sources (including deforestation) were estimated to account for about 7

Table 2. Global Natural and Anthropogenic Sources and Absorption of Greenhouse Gases, 1992

Gas	Sources		Absorption	Annual Increase in Gas in the Atmosphere
	Natural	Human-Made		
Carbon Dioxide (Million Metric Tons of Carbon)	150,000	7,100	154,000	3,100–3,500
Methane (Million Metric Tons of Gas)	110–210	300–450	460–660	35–40
Nitrous Oxide (Million Metric Tons of Gas)	6–12	4–8	10–17	3–5

Source: Summarized from ranges appearing in Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), pp. 17-19.

²Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 5.

³Note, however, that changing air temperature from other causes will change the equilibrium amount of water vapor contained in the atmosphere. This may be a “feedback” effect acting to accelerate or slow global climate change.

⁴Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 77.

billion metric tons of carbon per year in the early 1990s. The principal anthropogenic source is the combustion of fossil fuels, which accounts for about three-quarters of total anthropogenic emissions of carbon worldwide. Natural processes—primarily, uptake by the ocean and photosynthesis—absorb substantially all the naturally produced carbon dioxide and some of the anthropogenic carbon dioxide, leading to an annual net increase in carbon dioxide in the atmosphere of 3.1 to 3.5 billion metric tons.⁵

Methane. Methane is also a common compound. The methane cycle is less well understood than the carbon cycle. Natural methane is released primarily by anaerobic decay of vegetation, by the digestive tracts of termites in the tropics, and by several other lesser sources. The principal anthropogenic sources are leakages from the production of fossil fuels, human-promoted anaerobic decay in landfills, and the digestive processes of domestic animals. The main sources of absorption are thought to be decomposition (into carbon dioxide) in the atmosphere and decomposition by bacteria in soil. Known and unknown sources of methane are estimated to total about 600 million metric tons annually; known sinks (i.e., absorption by natural processes) total about 560 million metric tons. The annual increase in methane concentration in the atmosphere accounts for the difference of 35 to 40 million metric tons.

Nitrous Oxide. The sources and absorption of nitrous oxide are much more speculative than those for other greenhouse gases. The principal natural sources are thought to be bacterial breakdown of nitrogen compounds in soils, particularly forest soils, and fluxes from ocean upwellings. The primary human-made sources are enhancement of natural processes through application of nitrogen fertilizers, combustion of fuels, and certain industrial processes. The existence of significant unidentified sources of nitrous oxide has set off a search for new sources, one consequence of which has been recent revisions to the IPCC emissions estimations methods for nitrous oxide from nitrogen fertilization of soils. The most important sink is thought to be decomposition in the stratosphere. Worldwide, estimated known sources of nitrous oxide total 13 to 20 million metric tons annually, and known sinks total 10 to 17 million metric tons. The annual increase in concentrations in the atmosphere is thought to total about 4 million metric tons.

Halocarbons and Other Gases. In the twentieth century, human ingenuity has created an array of “engineered” chemicals, not normally found in nature,

whose special characteristics render them particularly useful. Some engineered chemicals are also greenhouse gases. The best known are the chlorofluorocarbons (CFCs), particularly CFC-12, often known by its trade name, “Freon-12.” CFCs have many desirable features: they are relatively simple to manufacture, inert, non-toxic, and nonflammable. Because CFCs are chemically stable, once emitted, they remain in the atmosphere for hundreds or thousands of years. Because they are not found in nature, these molecules absorb reflected infrared radiation at wavelengths that otherwise would be largely unabsorbed, and they are potent greenhouse gases, with a direct radiative forcing effect hundreds or thousands of times greater, gram-per-gram, than that of carbon dioxide.

Because of their long atmospheric lives, a portion of the CFCs emitted into the atmosphere eventually find their way into the stratosphere, where they can be destroyed by sunlight. This reaction, however, releases free chlorine atoms into the stratosphere, and the free chlorine atoms tend to combine with stratospheric ozone, which protects the surface of the Earth from certain wavelengths of potentially damaging solar ultraviolet radiation (ultraviolet radiation, for example, causes human and animal skin cancers). The destruction of stratospheric ozone, notwithstanding its potential damage to living organisms, exerts a net cooling effect on the surface of the planet, making the net effects of CFCs on radiative forcing ambiguous.

The threat posed by CFCs to the ozone layer has caused the United States and many other countries to commit themselves to phasing out the production of CFCs and their chemical cousins, hydrochlorofluorocarbons (HCFCs), pursuant to an international treaty, the 1987 Montreal Protocol. As use of CFCs has declined, many related chemicals have emerged as alternatives, including HCFCs and hydrofluorocarbons (HFCs). HCFCs are similar to CFCs, but they are more reactive and consequently have shorter atmospheric lives, with less effect on the ozone layer and smaller direct global warming effects. HCFCs are also being phased out, but over a much longer time scale.

HFCs have no chlorine and consequently have no effect on the ozone layer, but they have potentially powerful direct effects on climate. HFCs were rare before 1990, but in 1994 HFC-134a was adopted as the standard motor vehicle air conditioning refrigerant in virtually all new cars made in America. Consequently, HFC emissions are now rising rapidly, though from a negligible base.

⁵One metric ton equals 1.102 short tons.

Another new class of engineered halocarbons are the perfluorocarbons (PFCs), which include CF_4 , C_2F_6 , and C_3F_8 . PFCs are emitted as byproducts of aluminum smelting and are increasingly being used in the manufacture of semiconductors.

Sulfur hexafluoride (SF_6) is used as an insulator in utility-scale electrical equipment and as a cover gas in magnesium smelting. It is not a halocarbon, but it is a powerful greenhouse gas. Other chemicals not yet identified may exhibit similar radiative properties. All of these chemicals are potent greenhouse gases, because they combine relative scarcity in the atmosphere with very long atmospheric lifetimes.

The solvents carbon tetrachloride, methyl chloroform, and methylene chloride are regulated in the United States both as ozone depleters and for toxicity. All these gases have direct radiative forcing effects, which are offset to some degree by their ozone-depleting effects.

With the advent of the Framework Convention and the Kyoto Protocol, the halocarbon and other industrial chemicals can be grouped into two categories:

- Ozone-depleting chemicals regulated under the Montreal Protocol but excluded from the Framework Convention (CFCs, HCFCs, and others)
- "Kyoto gases" (HFCs, PFCs, and sulfur hexafluoride).

The "Kyoto gases" are deemed to "count" for climate change policy analysis. The ozone depleters are excluded.

Radiatively Important Gases. In addition there are a set of man-made pollutants, emitted primarily as byproducts of combustion (both of fossil fuels and of biomass), that have indirect effects on global warming: carbon monoxide, nitrogen oxides, nonmethane volatile organic compounds (NMVOCs) and sulfur dioxide. These compounds, regulated in the United States pursuant to the Clean Air Act, are often referred to (along with particulates and lead) as "criteria pollutants." The criteria pollutants are reactive compounds, and they tend to remain in the atmosphere for only hours or days. The sequence of reactions that removes carbon monoxide, nitrogen oxides and NMVOCs from the atmosphere, however, tends to promote the formation of ozone (O_3), a reactive and unstable molecular

form of oxygen. Ozone in the stratosphere protects life on Earth from ultraviolet radiation, but ozone at ground level in high concentrations causes respiratory distress in people and animals and, also, is itself a potent (though short-lived) greenhouse gas.⁶

It has not proved possible to make a general determination of the contribution of ozone precursors to global warming. The reactions that produce ozone are strongly affected by the relative concentrations of various pollutants, the ambient temperature, and local weather conditions. Emissions of criteria pollutants can create very high, though localized, ozone concentrations under favorable conditions (for example, a warm, sunny day combined with still air and low humidity) and negligible concentrations under unfavorable conditions. The criteria pollutants are included in this report for completeness.

Sulfur dioxide, on the other hand, probably exerts a net cooling effect on the climate. Sulfur dioxide creates tiny solid particles (aerosols) in the atmosphere, which in turn act as nuclei for collections of water droplets and stimulate cloud formation. The clouds, in turn, reflect sunlight back into space, cooling the planet. The most important such gas is sulfur dioxide (SO_2), which is emitted largely as a byproduct from the combustion of sulfur-containing fossil fuels, particularly coal. Sulfur dioxide reacts in the air to form sulfate compounds that are effective in promoting cloud formation. Sulfur dioxide emissions are regulated in the United States under the Clean Air Act, and their concentrations have declined considerably in recent years. Particulate emissions are also likely to exert a net cooling effect by promoting cloud formation.

Relative Forcing Effects of Various Gases

Some greenhouse gases are more potent in affecting global temperatures than are others. As a result, comparable increases in the concentrations of different greenhouse gases can have vastly different heat-trapping effects. Among those identified, carbon dioxide is among the least effective as a greenhouse gas. Other compounds, on a gram-per-gram basis, appear to have much greater effects.⁷

It would be useful to determine the precise relative effectiveness of various greenhouse gases in affecting the Earth's climate. That information would help

⁶The U.S. Environmental Protection Agency has set a National Ambient Air Quality Standard for acceptable atmospheric concentrations of ozone at 0.12 parts per million. The standard was set on the basis that concentrations of this magnitude could cause respiratory distress in vulnerable individuals. Higher concentrations (above 0.3 parts per million) would cause respiratory distress for most individuals.

⁷Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 22.

policymakers know whether it would be more effective to concentrate effort on reducing the very small emissions of powerful greenhouse gases, such as HFC-134a, or whether they should direct their efforts to controlling the very large emissions of relatively ineffective gases, such as carbon dioxide.

There has been extensive study of the relative effectiveness of various greenhouse gases in trapping the Earth's heat. Such research has led to the development of the concept of a "global warming potential," or GWP. The GWP is intended to illustrate the relative impacts on global warming of various gases, compared with that of carbon dioxide. Over the past few years, the IPCC has conducted an extensive research program aimed at summarizing the effects of various greenhouse gases through a set of GWPs. The results of that work were released in 1995 in an IPCC report, *Climate Change 1994*⁸ and updated in *Climate Change 1995*.⁹

The IPCC's work has established that the effects of various gases on global warming are too complex to permit them to be easily summarized as a single number. The complexity takes several forms:

- Each gas absorbs radiation in a particular set of wavelengths, or "window," in the spectrum. In some cases, where concentrations of the gas are low and no other gases block radiation in the same window, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, a larger and larger portion of the total light passing through the "window" will already have been captured, and the marginal effects of additional emissions will 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 carbon dioxide, tends to be less than that of a rare gas, such as sulfur hexafluoride. This "diminishing return" effect implies that increasing the concentration 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.
- Various natural processes cause many greenhouse gases to decompose into other gases or to be absorbed by the ocean or ground. These processes

can be summarized in terms of the "atmospheric lifetime" of a particular gas, or the period of time it would take for natural processes to remove a unit of emissions from the atmosphere. Some gases, such as CFCs, have very long atmospheric lifetimes, in the hundreds of years. Others, such as carbon monoxide, have lives measured in hours or days. Methane, which decays into carbon dioxide over a period of a few years, has a much larger short-run effect on global warming than does an equivalent amount of carbon dioxide; however, over longer and longer periods—from 10 years to 100 years to 500 years, for example—the differences between the GWPs of methane and carbon dioxide become less significant.

- Many gases are chemically active, and they may react in the atmosphere in ways that promote or hinder the formation of other greenhouse gases. For example, nitrogen oxides and carbon monoxide combine to promote the formation of ozone, whereas CFCs tend to destroy atmospheric ozone, thus promoting global cooling. Such indirect effects have sometimes proved difficult to summarize in terms of global warming potentials. Indirect effects also imply that changes in relative concentrations of various greenhouse gases would tend to change their relative effects.

Despite such complexity, the scientific community is working to develop GWP approximations. Table 3 summarizes the consensus results of the most recent studies by scientists working on behalf of the IPCC, showing estimates of atmospheric lifetimes and global warming potentials across various time scales.

The IPCC has also devoted effort to the study of indirect and interactive effects of various gases—particularly the indirect effects of CFCs and HCFCs on the ozone layer—compared with their direct radiative forcing effects. The IPCC presented GWP estimates for the first time in 1996 that quantified the direct and indirect effects of certain CFCs and HCFCs. Certain chemicals (halon-1301 and carbon tetrachloride, for example) are now believed to exert a net cooling influence—i.e., to have a negative GWP. All the net GWPs for CFCs and HCFCs are considerably lower than their direct GWPs.¹⁰

⁸Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

⁹Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

¹⁰Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 122.

Table 3. 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	Variable	1	1	1
Methane	12 ± 3	56	21	7
Nitrous Oxide	120	280	310	170
HFCs, PFCs, and Sulfur Hexafluoride				
HFC-23	264	9,200	12,100	9,900
HFC-125	33	4,800	3,200	11
HFC-134a	15	3,300	1,300	420
HFC-152a	2	460	140	42
HFC-227ea	37	4,300	2,900	950
Perfluoromethane	50,000	4,400	6,500	10,000
Perfluoroethane	10,000	6,200	9,200	14,000
Sulfur Hexafluoride	3,200	16,300	23,900	34,900

Note: The typical uncertainty for global warming potentials is estimated by the Intergovernmental Panel on Climate Change at ±35 percent.

Source: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 121.

Global Climate Change Policy Developments

Rising concentrations of carbon dioxide in the atmosphere were first detected in the late 1950s, and observations of atmospheric concentrations of methane, nitrous oxide, and other gases began in the late 1970s. Concern about the effects of rising atmospheric concentrations of greenhouse gases remained largely the province of atmospheric scientists and climatologists, however, until the mid-1980s, when a series of international scientific workshops and conferences began to move the topic onto the agenda of United Nations specialized agencies, particularly, the World Meteorological Organisation (WMO).

The IPCC was established under the auspices of the United Nations Environment Program and the WMO in late 1988, to accumulate available scientific research on climate change and to provide scientific advice to policymakers. A series of international conferences provided impetus for an international treaty aimed at limiting the human impact on climate. In December

1990, the United Nations established the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (generally called the INC). Beginning in 1991, the INC hosted a series of negotiating sessions that culminated in the adoption, by more than 160 countries, including the United States, of the Framework Convention on Climate Change, opened for signature at the “Earth Summit” in Rio de Janeiro, Brazil on June 4, 1992.¹¹

From the Framework Convention to the Kyoto Protocol

The objective of the Framework Convention is stated as follows:

*The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.*¹²

¹¹The Framework Convention was “adopted” by a vote of the conference of the parties on May 9th, while the signatures and ratifications of member states flowed in over a period of years. The treaty “entered into force” in 1994. There is a discussion of the development of the Convention in D. Bodanzky, “Prologue to the Climate Convention,” in I. Mintzer and J.A. Leonard (eds.), *Negotiating Climate Change: The Inside Story of the Rio Convention* (Cambridge, UK: Cambridge University Press, 1994), pp. 49-66.

¹²The official text of the Framework Convention can be found at web site www.unfccc.de/index.html.

The Framework Convention divided its signatories into two groups: the countries listed in Annex I to the Protocol, and all others. The Annex I countries are developed industrial states: the United States, Eastern and Western Europe, Russia and the Ukraine, Japan, Australia, New Zealand, and Canada.¹³

The Convention requires all parties to undertake “policies and measures” to limit emissions of greenhouse gases, and to provide national inventories of emissions of greenhouse gases (Article 4.1a and b). Annex I parties are further required to take actions “with the aim of returning . . . to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases” (Article 4.2a and b). The signatories subsequently agreed that Annex I parties should provide annual inventories of greenhouse gas emissions.

In April 1993, President Clinton committed to stabilizing U.S. emissions of greenhouse gases at the 1990 level by 2000, using an array of voluntary measures. In the following years, however, greenhouse gas emissions in the United States and many other Annex I countries continued to increase. The climate negotiators, continuing to meet as “the Conference of the Parties [to the Framework Convention]” (COP), took up the question of how to limit emissions in the post-2000 period, a topic on which the Framework Convention was silent. In 1995, COP-1, held in Berlin, Germany, agreed to begin negotiating a post-2000 regime. In 1996, COP-2, held in Geneva, Switzerland, agreed that the regime would encompass binding limitations on emissions for the parties, to be signed at COP-3, which was to be held in Kyoto, Japan, in December 1997.

The Kyoto Protocol

The most fundamental feature of the Kyoto Protocol to the Framework Convention, adopted on December 11, 1997, is a set of quantified greenhouse gas emissions targets for Annex I countries, which collectively are about 5 percent lower than the 1990 emissions of those countries taken as a group.¹⁴ Developing country signatories do not have quantified targets. Some of the key features of the Protocol are summarized below:

- **Differentiated Targets.** Each Annex I signatory has a “quantified emissions reduction limitation commitment,” which limits the signatory to some fraction, ranging from 90 to 110 percent, of its 1990 greenhouse gas emissions.¹⁵ Both the European Union (EU) and the individual members of the EU signed the Protocol and are responsible for meeting their commitments.
- **Commitment Period.** Each target is defined as the average of the signatory’s emissions over the 5-year period 2008-2012, called “the commitment period.”
- **Six Gases.** Participants are to limit their emissions of carbon dioxide, methane, nitrous oxide, HFCs, PFCs, and sulfur hexafluoride, weighted by the GWP of each gas. HFCs and PFCs are actually classes of gases with multiple members, but the term “six gases” has stuck. Participants may use 1995 as the baseline for HFCs, PFCs, and sulfur hexafluoride, instead of 1990.
- **Demonstrable Progress.** Annex I countries are required to have made “demonstrable progress” toward achieving their commitments by 2005.
- **Land Use and Forestry.** The Protocol includes complicated provisions on forestry, the implication being that some emissions and sequestration arising from changes in land use and forestry since 1990 can be counted against the target.
- **Flexibility Mechanisms.** The Protocol includes an array of methods by which Annex I countries can spread and reduce the cost of emissions limitations. The flexibility mechanisms include:
 - **Emissions Trading.** Annex I countries can transfer portions of their quotas to one another.
 - **Joint Implementation.** Annex I countries can undertake emissions reduction projects in other Annex I countries and receive a negotiated share of the emissions reductions generated by the projects.
 - **Joint Fulfillment.** Like-minded Annex I countries (such as the EU) may band together to reallocate

¹³The Annex I grouping has undergone a number of changes. Russia, the Ukraine, Latvia, Estonia, and Lithuania (but not the Central Asian Republics) are now part of Annex I. Belarus participated for a while but did not join the Kyoto Protocol. Turkey initially joined the Convention but subsequently asked to withdraw from Annex I status and did not join the Kyoto Protocol. Czechoslovakia has divided into the Czech Republic and Slovakia, and two Yugoslav successor states, Croatia and Slovenia, have joined Annex I. Lichtenstein and Monaco have also joined the Kyoto Protocol. In June 1999, Kazakhstan applied for Annex I status.

¹⁴The text of the Kyoto Protocol can also be found at web site www.unfccc.de/index.html.

¹⁵Several Eastern European states have been permitted to use emissions from the late 1980s, rather than 1990, as their baseline. All signatories may elect to use 1995 emissions of HFCs, PFCs, and sulfur hexafluoride as the baseline rather than 1990 emissions.

national targets within the group, so long as the collective target is met.

- **Clean Development Mechanism.** Annex I countries may undertake emissions reduction projects in non-Annex I countries and receive credits countable against national targets.

- **Entry into Force.** The Protocol enters into force when 55 countries *and* Annex I signatories with carbon dioxide emissions totaling 55 percent of total Annex I emissions “have deposited their instruments of ratification, acceptance, approval, or accession.” As of August 27, 1999, 84 countries (including 25 Annex I countries) had signed (not ratified) the Protocol. Fourteen countries (many of them small island states) have ratified the Protocol to date. No Annex I country has yet ratified the Protocol.

The Kyoto Protocol and the United States

The U.S. Government formally signed the Kyoto Protocol on November 12, 1998. Under the U.S. Constitution, however, the Government may adhere to treaties only with the “advice and consent” of the Senate.¹⁶ The Senate placed (in advance) certain conditions on the provisions of a Climate Change Treaty to which it would be prepared to consent. Those conditions were embodied in the Byrd-Hagel Resolution (S.Res. 98), a “sense of the Senate” resolution, which was passed by a vote of 95 to 0 on July 25, 1997. The Byrd-Hagel resolution specifies that:

(1) the United States should not be a signatory to any protocol to, or other agreement regarding, the United Nations Framework Convention on Climate Change of 1992, at negotiations in Kyoto in December 1997, or thereafter, which would—

(A) mandate new commitments to limit or reduce greenhouse gas emissions for the Annex I Parties, unless the protocol or other agreement also mandates new specific scheduled commitments to limit or reduce greenhouse gas emissions for Developing Country Parties within the same compliance period, or

(B) would result in serious harm to the economy of the United States; and

(2) any such protocol or other agreement which would require the advice and consent of the Senate to ratification should be accompanied by a detailed

explanation of any legislation or regulatory actions that may be required to implement the protocol or other agreement and should also be accompanied by an analysis of the detailed financial costs and other impacts on the economy of the United States which would be incurred by the implementation of the protocol or other agreement.

The Protocol has not yet been sent to the Senate. The view of the Executive Branch was expressed by the White House Press Secretary:

Signing does not legally commit the United States to implement the Protocol. The Protocol would become binding only with the advice and consent of the U.S. Senate. President Clinton has made clear that the United States regards the Kyoto Protocol as a work in progress, and that it will not be submitted for ratification without the meaningful participation of key developing countries in efforts to address climate change.¹⁷

Beyond the Kyoto Protocol

Since the signing of the Kyoto Protocol, the signatories have continued to shape the “work in progress.” The Conference of the Parties met in November 1998 in Buenos Aires (COP-4) and will meet again at the end of October 1999 in Bonn. The two “subsidiary bodies” of the Conference of the Parties have met repeatedly, but many issues remain unsettled.

One issue dividing Kyoto signatories is signified by the term “supplementarity.” Part of Article 17 of the Protocol (which describes emissions trading) says, “Any such trading shall be *supplemental* to domestic actions for the purpose of meeting quantified emission limitation and reduction commitments under that Article.” A similar sentence is included in Article 6 (Joint Implementation), and somewhat similar language (“... contribute to compliance . . .”) is included in Article 12 (Clean Development Mechanism). The EU takes the position that “supplemental” in this context means that emissions reductions achieved through trading, joint implementation, and/or the Clean Development Mechanism should account for only a limited portion of national emissions reductions under the Protocol, and that this limit should be quantified and spelled out. The view of the U.S. Government is that no such sublimit was intended, and that imposing a sublimit would raise the cost of compliance without providing any environmental benefit.

¹⁶Article II, Section 2, of the Constitution reads, in part: “He [the President] shall have power, by and with the advice and consent of the Senate, to make treaties, provided two thirds of the Senators present concur”

¹⁷Statement by the Press Secretary, the White House, November 12, 1998. See web site www.whitehouse.gov.

Another piece of unresolved business from Kyoto is the status of developing countries. Their status under the Kyoto Protocol itself is fairly clear: they do not have quantitative obligations, but they may participate in emissions reduction projects through the Clean Development Mechanism. The U.S. Government, however, has set “meaningful participation” by developing countries as a condition of submitting the Protocol to the Senate. At the Buenos Aires meeting, two developing countries, Argentina and Kazakhstan, agreed to

take on voluntary emissions limitation targets. Kazakhstan has since applied to become an Annex I country. Developing countries as a group, led by China, and the so-called “Group of 77,” have expressed opposition to the acceptance by any developing country of an emissions limitation target, even voluntarily, arguing that this is a violation of the principle of “common but differentiated” responsibilities articulated in the Framework Convention.¹⁸

¹⁸This difference of view manifested itself at the fourth meeting of the Conference of the Parties in Buenos Aires in November 1998. The Argentine government expressed a desire to accept voluntarily an emissions reduction commitment, and the United States and other governments asked that the question of voluntary commitments be placed on the agenda for discussion. China and the “Group of 77” developing countries opposed inclusion of this item on the conference agenda, and the topic was not formally discussed. See *Position Paper of the Group of 77 and China on the Provisional Agenda*, FCCC/SBI/1998/MISC.3, web site www.unfccc.de/resource/docs/1998/sbi/misc03.htm.

2. Carbon Dioxide Emissions

Overview

U.S. Anthropogenic Carbon Dioxide Emissions, 1990-1998

	Carbon Dioxide	Carbon Equivalent
Estimated 1998 Emissions (Million Metric Tons)	5,483.9	1,495.5
Change Compared to 1997 (Million Metric Tons)	18.5	5.1
Change from 1997 (Percent)	0.3%	0.3%
Change Compared to 1990 (Million Metric Tons)	544.4	148.5
Change from 1990 (Percent)	11.0%	11.0%

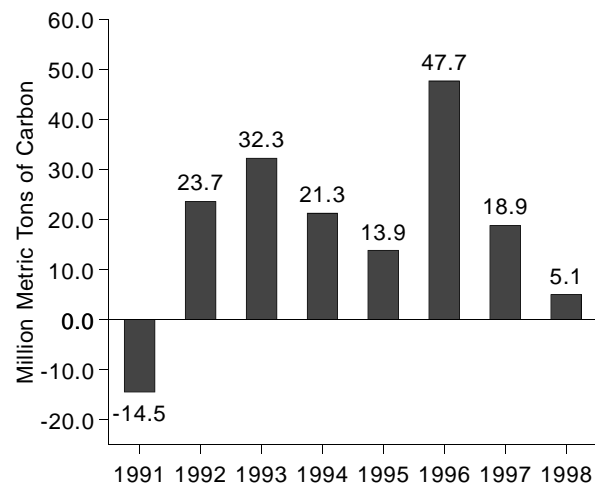
Total 1998 emissions of carbon dioxide were 1,495.5 million metric tons of carbon (Table 4), or 5.1 million metric tons (0.3 percent) more than in 1997—the slowest rate of growth since 1991, when a recession in the U.S. economy caused emissions to decline. The slow growth of carbon emissions in 1998 occurred in spite of 3.9-percent annual growth in U.S. real gross domestic product (GDP).

In the United States 98 percent of carbon dioxide emissions are caused by the combustion of fossil fuels; consequently, carbon emissions and energy use are highly correlated. Historically, economic growth, the weather, and movements in energy prices have caused year-to-year fluctuations in energy consumption and resulting carbon emissions (Figure 1).

Residential and commercial energy consumption is dominated by electricity use for air conditioning and fuel use for winter heating. The United States experienced a warmer-than-normal summer in 1998 with cooling degree-days 14.4 percent above normal, followed by a warm winter with heating degree-days

12.1 percent below normal.¹⁹ In terms of energy demand, however, heating degree-days outweigh cooling degree-days. Thus, the warmer winter more than offset the warmer summer. As a result of the weather, residential emissions of carbon dioxide declined by 0.1 percent, and commercial sector emissions rose by only 0.2 percent.

Figure 1. Annual Change in U.S. Carbon Dioxide Emissions, 1990-1998



Source: Estimates presented in this chapter.

Industrial—and especially manufacturing—energy consumption, in principle, is much less affected by the weather and more strongly affected by economic fluctuations. In 1998 industrial energy emissions declined by 1.3 percent. The underlying cause of the decline in industrial emissions is not entirely clear, but a significant contributing factor was slow growth in some of the most energy-intensive basic industries (chemicals and paper products) and an actual decline in the output of at least one (primary metals) while less energy-intensive industries expanded rapidly. The industrial category also includes farms, whose energy consumption is affected by the weather.

Electricity consumption growth continued to outpace other energy in 1998 as measured by generation from

¹⁹Energy Information Administration, *Short-Term Energy Outlook*, DOE/EIA-0202(99/4Q) (Washington, DC, October 1999).

electric utilities. The 2.8-percent growth in electric utility output was closer to the rate of economic growth than was the growth in consumption of other energy forms. The amount of carbon released per kilowatt-hour (carbon output rate) increased for electricity generation in 1998 as more carbon-intensive oil was consumed than in 1997. The increase in the carbon output rate caused electricity-related carbon dioxide emissions to rise by 3.2 percent, from 533 million metric tons of carbon in 1997 to 550 million metric tons in 1998. Early estimates indicate that nonutility generators emitted an additional 56 million metric tons of carbon into the atmosphere, bringing the total to 606 million metric tons.²⁰

Carbon dioxide emissions from energy production and industrial processes (noncombustion emissions) together accounted for about 2 percent of carbon dioxide emissions in 1998, or 27.9 million metric tons. These sources contributed 0.5 million metric tons to the 1998 rise in emissions (Table 4). Emissions from cement production processes (excluding the energy portion) rose from 10.3 million metric tons to 10.6 million metric tons, and emissions from natural gas flaring increased from 4.2 million metric tons to 4.3 million metric tons.

Energy Consumption

Energy End-Use Sector Sources of Carbon Dioxide Emissions, 1990-1998

Sector	Million Metric Tons Carbon		Percent Change	
	1990	1998	1990-1998	1997-1998
Transportation	431.8	484.9	12.3%	2.4%
Industrial	453.7	477.7	5.3%	-1.3%
Commercial	206.7	238.4	15.3%	0.2%
Residential	253.1	284.5	12.4%	-0.1%

Note: Electric utility emissions are distributed across sectors.

Year-to-year changes in energy consumption and carbon dioxide emissions tend to be dominated by weather, economic fluctuations, and movements in energy prices. During the 1990s, the greatest growth in

carbon emissions occurred in 1993 and 1996, both colder-than-average years with heating degree-days 17 percent above 1990 (Figure 1). Economic growth, however, was faster in 1996, resulting in higher emissions growth than in 1993. The next highest growth in emissions occurred in 1992, 1994, and 1997. In 1992 the Nation had both moderate GDP growth and a higher number of heating degree-days than in 1991. Both 1994 and 1997 were characterized by stronger GDP growth than 1992, but decreases in heating degree-days from the year before offset the GDP growth. In 1995, when economic growth was moderate and there was almost no change in heating degree-days from 1994, the growth of carbon emissions was moderate.

While 1998 had strong economic growth, it was warmest year in the decade of the 1990s. The decline in heating degree-days from 1997 offset much of the increase in emissions related to economic growth. The only year of the decade in which the economy slowed was 1991, and with only a moderate rise in heating degree-days from the year before, emissions were lower.

Over longer time spans, changes in consumption are influenced by other factors such as population shifts and energy consumers' choice of fuels, appliances, and capital equipment (e.g., vehicles, aircraft, and industrial plant and equipment). The energy-consuming capital stock of the United States—the cars and trucks, airplanes, heating and cooling plants in homes and businesses, steel mills, aluminum smelters, cement plants, and petroleum refineries—change slowly from one year to the next, because capital stock is retired only as it breaks down or begins to operate inefficiently.

For this year's report, the sectoral shares presented below were adjusted from the original data source. A detailed explanation of the adjustments is provided in Appendix A.

Residential Sector

Residential emissions accounted for 19 percent of 1998 U.S. energy-related carbon dioxide emissions. More than two-thirds of that amount was accounted for by the residential sector's pro-rated share of electric utility emissions. Electricity-related residential emissions increased by 5.1 percent in 1998 compared with 1997, probably due to a 22-percent increase over 1997 in national-level cooling degree-days, which would stimulate electricity consumption for air conditioning.

²⁰U.S. Department of Energy and U.S. Environmental Protection Agency, *Report to the President on Carbon Dioxide Emissions from the Generation of Electric Power in the United States*, Draft Report (Washington, DC, September 29, 1999).

In contrast, emissions from the direct combustion of fuels in the residential sector (primarily natural gas) declined by 9.5 percent as a result of lower winter heating demand, although minor amounts of fuels were consumed directly for water heating, cooking, and clothes drying. A much warmer-than-normal winter, with heating degree-days 15 percent lower in 1998 than in 1997, was the primary cause of the decline.

Total carbon emissions from the residential sector declined by 0.1 percent in 1998 (Table 9). Year-to-year residential sector emissions are heavily influenced by the weather. Over longer periods, the movement of populations into the Sunbelt tends to increase summer air conditioning consumption and promote the use of electric heat pumps, which increases indirect emissions from electricity use. Growth in the number of households, resulting from increasing population and immigration, contributes to more residential energy consumption. In addition, the trend in residential homes is to more living space, which needs to be lighted, heated, and cooled. On the other hand, improvements in building shell efficiency offset some of the effect of the trend toward larger living spaces. Since 1990, residential sector carbon emissions have grown at an annual rate of 1.5 percent. In 1998 they were 31.4 million metric tons higher, accounting for 22.4 percent of the total increase in emissions from fossil fuel use since 1990.

Commercial Sector

Commercial sector emissions account for about 16 percent of total emissions, of which almost three-quarters is the sector's pro-rated share of electricity emissions. Although commercial sector emissions largely have their origin in the space heating and cooling requirements of structures such as office buildings, lighting is a more important component of energy demand than it is in the residential sector. Thus, although commercial sector emissions are strongly affected by the weather, they are affected less than residential sector emissions. In the longer run, because commercial activity is a factor of the larger economy, emissions from the commercial sector are more affected by economic trends and less affected by population growth than are emissions from the residential sector.

Emissions from the commercial sector's pro-rated share of electricity consumption increased by 2.3 percent in 1998, while direct combustion of fuels (dominated by natural gas, as in the residential sector) declined by 5.8 percent. Overall, emissions increased by 0.2 percent in 1998 (Table 10). Since 1990, the growth in carbon emissions from the commercial sector has averaged 1.8 percent per year—the most rapid growth of the four

energy-use sectors. Since 1990, commercial sector emissions have risen by 31.7 million metric tons, accounting for 22.6 percent of the total increase in energy-related emissions since 1990.

Transportation Sector

Transportation sector emissions accounted for almost one-third of total energy-related carbon dioxide emissions in 1998. Almost all (98 percent) of transportation sector emissions result from the consumption of petroleum products, particularly, motor gasoline (61 percent of transportation sector emissions); middle distillates (diesel fuel), at 20 percent; jet fuel (13 percent of the total), and residual oil (i.e., heavy fuel oil, largely for maritime use) at 3 percent of total emissions. Motor gasoline, of course, is largely used in automobiles and light trucks, and middle distillates are used in heavy trucks, locomotives, and ships.

Emissions attributable to the transportation sector grew by 2.4 percent in 1998—from 473.4 million metric tons to 484.9 million metric tons of carbon (Table 8). Emissions from motor gasoline, by far the largest single source, grew by 2.8 percent. Jet fuel consumption expanded by 1.5 percent, and consumption of middle distillates grew by 3.7 percent. Transportation consumption of residual fuel declined by 3.8 percent, which is consistent with the trend in recent years.

Since 1990, emissions related to the transportation sector have grown annually at a rate of 1.5 percent. The growth since 1990 has meant that transportation emissions have increased by a total of 53.1 million metric tons, accounting for 37.9 percent of the growth from all sectors.

Industrial Sector

Industrial sector emissions, like transportation sector emissions, accounted for about one-third of total energy-related carbon dioxide emissions in 1998. Electricity consumption accounted for 37.4 percent of total industrial sector emissions, natural gas for 29.3 percent, petroleum for 21.1 percent, and coal for 11.8 percent of total emissions. Generally, industrial sector emissions are strongly affected by the growth of the economy.

Carbon emissions related to industrial activities declined by 1.3 percent in 1998—from 483.7 million metric tons to 477.7 million metric tons of carbon (Table 7). As in other sectors, the pro-rated share of electric utility emissions increased by 2.1 percent, while emissions from the direct combustion of fuels declined by 3.1 percent.

Carbon Dioxide Emissions

Since 1990, the growth in industrial sector emissions has averaged 0.6 percent per year. Total energy-related industrial emissions were 5.3 percent (24 million metric tons) higher in 1998 than they were in 1990, accounting for 17.1 percent of the total growth in carbon dioxide emissions related to energy consumption.

The industrial sector consists of the manufacturing, construction, mining, and agricultural sectors in the United States. Of these, manufacturing accounts for 80 percent of industrial energy consumption.²¹ Six industry groups—petroleum refining, chemicals and related products, primary metals, paper, food, and stone, clay and glass—collectively accounted for 87 percent of manufacturing energy consumption and 81 percent of carbon emissions (see box on page 17). Therefore, about two-thirds of the total carbon dioxide emissions related to industrial energy consumption can be attributed to those industries.

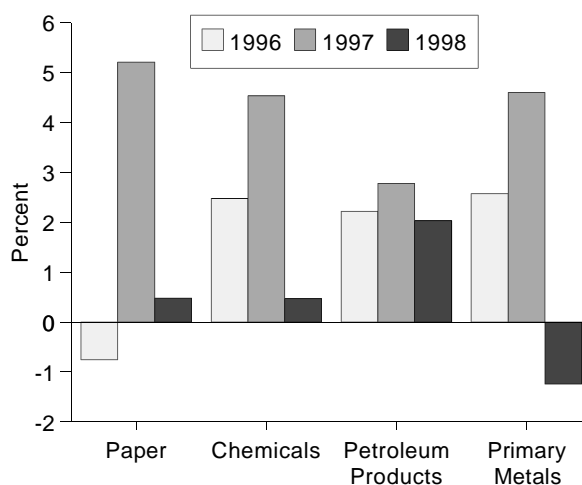
Industrial sector emissions also include those from “nonutility electricity generators.” Historically, non-utility generators have consisted largely of industrial sector autogeneration and cogeneration. In recent years, however, there have been increasing numbers of so-called “independent power producers,” operating unregulated wholesale electricity generation plants. During 1998, the sale or conversion of existing electric utility plants to independent power producer status accelerated.

As Figure 2 indicates, while output indices of the energy-intensive industries (paper and products, chemicals and products, petroleum products, and primary metals) demonstrated strong growth in 1997, in 1998 the paper and chemicals industries grew slowly and primary metals declined. The petroleum products industry grew at about half the rate of the economy. The box on page 17 discusses the importance of the energy-intensive industries to overall emissions, using data from EIA’s Manufacturing Energy Consumption Survey (MECS).

A survey of manufacturers was conducted in 1998, but the results are not yet available. When these results become available they will shed light on how, despite strong economic growth in 1998, industrial energy demand and related emissions declined. While awaiting the results of the 1998 MECS, some evidence is available on industrial energy consumption from other sources. The Chemical Manufacturers Association (CMA) publishes an annual estimate of the energy and feedstock consumption of its members, which include

most of the large chemical industry firms specializing in basic petrochemicals. The American Iron and Steel Institute (AISI) also publishes data on the energy consumption of its membership, which include much (but not all) of the American steel industry. Both CMA and AISI indicate declining energy consumption among their membership in 1998.²²

Figure 2. Industrial Output Growth, 1996-1998



Source: U.S. Federal Reserve Board, Industrial Production Indices, web site www.bog.frd.fed.us/releases/G17.

Electric Utilities

Electric Utility Carbon Dioxide Emissions by Fuel Input, 1990 and 1998

Fuel	Million Metric Tons Carbon		Percent Change	
	1990	1998	1990-1998	1997-1998
Petroleum	26.4	24.8	-6.2%	41.6%
Natural Gas	41.2	47.8	16.0%	9.8%
Coal	409.0	477.3	16.7%	1.2%
Geothermal	0.1	*	-39.7%	-5.4%
Total	476.7	549.8	15.3%	3.2%

*Less than 0.05 million metric tons.

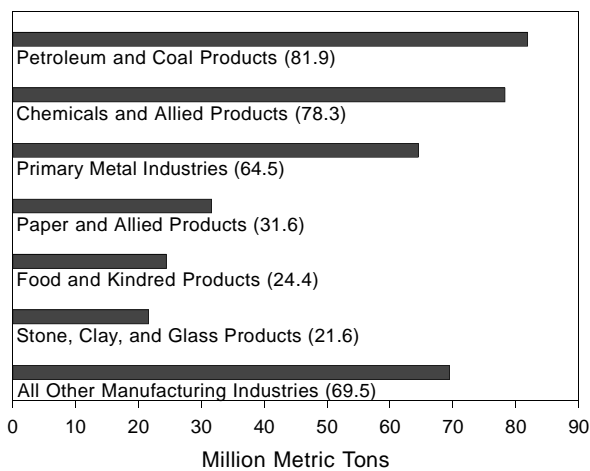
²¹The percentage is based on 1994, the last year for which manufacturing data are available. The calculation is 371.1 divided by 466.2.

²²See: Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1998* (Arlington, VA, August 1999), and American Iron & Steel Institute, *Iron and Steel Annual Statistical Report 1998* (Washington, DC, 1999).

Energy-Related Carbon Emissions in Manufacturing

Manufacturing, which accounts for 80 percent of industrial energy consumption, also accounts for 80 percent of industrial energy-related carbon emissions. In 1994, two industries, petroleum and chemicals, emitted over 40 percent of the energy-related carbon in manufacturing. The next four largest emitters (primary metals, paper, food, and the stone, glass, and clay products industry) produced the other 40 percent of the energy-related carbon emissions from manufacturing (see figure).

Total Energy-Related Carbon Emissions for Selected Manufacturing Industries, 1994



Source: Energy Information Administration, Form EIA-846, "1994 Manufacturing Energy Consumption Survey," and Form EIA-810, "Monthly Refinery Report" (1994).

The carbon intensity of energy use is the amount of carbon emitted per unit of energy used. Both the mix of energy sources used and the uses of energy affect carbon intensity. Overall, manufacturing industries had a carbon intensity of 17.16 million metric tons per quadrillion Btu in 1994; however, the carbon intensities of the various industries differed markedly.

The petroleum industry and the chemical industry both convert energy sources into products, such as petrochemical feedstocks and plastics. Only part of the carbon content is emitted to the atmosphere, the rest being sequestered in the product (see Table A2). As a result of the nonfuel use of energy sources, the petroleum and chemical industries had lower than average carbon intensities in 1994, 12.91 and 14.69 million metric tons per quadrillion Btu, respectively.

The paper industry uses wood byproducts extensively, yielding a carbon intensity of 11.87 million metric tons per quadrillion Btu in 1994. The carbon emissions from wood combustion are considered to be zero, because the carbon emitted has been recently sequestered and the regrowing of the trees will resequester the emitted carbon. In contrast, the primary metals industry relies heavily on coal and, to a lesser extent, on electricity (much of which is generated using coal). Both coal and electricity are carbon-intensive fuels, resulting in an overall carbon intensity of 26.19 million metric tons per quadrillion Btu for this industry in 1994.

The food industry and the stone, metal, and glass industry both had carbon intensities that were slightly above the average for all manufacturing industries. However, the carbon intensities for these two industries, and for the primary metals industry, were comparable to those for "All Other Manufacturing Industries" (25.45 million metric tons per quadrillion Btu).

Electricity use is the main source of carbon emissions in industries outside the top six emitters of carbon. Other manufacturing includes industries such as textile mill products, furniture and fixtures, leather and leather products, fabricated metal products, industrial machinery, and electric and electronic products. Their collective carbon intensity was 25.45 million metric tons per quadrillion Btu in 1994.

The consumption data upon which this inventory is based include only regulated electric utilities in the electricity sector. Consumption by nonutility generators is included in the industrial sector. A report prepared by the Department of Energy and the Environmental Protection Agency pursuant to the Presidential Directive of April 15, 1999, estimates that total carbon emissions from all electricity generation increased from

583.9 million metric tons of carbon in 1997 to 605.5 million metric tons in 1998, an increase of 3.7 percent, or almost the rate of growth of the economy. Subtracting the amount contained in this inventory from the total for all generation contained in that report would imply that nonutility emissions increased by 8.9 percent, from 51.1 million metric tons in 1997 to 55.7 million metric tons in 1998.²³

²³U.S. Department of Energy and U.S. Environmental Protection Agency, *Report to the President on Carbon Dioxide Emissions from the Generation of Electric Power in the United States*, Draft Report (Washington, DC, September 29, 1999).

In this inventory, the emissions of the electric utility sector are assigned to the energy-consuming sectors presented above. However, because electric utility emissions account for 37 percent of total U.S. energy-related carbon dioxide emissions, they are also discussed separately. Carbon emissions from the electric utility sector grew at a much greater rate than national emissions between 1997 and 1998: 3.2 percent or 17 million metric tons (Table 11). Since 1990, electric utility emissions have grown by 15 percent, while overall emissions have grown by 10 percent.

During most of the 1980s and the first half of the present decade, the carbon output rate of power generation (measured as quantity of carbon dioxide emitted per kilowatt-hour of electricity generated) steadily declined. Increasing power generation from nuclear power, the expansion of natural-gas-fired generation, and improving thermal efficiencies from existing plants all have contributed to this trend. Since 1995, however, the carbon output rate of power generation has begun to rise again. In 1995 nuclear power provided 22 percent of utility generation, but in 1998 it provided less than 21 percent. Petroleum-fired generation, on the other hand, rose from 2.0 percent of utility generation in 1995 to 3.4 percent in 1998. The average price of heavy fuel oil paid by electric utilities was 20 percent lower in 1998 than in 1995.

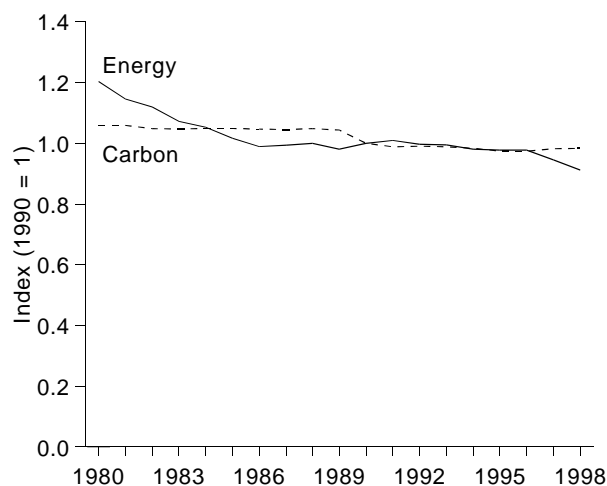
Energy Intensity Versus Carbon Intensity in Emissions Trends

In order to analyze trends in carbon emissions, it is important to evaluate both energy intensity (Btu per dollar of GDP) and carbon intensity (carbon per unit of energy consumed). When the economy grows and carbon emissions remain almost flat, as they did in 1998, it means that either the energy intensity, the carbon intensity, or some combination of both declined by nearly the same amount as economic output expanded. In 1998, energy intensity rather than carbon intensity was the principal source of low emissions growth. Carbon intensity actually rose slightly as temporarily inexpensive oil, which is more carbon-intensive than natural gas, was substituted for natural gas in the generation of electricity. These offsetting trends are discussed below.

As Figure 3 indicates, the trends in carbon intensity and energy intensity have begun to diverge. Following the energy price spikes in the 1970s and early 1980s, energy intensity went through a decline until the mid-1980s. Energy intensity leveled off for about the next decade as energy prices dropped and remained stable. Energy intensity rose slightly in 1991, a recession year.

Consumption of energy is relatively inelastic with respect to people's income. Therefore, consumption of energy did not fall as fast as consumption of other goods and services in the economy. In the early 1990s energy intensity began to fall again, and between 1996 and 1998 it fell by 6.6 percent. What is important about the current fall is that, unlike past declines in energy intensity, energy prices have been stable or decreasing. Various factors have contributed to this decline, and weather in particular has played a role in the drop between 1996 and 1998. Another factor is an increase in the non-energy-intensive sectors of the economy relative to the traditional energy-intensive manufacturing industries.

Figure 3. Changes in U.S. Energy Intensity and Carbon Intensity, 1980-1998



Sources: Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384 (Washington, DC, various years), and estimates documented in this report.

Carbon intensity has shown a different pattern. Throughout the 1980s carbon intensity remained largely unchanged. Beginning in the late 1980s two trends began to emerge which affected the carbon output of the entire economy. Independent power producers began to take an increasing share of the electricity market, and their generation mix is overwhelmingly gas-fired, a lower carbon-intensive fuel. At the same time, electric utilities began to rely less on petroleum to generate electricity and increased the operating capability of nuclear power facilities.

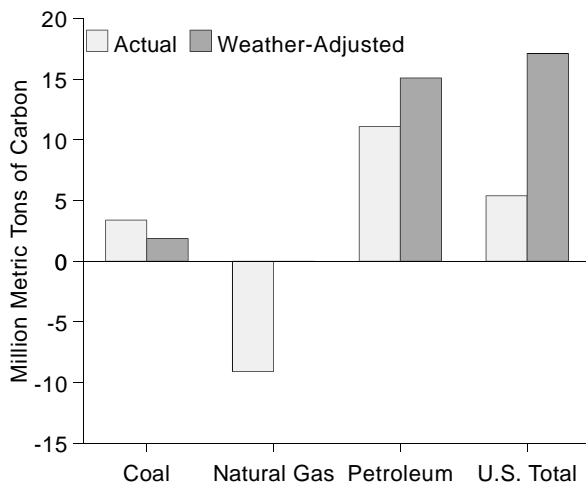
Between 1991 and 1995 carbon intensity fell. After 1995, however, the trend was reversed as petroleum generation began to grow again and coal generation grew by 9.4 percent between 1995 and 1998 as opposed to

4.9 percent between 1992 and 1995. In 1998, carbon intensity was 1.7 percent below the 1990 level, whereas in 1996 it had fallen to 2.6 percent below. If carbon intensity had fallen by the same amount as energy intensity, emissions of carbon dioxide from fossil fuel burning would be 2.3 percent above the 1990 level of emissions, rather than the current level of 10 percent above 1990.

Weather-Adjusted Carbon Dioxide Emissions

To examine the effect of weather on 1998 reported emissions, EIA undertook a series of “weather adjusted” cases of its short-term energy forecasting model, the Short-Term Integrated Forecasting System (STIFS). This model is used primarily to prepare 2-year quarterly forecasts of U.S. energy production and consumption. Two model cases were run for the years 1997 and 1998, one in which actual weather parameters were used and another in which normal weather (heating and cooling degree-days) were used. Both cases used actual historical values for all other variables that are not determined by the model. The percentage increments from the two cases were applied to the actual values from this report in order to estimate the weather-related effect. Figure 4 illustrates actual and weather-adjusted growth in energy-related carbon emissions by fuel and for the U.S. total from 1997 to 1998.

Figure 4. Change in Actual and Weather-Normalized Carbon Emissions by Fuel, 1997-1998



Source: Energy Information Administration, Office of Energy Markets and End Use, Short-Term Integrated Forecasting System (STIFS).

The weather-adjusted emissions for 1998 were 17.1 million metric tons (1.2 percent) higher than the weather-adjusted emissions for 1997, indicating that the growth in emissions would have been about three times higher had the weather been normal in both years. The 1.2-percent growth rate is the annual average rate of growth between 1990 and 1998; however, because 1998 was a year of above-average economic growth, one would expect an even higher growth rate for 1998 than the 1.2-percent average under normal weather assumptions.

Adjustments to Energy Consumption

Total energy consumption and the carbon emissions upon which they are based correspond to EIA’s coverage of energy consumption, which includes the geographic area of the United States as 50 States and the District of Columbia. However, the United States is also responsible for emissions emanating from its territories. On the other hand, the Intergovernmental Panel on Climate Change (IPCC) definition of energy consumption excludes international bunker fuels from the statistics of all countries. Therefore this emissions category is estimated and subtracted from the national total. These sources are enumerated and described as “adjustments to energy.”

U.S. Territories

Energy-related carbon dioxide emissions for the U.S. territories are added as an adjustment in keeping with IPCC guidelines for national emissions inventories. The territories included are Puerto Rico, the U.S. Virgin Islands, American Samoa, Guam, U.S. Pacific Islands and Wake Island. Almost all the commercial energy consumed in the territories consists of petroleum products, although small amounts of coal are imported into Puerto Rico and the Virgin Islands. In 1998, total carbon emissions are estimated to have been 12 million metric tons (Table 4). This emissions estimate for the U.S. territories differs from those in past editions of this report because the entire time series has been adjusted to different consumption estimates.

International Bunker Fuels

International bunker emissions, accounting for about 2 percent of U.S. carbon dioxide emissions, are deducted from national emissions. The energy statistics of the International Energy Agency, using a format designed to be consistent with practice in international trade,

have always excluded marine bunker fuels from domestic consumption. Marine bunker fuels are defined as fuel sold to ships moving in international trade. When the IPCC began developing its guidelines for national emissions inventories in the early 1990s, the practice of excluding marine bunker fuels was extended to international aviation fuels, defined as fuel consumed by aircraft moving between international destinations. Thus, the IPCC, in effect, invented the concept of international aviation bunkers. No country in the world, including the United States, collects the statistics needed to properly measure this concept.

In the case of the United States, sufficient information is available to estimate emissions from both ships and aircraft moving internationally, using unpublished data collected by the U.S. Department of Commerce and used to prepare the services account of the U.S. balance-of-payments statistics.²⁴ This year's report includes, for the first time, estimates of jet fuel consumed by foreign commercial aircraft operating out of U.S. airports. The entire time series has been adjusted to reflect this new information. The current estimate continues to exclude military bunkers, pending the receipt of additional information from the U.S. Department of Defense.

The international bunker fuels estimate is based on purchases of distillate and residual fuels by foreign-bound ships at U.S. seaports, and on jet fuel purchases by domestic and foreign international air carriers at U.S. airports. In 1998, approximately 30 million metric tons of carbon were emitted from international bunker fuels, or 6.7 percent more than in 1997 (Table 4). Just over half of the international bunker fuel carbon emissions are from the combustion of jet fuels, and marine bunker emissions (largely from residual fuels) account for the rest.

Other Carbon Dioxide Emissions

Energy Production

In addition to emissions resulting from fossil energy consumed, oil and gas production leads to emissions of carbon dioxide from sources other than the combustion of those marketed fossil fuels. The two energy production sources estimated for this inventory are:

- Flared natural gas, which is flared either because the cost of bringing the gas to market is prohibitive or because the gas is of insufficient quality to sell

Other U.S. Carbon Dioxide Emissions, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Carbon)	27.9
Change Compared to 1997 (Million Metric Tons Carbon)	0.5
Change from 1997 (<i>Percent</i>)	1.7%
Change Compared to 1990 (Million Metric Tons Carbon)	5.4
Change from 1990 (<i>Percent</i>)	24.1%

- Carbon dioxide scrubbed from natural gas (to improve its heat content and quality) and subsequently vented to the atmosphere.

EIA assumes that all natural gas reported in the category "Vented and Flared Gas" is actually flared (combusted) and therefore is a carbon dioxide emission rather than a (non-combusted) methane emission. In 1998, about 4.3 million metric tons of carbon were emitted by flaring (Table 4).

By computing the difference between the estimated carbon dioxide content of raw gas and the carbon dioxide content of pipeline gas, the amount of scrubbed carbon dioxide can be calculated. This amount was 4.9 million metric tons of carbon in 1998 (Table 4).

Industrial Process Emissions

Industrial process emissions are non-combustion industrial emissions, usually caused by chemical reactions involving carbonate rock. They accounted for about 1.2 percent of total U.S. carbon dioxide emissions in 1998. Process-related emissions from these industrial sources depend largely on the level of activity in the construction and fertilizer industries, because the principal source of emissions is the calcination of limestone to make cement and lime (although there are a large number of other, smaller sources).

Carbon dioxide emissions from industrial processes accounted for 18.7 million metric tons of carbon in 1998 (Table 12), an increase of 2.5 million metric tons of carbon compared with 1990. More than one-half of the carbon dioxide emissions from industrial processes are from cement manufacture. When calcium carbonate is heated (calcined) in a kiln, it is converted to lime and

²⁴More details are included in Appendix A, "Estimation Methods."

carbon dioxide. The lime is combined with other materials to produce clinker (an intermediate product from which cement is made), and the carbon dioxide is released to the atmosphere. In 1998, the United States manufactured an estimated 85.5 million metric tons of cement, resulting in the direct release of carbon dioxide containing about 10.6 million metric tons of carbon into the atmosphere. (This calculation is independent of the carbon released by the energy consumed in making cement.) This represents an increase in emissions of 1.7 million metric tons of carbon or 19.2 percent compared with 1990 and an increase of about 0.3 million metric tons or 3.5 percent compared with 1997.

There are numerous other industrial processes in which carbonate minerals are used in ways that release carbon dioxide into the atmosphere, including the use of limestone in the production of lime, in flue gas desulfurization, and in the manufacture and some uses of soda ash. Carbon dioxide is also released during aluminum smelting, when carbon anodes (with the carbon derived from nonfuel use of fossil fuels) are vaporized in the presence of aluminum oxide. Approximately 8.0 million metric tons of carbon per year are contained in emissions from these other industrial process sources.

Carbon Dioxide Emissions

Table 4. U.S. Carbon Dioxide Emissions from Energy and Industry, 1990-1998
(Million Metric Tons of Carbon)

Fuel Type or Process	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Energy Consumption									
Petroleum	590.4	576.1	586.7	587.7	600.3	596.3	618.7	625.5	636.7
Coal	481.5	475.7	478.3	494.6	496.4	501.2	521.8	535.5	538.9
Natural Gas	273.2	278.1	286.3	295.8	301.5	314.1	320.0	318.9	309.8
Geothermal	0.1	0.1	0.1	0.1	*	*	*	*	*
Total Energy Consumption .	1,345.2	1,330.0	1,351.3	1,378.2	1,398.3	1,411.7	1,460.5	1,480.0	1,485.4
Adjustments to U.S. Energy									
U.S. Territories	8.7	9.8	9.4	10.7	11.0	11.0	10.1	10.9	12.0
Bunker Fuels	-29.3	-29.8	-27.4	-24.9	-24.8	-25.7	-26.1	-27.9	-29.8
Total Adjustments	-20.7	-20.0	-18.0	-14.2	-13.8	-14.7	-16.1	-17.0	-17.8
Adjusted Total Energy	1,324.5	1,309.9	1,333.3	1,364.0	1,384.5	1,397.0	1,444.4	1,463.0	1,467.6
Other Sources									
Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.2	4.3
CO ₂ in Natural Gas	3.8	4.0	4.2	4.4	4.6	4.6	4.8	4.9	4.9
Cement Production	8.9	8.7	8.8	9.3	9.8	9.9	9.9	10.3	10.6
Other Industrial	7.3	7.2	7.2	7.1	7.2	7.6	7.9	8.0	8.0
Total Other Sources	22.5	22.6	22.9	24.6	25.4	26.8	27.1	27.4	27.9
Total	1,347.0	1,332.6	1,356.3	1,388.6	1,409.9	1,423.8	1,471.5	1,490.4	1,495.5

*Less than 5,000 metric tons of carbon.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Emissions coefficients are annualized for coal, motor gasoline, liquefied petroleum gases, jet fuel, and crude oil. Includes emissions from bunker fuels. Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Table 5. U.S. Carbon Dioxide Emissions from Energy Consumption by End-Use Sector, 1990-1998
(Million Metric Tons of Carbon)

End Use	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Energy Consumption									
Residential	253.1	257.1	255.9	271.7	268.3	270.3	285.9	284.8	284.5
Commercial	206.7	206.4	205.4	211.3	213.8	217.9	226.0	238.0	238.4
Industrial	453.7	442.2	458.8	458.9	467.1	466.0	480.0	483.7	477.7
Transportation	431.8	424.3	431.1	436.4	449.1	457.6	468.7	473.4	484.9
Total Energy	1,345.2	1,330.0	1,351.3	1,378.2	1,398.3	1,411.7	1,460.5	1,480.0	1,485.4
Electric Utility ^a	476.7	473.3	472.8	490.5	494.0	495.2	513.0	532.8	549.8

^aEstimates of additional carbon dioxide emissions from the use of limestone and soda ash in flue gas desulfurization are included in Table 12.

P = preliminary data.

Notes: Includes energy from petroleum, coal, and natural gas. Electric utility emissions are distributed across consumption sectors. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Table 6. U.S. Carbon Sequestered by Nonfuel Use of Energy, 1990-1998
(Million Metric Tons of Carbon)

End Use	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Industrial									
Petroleum									
Liquefied Petroleum Gases . . .	16.2	18.6	18.7	18.2	20.9	21.4	22.2	22.3	21.3
Distillate Fuel	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residual Fuel	0.5	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.5
Asphalt and Road Oil	24.1	22.2	22.7	23.7	24.2	24.3	24.2	25.2	26.0
Lubricants	1.9	1.7	1.7	1.8	1.8	1.8	1.7	1.8	1.9
Other	19.7	19.3	20.5	22.6	23.3	23.5	24.1	26.1	27.6
Pentanes Plus	1.2	0.7	0.9	4.0	3.8	4.4	4.7	4.3	3.9
Petrochemical Feed	12.6	12.6	13.4	13.6	14.1	13.6	13.8	15.9	16.1
Petroleum Coke	2.6	2.2	3.4	2.3	2.5	2.7	2.9	3.1	4.3
Waxes and Miscellaneous	3.4	3.7	2.7	2.7	2.9	2.7	2.7	2.8	3.4
Coal	0.4	0.4	0.8	0.6	0.5	0.6	0.6	0.5	0.5
Natural Gas	4.1	3.9	3.5	4.0	5.0	5.1	5.1	5.4	5.3
Transportation									
Lubricants	1.8	1.6	1.6	1.7	1.7	1.7	1.6	1.7	1.8
Total	68.7	68.3	70.2	73.1	78.1	78.9	80.2	83.8	85.1

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Source: EIA estimates documented in this chapter and in Appendix A.

Table 7. U.S. Carbon Dioxide Emissions from Energy Use in the Industrial Sector, 1990-1998
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Petroleum									
Motor Gasoline	3.6	3.7	3.7	3.5	3.7	3.9	3.9	4.1	4.2
LPG	12.0	12.1	12.7	12.1	12.9	12.7	13.8	14.2	13.6
Distillate Fuel	23.3	22.4	22.5	21.7	21.8	21.1	22.2	22.4	21.9
Residual Fuel	8.4	6.5	7.7	9.0	8.5	6.7	6.7	5.8	4.5
Lubricants	1.9	1.7	1.7	1.7	1.8	1.8	1.7	1.8	1.9
Kerosene	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4
Other	51.4	48.4	55.3	49.5	52.1	49.4	55.2	56.9	54.2
Total	100.7	95.0	103.9	97.7	101.2	96.0	103.8	105.6	100.9
Coal	68.3	64.5	61.8	61.7	62.0	61.8	59.9	58.8	56.3
Coking Coal (Net Imports)	0.1	0.2	0.9	0.7	1.5	1.5	0.6	1.2	1.7
Natural Gas	118.3	120.2	125.9	131.3	132.7	140.2	145.0	142.9	140.0
Electricity	166.2	162.2	166.4	167.5	169.7	166.4	170.6	175.2	178.8
Total	453.7	442.2	458.8	458.9	467.1	466.0	480.0	483.7	477.7

*Less than 5,000 metric tons of carbon.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Carbon Dioxide Emissions

Table 8. U.S. Carbon Dioxide Emissions from Energy Use in the Transportation Sector, 1990-1998
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Petroleum									
Motor Gasoline	260.6	259.2	263.1	268.9	273.3	279.0	284.0	286.5	294.6
LPG	0.4	0.3	0.3	0.3	0.6	0.3	0.3	0.3	0.2
Jet Fuel	60.1	58.1	57.6	58.1	60.4	60.0	62.7	63.3	64.2
Distillate Fuel	75.7	72.6	75.3	77.3	82.5	85.1	89.7	93.5	96.9
Residual Fuel	21.9	22.0	23.0	19.4	19.1	19.7	18.4	15.5	14.9
Lubricants	1.8	1.6	1.6	1.6	1.7	1.7	1.6	1.7	1.8
Aviation Gas	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7
Total	421.2	414.6	421.6	426.4	438.2	446.5	457.4	461.5	473.4
Natural Gas	9.8	9.0	8.8	9.3	10.2	10.4	10.6	11.2	10.8
Electricity	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.7
Total	431.8	424.3	431.1	436.4	449.1	457.6	468.7	473.4	484.9

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Table 9. U.S. Carbon Dioxide Emissions from Energy Use in the Residential Sector, 1990-1998
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Petroleum									
LPG	6.3	6.7	6.6	6.8	6.8	6.9	7.5	7.5	7.2
Distillate Fuel	16.5	16.4	17.1	18.0	17.4	17.4	18.4	17.8	15.4
Kerosene	1.2	1.4	1.3	1.5	1.3	1.5	1.7	1.8	2.1
Total	24.0	24.5	24.9	26.3	25.4	25.8	27.6	27.1	24.8
Coal	1.6	1.4	1.5	1.5	1.4	1.4	1.4	1.5	1.5
Natural Gas	65.1	67.5	69.4	73.4	71.7	71.8	77.6	73.7	66.3
Electricity	162.4	163.7	160.1	170.5	169.8	171.3	179.3	182.6	191.9
Total	253.1	257.1	255.9	271.7	268.3	270.3	285.9	284.8	284.5

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Table 10. U.S. Carbon Dioxide Emissions from Energy Use in the Commercial Sector, 1990-1998
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Petroleum									
Motor Gasoline	2.1	1.6	1.5	0.6	0.5	0.4	0.5	0.8	0.8
LPG	1.1	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3
Distillate Fuel	9.6	9.5	9.2	9.2	9.2	9.1	9.4	8.8	8.3
Residual Fuel	5.0	4.5	4.1	3.7	3.7	3.1	3.0	2.4	1.9
Kerosene	0.2	0.2	0.2	0.3	0.4	0.4	0.4	0.5	0.6
Total	18.0	17.1	16.1	14.9	14.9	14.1	14.6	13.9	12.9
Coal	2.4	2.2	2.2	2.2	2.1	2.1	2.1	2.2	2.2
Natural Gas	38.8	40.4	41.5	42.4	42.9	44.9	46.8	47.6	44.9
Electricity	147.4	146.7	145.6	151.8	153.9	156.8	162.4	174.3	178.4
Total	206.7	206.4	205.4	211.3	213.8	217.9	226.0	238.0	238.4

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Table 11. U.S. Carbon Dioxide Emissions from Electric Utilities, 1990-1998
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Petroleum									
Heavy Fuel Oil	24.0	22.7	18.0	19.8	17.8	11.5	12.8	14.6	20.7
Light Fuel Oil	1.7	1.6	1.3	1.5	1.9	1.8	1.9	1.7	2.5
Petroleum Coke	0.7	0.6	0.8	1.0	0.7	0.6	0.6	1.2	1.5
Coal	409.0	407.3	411.9	428.6	429.4	434.4	457.7	471.7	477.3
Natural Gas	41.2	41.1	40.7	39.5	44.0	46.8	39.9	43.6	47.8
Geothermal	0.1	0.1	0.1	0.1	0.1	*	*	*	*
Total	476.7	473.3	472.8	490.5	494.0	495.2	513.0	532.8	549.8

*Less than 5,000 metric tons of carbon.

P = preliminary data.

Notes: Independent Power Producers and cogeneration facilities are included in industrial emissions. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Source: EIA estimates documented in this chapter and in Appendix A.

Carbon Dioxide Emissions

Table 12. U.S. Carbon Dioxide Emissions from Industrial Processes, 1990-1998
(Million Metric Tons of Carbon)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Cement Manufacture									
Clinker Production	8.90	8.66	8.75	9.25	9.82	9.85	9.91	10.24	10.61
Masonry Cement	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	8.91	8.68	8.77	9.27	9.84	9.87	9.93	10.27	10.63
Other Industrial									
Limestone Consumption									
Lime Manufacture	3.39	3.36	3.47	3.58	3.73	3.96	4.11	4.22	4.13
Iron Smelting	0.47	0.44	0.37	0.31	0.30	0.31	0.30	0.31	0.31
Steelmaking	0.08	0.09	0.07	0.13	0.15	0.14	0.11	0.09	0.10
Copper Smelting	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05
Glass Manufacture	0.03	0.03	0.04	0.05	0.08	0.09	0.05	0.02	0.02
Flue Gas Desulfurization	0.18	0.19	0.19	0.18	0.19	0.24	0.26	0.28	0.28
Total	4.20	4.14	4.19	4.29	4.50	4.79	4.89	4.97	4.89
Dolomite Consumption	0.13	0.10	0.08	0.07	0.07	0.06	0.09	0.09	0.09
Soda Ash Manufacture	0.92	0.92	0.94	0.91	0.92	1.04	1.03	1.08	1.10
Soda Ash Consumption									
Glass Manufacture	*	*	*	*	*	*	*	*	*
Flue Gas Desulfurization	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
Sodium Silicate	0.05	0.05	0.05	0.06	0.06	0.07	0.06	0.07	0.07
Sodium Tripolyphosphate	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total	0.10	0.10	0.10	0.11	0.11	0.13	0.12	0.14	0.13
Carbon Dioxide Manufacture	0.24	0.25	0.26	0.26	0.27	0.29	0.30	0.31	0.32
Aluminum Production	1.62	1.65	1.62	1.48	1.32	1.35	1.43	1.44	1.48
Shale Oil Production	0.05	*	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Other Industrial	7.27	7.16	7.19	7.12	7.19	7.65	7.86	8.02	8.02
Total	16.18	15.84	15.96	16.40	17.04	17.52	17.79	18.29	18.65

*Less than 5,000 metric tons of carbon.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Methodologies and sources of trend data documented in Appendix A.

3. Methane Emissions

Overview

	Methane	Carbon Equivalent
Estimated 1998 Emissions (Million Metric Tons)	28.8	165.4
Change Compared to 1997 (Million Metric Tons)	-0.4	-2.5
Change from 1997 (Percent)	-1.5%	-1.5%
Change Compared to 1990 (Million Metric Tons)	-1.4	-7.8
Change from 1990 (Percent)	-4.5%	-4.5%

In 1998, U.S. anthropogenic methane emissions totaled 28.8 million metric tons, a decline of about 0.4 million metric tons from 1997 levels (Table 13). The decline is attributed to an increase in methane recovery for energy use at U.S. landfills, from 1.7 million metric tons to 2.2 million metric tons between 1997 and 1998 (Table 18). In order to qualify for a Federal tax credit under Section 29 of the Windfall Profits Tax Act of 1980, methane recovery systems at landfills must have been operational by June 30, 1998. During 1997-1998, landfill gas developers raced to put new projects on line to beat the deadline. Also, the U.S. Environmental Protection Agency (EPA) recently implemented the New Source Performance Standards and Emissions Guidelines for landfills, giving operators an additional regulatory incentive to capture their emissions.

Total 1998 methane emissions were 1.4 million metric tons below the 1990 level, a decrease equivalent to 7.7 million metric tons of carbon, or roughly 0.4 percent of total U.S. anthropogenic greenhouse gas emissions. In addition to a 1.3 million metric ton decrease in emissions from landfills since 1990, there has also been a 1.1 million metric ton decrease in emissions from coal mines during the same period (Table 13). The 26-percent decline in emissions from coal mining is the result of a fourfold increase in methane recovery from coal mines and a shift in production away from gassy mines. Overall, methane emissions account for about 9 percent of total U.S. greenhouse gas emissions weighted by global warming potential.²⁵

Methane emissions estimates are more uncertain than carbon dioxide emissions estimates. Methane emissions usually are accidental or incidental to biological processes and may not be metered in any systematic way.²⁶ Thus, methane emission estimates must often rely on proxy measurements. U.S. anthropogenic methane emissions for 1998 also include preliminary data for several key sources; thus, the overall estimate must be described as preliminary. Emissions from two of these sources, coal mining and oil and gas systems, are almost one-third of all U.S. methane emissions. Coal production data on a mine-by-mine basis will not be available until December 1999. Estimates for emissions and recovery from degasification systems have been scaled to a limited set of data for selected mines obtained as part of EIA's 1605(b) Voluntary Reporting of Greenhouse Gases program. Similarly, large portions of estimated emissions from oil and gas systems in 1998 are scaled to total gas throughput for the year, because detailed industry activity data are not yet available.

There are three principal sources of U.S. methane emissions: energy production and consumption, waste management, and agriculture. A fourth source, industrial processes, adds about 0.5 percent to estimated

²⁵For a definition of global warming potential, see Chapter 1.

²⁶Wherever possible, estimates of methane emissions are based on measured data. In some cases, however, measured data are incomplete or unavailable. In the absence of measured data, emissions are calculated by multiplying some known activity data, such as coal production or natural gas throughput, by an emissions factor derived from a small sample of the relevant emissions source or through laboratory experiments. For a more detailed discussion of where measured data were used and how emissions factors were developed, see Appendix A. The absence of measured emissions data for most sources of methane emissions and the reliance on emissions factors represent a source of uncertainty (see Appendix C).

Major Sources of U.S. Methane Emissions, 1990-1998

Source	Million Metric Tons Methane		Percent Change	
	1990	1998	1990-1998	1997-1998
Energy	10.8	10.1	-6.3%	*
Waste Management	11.1	9.9	-11.3%	-4.8%
Agriculture	8.2	8.7	6.9%	0.6%
Industrial Processes	0.1	0.1	13.5%	0.5%

* Less than 0.05 million metric tons.

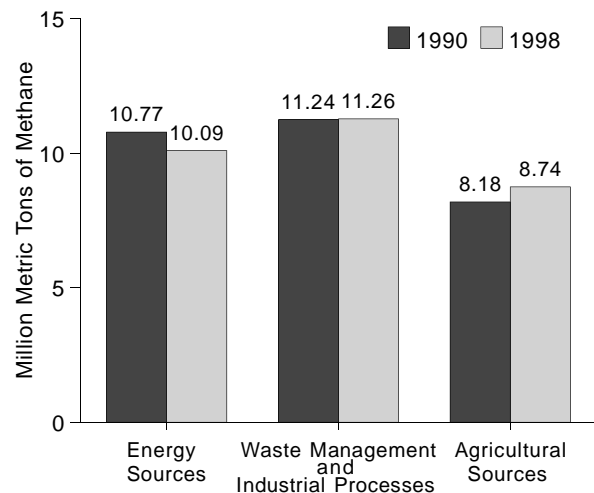
methane emission totals. Emissions from energy sources, representing 35 percent of all U.S. methane emissions (Figure 5), declined by more than 6 percent between 1990 and 1998, largely due to the 1.1 million metric ton drop in emissions from coal mining. Methane emissions from waste management, which account for about one-third of total methane emissions, decreased by more than 11 percent between 1990 and 1998 due to the drop in emissions from landfills. Emissions from agriculture represent about 30 percent of all U.S. methane emissions. Emissions from agriculture have grown by 6.9 percent since 1990, with approximately half the growth associated with increased swine populations and the resultant waste output. The majority of the remaining increase is associated with larger sized cattle, generating more methane emissions from enteric fermentation.

Energy Sources

U.S. methane emissions from energy sources were estimated at 10.1 million metric tons in 1998, virtually unchanged from 1997 levels and 0.7 million metric tons below the 10.8 million metric tons emitted in 1990. The decline between 1990 and 1998 resulted primarily from lower emissions from coal mines. Emissions from coal mines dropped by 26 percent (1.1 million metric tons) between 1990 and 1998. This decline resulted from the increased capture and use of methane from coal mine degasification systems and a shift in production away from some of the Nation's gassiest mines in Central Appalachia. A decrease of 0.13 million metric tons in estimated emissions from stationary combustion made

a smaller contribution to the overall drop in emissions from energy sources. Together, the declines in emissions from coal mining and stationary combustion more than compensated for the increase of 0.57 million metric tons in emissions from the oil and gas system attributed to increasing U.S. consumption of natural gas between 1990 and 1998.

Figure 5. U.S. Methane Emissions by Source, 1990 and 1998



Source: Estimates presented in this chapter.

Coal Mining

U.S. Methane Emissions from Coal Mining, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	3.1
Change Compared to 1997 (Million Metric Tons Methane)	*
Change from 1997 (Percent)	-0.3%
Change Compared to 1990 (Million Metric Tons Methane)	-1.1
Change from 1990 (Percent)	-26.1%

*Less than 0.05 million metric tons.

The preliminary estimate of methane emissions from coal mines for 1998 is 3.1 million metric tons (Table 14), a decrease of 0.3 percent from the 1997 level.²⁷ Coal production at surface mines rose by 4 percent between 1997 and 1998, adding 0.02 million metric tons to

²⁷See Appendix D, "Emissions Sources Excluded," for a discussion of emissions from abandoned coal mines.

emissions. This increase was offset by a 0.04 million metric ton decrease in emissions from ventilation systems in gassy mines, attributed to the continued decrease in the number of gassy mines in operation, which reached a decade low number of 116 in 1998.²⁸ The final 1997 emissions estimate was revised slightly from the October 1998 edition of *Emissions of Greenhouse Gases in the United States*. Final production data were just above previously estimated levels, raising estimated 1997 emissions by about 0.01 million metric tons.

Between 1990 and 1998, methane emissions from coal mines dropped by more than 26 percent from the 1990 level of 4.26 million metric tons. The decline is attributed to three important trends: (1) methane recovery from active coal mines for use as an energy resource increased from 0.25 million metric tons in 1990 to about 1 million metric tons in 1998; (2) methane drainage from active mines decreased by some 0.1 million metric tons between 1990 and 1998; and (3) methane emissions from ventilation systems at gassy mines dropped by about 0.3 million metric tons between 1990 and 1998 (Table 14).²⁹

Oil and Gas Production, Processing, and Distribution

Methane emissions from U.S. oil and gas systems in 1998 were 6.3 million metric tons (Table 15), up by 0.3 percent from 1997 levels but 10 percent above 1990 levels. Emissions have grown steadily between 1990 and 1998 due to increased production and consumption of natural gas. Between 1990 and 1998, total gas withdrawals grew by 14 percent, gas processed increased by 15 percent, and distribution main pipeline miles rose by 14 percent.

Just over one-third of the increase in emissions from oil and gas operations between 1990 and 1998 is attributable to emissions from gas production, which grew from 1.47 million metric tons in 1990 to 1.67 million metric tons in 1998. Another third is attributable to gas distribution systems, where emissions rose from 1.36 million metric tons of methane in 1990 to 1.55 million metric tons in 1998. Most of the remaining portion of the emissions escalation can be traced to transmission and storage emissions, which increased by 0.1 million metric tons between 1990 and 1998.³⁰ Methane emissions from oil wells were level between 1990 and 1998 as the number of wells in operation dropped by 8 percent. Emissions from oil refining and transport rose by more than 13 percent during the period as crude oil imports grew by 45 percent.

Stationary Combustion

U.S. Methane Emissions from Oil and Gas Production, Processing, and Distribution, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	6.3
Change Compared to 1997 (Million Metric Tons Methane)	*
Change from 1997 (Percent)	0.3%
Change Compared to 1990 (Million Metric Tons Methane)	0.6
Change from 1990 (Percent)	10.0%

*Less than 0.05 million metric tons.

U.S. Methane Emissions from Stationary Combustion, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	0.43
Change Compared to 1997 (Million Metric Tons Methane)	-0.01
Change from 1997 (Percent)	-1.2%
Change Compared to 1990 (Million Metric Tons Methane)	-0.13
Change from 1990 (Percent)	-23.2%

²⁸A gassy mine is defined as emitting more than 100,000 cubic feet of methane per day.

²⁹The EPA believes that a significant portion of methane recovery from coal mines should not be deducted from current-year emissions, because the gas is being drained from coal seams that will be mined only in future years, if at all. The relationship between estimates of emissions from degasification and estimates of gas recovery is under review and may be revised in a future report.

³⁰The EPA estimates that the companies participating in the Natural Gas STAR program together avoided more than 384,000 metric tons of methane emissions in 1998. Program participants avoided 94,000 metric tons in 1993, 157,000 metric tons in 1994, 201,000 metric tons in 1995, 226,000 metric tons in 1996, and 318,000 metric tons in 1997. Program participants report annually on emissions reductions achieved through such activities as equipment replacement, enhanced inspection and maintenance, and improved operations management. Participating companies may either use their own techniques to estimate reductions achieved or employ default values developed by the EPA and the Gas Research Institute.

Methane Emissions

U.S. methane emissions from stationary combustion in 1998 were 0.4 million metric tons, nearly the same as the 1997 level but 23 percent lower than 1990 levels (Table 16). After remaining relatively stable between 1990 and 1996, residential wood consumption dropped in 1997 and 1998, reaching 26 percent below 1990 levels. Residential wood consumption typically accounts for about 90 percent of methane emissions from stationary combustion. Methane emissions are the result of incomplete combustion, and residential woodstoves and fireplaces provide much less efficient combustion than industrial or utility boilers. Thus, although the residential sector consumes about one-quarter the amount of wood that the industrial sector consumes, emissions from wood consumption for the residential sector are 13 times higher than those for the industrial sector.

Estimates of residential wood combustion are, however, very uncertain (see Appendix C). The universe of wood consumers is large and heterogeneous, and wood for residential consumption is typically obtained from sources outside the documented economy. EIA relies on its Residential Energy Consumption Survey (RECS) to estimate residential wood consumption. This survey includes only primary residences and thus systematically underestimates consumption by as much as 5 percent. Beginning in 1998, EIA wood consumption estimates were adjusted to account for wood consumption in second homes.³¹ EIA is now in the process of completing a new RECS, which will provide wood consumption data through 1997. Preliminary data from the survey are used for the first time in this year's report. Wood consumption data for the years between the EIA surveys are interpolated and adjusted for variations in heating and cooling degree-days.

Mobile Combustion

U.S. Methane Emissions from Mobile Combustion, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	0.24
Change Compared to 1997 (Million Metric Tons Methane)	*
Change from 1997 (Percent)	-0.1%
Change Compared to 1990 (Million Metric Tons Methane)	-0.01
Change from 1990 (Percent)	-3.0%

*Less than 0.005 million metric tons.

Methane emissions from mobile combustion in 1998 are estimated at 0.24 million metric tons, unchanged from 1997 levels (Table 17). This estimate includes emissions from motor vehicles and other sources. Other sources include air, rail and marine transport, and farm and construction equipment. Currently, methane emissions from passenger cars and light-duty trucks represent more than 82 percent of overall methane emissions from mobile combustion.

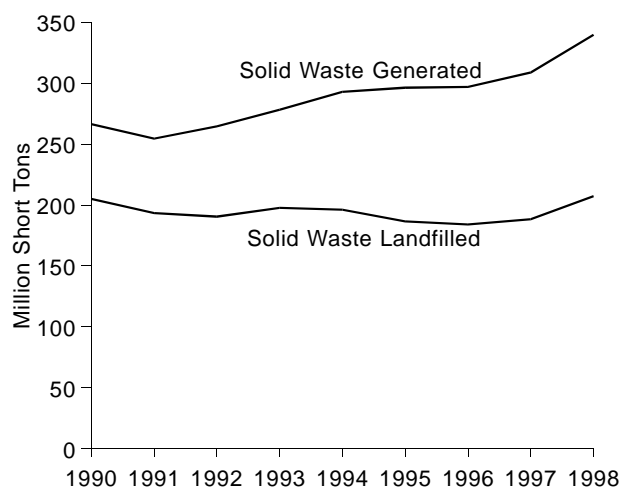
Between 1980 and 1991, methane emissions from mobile sources declined by 15 percent, primarily due to the drop in emissions from passenger cars. Catalytic converters, used on U.S. vehicles to control emissions, have grown more efficient in reducing methane emissions over time. Thus, as the U.S. fleet is replaced, the remaining vehicles have lower emissions profiles than their earlier counterparts. The downward trend in emissions was altered in 1992 as the size of the U.S. fleet of light duty trucks began to rise. Between 1992 and 1998 the number of light-duty trucks rose by 20 percent. Although methane emissions from passenger cars continued to decline from 1992 to 1998, that decrease was more than offset by the sharp rise in emissions from light-duty trucks during the period. Consequently, the share of total methane emissions from mobile sources attributed to light-duty trucks has risen from 27 percent in 1992 to 39 percent in 1998.

Waste Management

Although shrinking, emissions from waste management still account for about one-third of U.S. anthropogenic methane emissions. In 1998, estimated emissions from waste management were 9.9 million metric tons, the lowest in two decades (Table 13). Emissions from waste management were 11.1 million metric tons in 1990, about 1.2 million metric tons above the 1998 level. Ninety-eight percent of emissions from waste management are attributed to emissions from landfills. The remainder are associated with domestic wastewater treatment. The landfill share would be lower if more information on emissions from industrial wastewater treatment were available (see Appendix D, "Emissions Sources Excluded"). A diminishing portion of municipal solid waste is landfilled each year as recycling and composting programs expand (Figure 6). Also, increasing amounts of methane are being captured and used as an energy resource or flared to control odor or emissions of other pollutants. These developments have reduced waste management emissions.

³¹Energy Information Administration, *Renewable Energy Annual 1998*, DOE/EIA-0603(98) (Washington, DC, December 1998), p. 49.

Figure 6. U.S. Solid Waste Generated and Landfilled, 1990-1998



Source: *Biocycle*, "Nationwide Survey: The State of Garbage in America" (various years).

Landfills

U.S. Methane Emissions from Landfills, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	9.7
Change Compared to 1997 (Million Metric Tons Methane)	-0.5
Change from 1997 (Percent)	-4.9%
Change Compared to 1990 (Million Metric Tons Methane)	-1.3
Change from 1990 (Percent)	-11.5%

Methane emissions from U.S. landfills in 1998 were an estimated 9.7 million metric tons, their lowest level since the late 1970s. Estimated emissions were 5 percent below 1997 levels and 12 percent below the 1990 level (Table 18). The declines since 1990 and 1997 are almost entirely attributable to increased methane recovery at landfills. Between 1990 and 1997 the volume of municipal waste generated in the United States grew by 16

percent.³² Meanwhile, the amount of waste reaching landfills and subject to decomposition decreased from 77 percent to 61 percent, primarily due to increased curbside recycling and also to composting. As a result, methane generation from decomposition at landfills grew by just 3 percent between 1990 and 1998. A robust economy, particularly in the housing sector, resulted in a 10-percent increase in waste generation between 1997 and 1998. The percentage of waste reaching landfills was unchanged between 1997 and 1998, leading to increased volumes of waste landfilled in 1998. Because most emissions lag several years behind waste generation, methane generation rates may increase over the next several years.

The increase in methane recovery from landfills between 1990 and 1998 outstripped the slow growth in methane generated at landfills during that period. The growth in methane recovery for energy probably was caused by the prospective expiration of the Federal Section 29 (of the Internal Revenue Code) tax credit for alternative energy sources. This credit provides a subsidy roughly equivalent to 1 cent per kilowatt-hour for electricity generated using landfill gas. In order to qualify for the tax credit, gas-to-energy systems were required to be operational by June 30, 1998. There was a rush to get systems on line by the deadline, increasing the number of operational projects from an estimated 150 in 1997 to more than 200 in 1998.³³ According to the EPA's Landfill Methane Outreach Program, there are now more than 280 landfills recovering methane for energy.³⁴ Between 1997 and 1998, methane recovered for energy rose from 1.7 million metric tons to 2.2 million metric tons. Based on the continued increase in the number of projects, this number can be expected to continue to grow over the next several years. Capture and flaring of landfill gas also increased from 0.3 million metric tons in 1990 to 0.7 million metric tons in 1998.

Domestic and Commercial Wastewater Treatment

Methane emissions from domestic and commercial wastewater treatment are a function of the share of organic matter in the wastewater stream and the conditions under which it decomposes. Wastewater may be treated aerobically or anaerobically. If it is treated aerobically, methane emissions will be low. Under anaerobic conditions, methane emissions will be high. There is little data available on wastewater

³²"Nationwide Survey: The State of Garbage in America, 1998," *Biocycle* (April 1999).

³³M. McGuigan and W.G. Vogt, SCS Engineers, "Greenhouse Gas Emission Reductions from U.S. Landfill Gas Utilization Projects: Landfills to the Rescue." Presented at the 22nd Annual Landfill Gas Symposium (Orlando, FL, March 1999).

³⁴See web site www.epa.gov/lmop/projects.htm.

U.S. Methane Emissions from Domestic and Commercial Wastewater Treatment, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	0.16
Change Compared to 1997 (Million Metric Tons Methane)	*
Change from 1997 (Percent)	1.0%
Change Compared to 1990 (Million Metric Tons Methane)	0.01
Change from 1990 (Percent)	8.4%

* Less than 0.005 million metric tons.

treatment methods. Data on flaring or energy recovery from methane generated by wastewater is also sparse. Thus, emissions are scaled to population data. With the U.S. population growing slowly, methane emissions from domestic and commercial wastewater treatment are estimated to have grown by 1 percent between 1997 and 1998 and by about 8 percent since 1990.

Agricultural Sources

Of the approximately 28.8 million metric tons of methane emitted from U.S. anthropogenic sources in 1998, 30 percent (8.7 million metric tons) are attributable to agricultural activities (Table 13). Ninety-four percent of methane emissions from agricultural activities result from livestock management. About two-thirds of this share can be traced to enteric fermentation, the natural digestive process in ruminant animals. The remaining one-third of emissions can be attributed to the anaerobic decomposition of livestock wastes. A small portion of U.S. methane emissions result from crop residue burning and wetland rice cultivation.

Estimated agricultural methane emissions increased by 0.06 million metric tons between 1997 and 1998. The 8.7 million metric ton total was 0.6 million metric tons higher than in 1990. Changes in agricultural emissions are caused by changes in the size and composition of animal populations. Cattle populations increased between 1990 and 1994 but have since declined. Thus, emissions from agriculture peaked in 1994. Swine populations rose in 1997 and 1998, contributing to slightly higher emission levels in those years than in 1996.

Enteric Fermentation in Domesticated Animals

U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	5.4
Change Compared to 1997 (Million Metric Tons Methane)	*
Change from 1997 (Percent)	-0.2%
Change Compared to 1990 (Million Metric Tons Methane)	0.2
Change from 1990 (Percent)	4.7%

*Less than 0.05 million metric tons.

Methane emissions from enteric fermentation in domesticated animals are estimated at 5.4 million metric tons for 1998, essentially unchanged from estimates for 1997 and 5 percent above 1990 levels (Table 19). After escalating from 1987 through 1994, emissions from enteric fermentation stabilized in 1995 and have since declined to near 1992 levels.

Because cattle account for about 95 percent of all emissions from enteric fermentation, trends in emissions correlate with trends in cattle populations. Between 1990 and 1994, cattle populations grew, but by 1995 they had largely stabilized, and between 1995 and 1998 they decreased. Similarly, average animal size increased between 1990 and 1994 before declining in 1995 and 1996. By 1998, however, average cattle size (excluding reductions in calf size) had risen to an all-time high. On a national average basis, cows are 5.6 percent larger than they were in 1990. Milk production in 1998 also increased from 1996 and 1997 levels.³⁵

Because animal size and milk production affect energy intake, and methane emissions are a function of energy intake, the decline in emissions associated with decreased cattle populations was mostly offset by the increase in animal size and milk production. A minor contributor to decreased emissions was the slaughter of calves at a younger age. Historical population trends and associated emissions traced back to 1980 yield a cyclical pattern as cattlemen respond to market price signals by increasing and decreasing their herds. The current stage is the middle of a downward cycle.

³⁵U.S. Department of Agriculture, National Agricultural and Statistics Service, Livestock, Dairy and Poultry Branch, web site <http://usda.mannlib.cornell.edu>.

Solid Waste of Domesticated Animals

U.S. Methane Emissions from Solid Waste of Domesticated Animals, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	2.8
Change Compared to 1997 (Million Metric Tons Methane)	*
Change from 1997 (Percent)	1.5%
Change Compared to 1990 (Million Metric Tons Methane)	0.3
Change from 1990 (Percent)	10.0%

*Less than 0.05 million metric tons.

Methane emissions from the solid waste of domesticated animals are estimated at 2.8 million metric tons in 1998, up slightly from 1997 levels (0.04 million metric tons). Emissions levels remain above the 1990 level of 2.6 million metric tons (Table 20). The 1998 growth in emissions is attributable to large increases in swine waste, particularly from swine bred for market. Methane emissions from swine waste reached their highest levels in 18 years and are an increasingly important source of methane emissions, growing by 13 percent from 1990 levels.³⁶ In 1998, 49 percent of emissions from the solid waste of domesticated animals were attributable to swine waste, and 43 percent were attributable to cattle waste.

Populations of swine bred for market grew by 12 percent between 1996 and 1998.³⁷ Absent the growth in swine populations and given the relatively small fluctuations in cattle populations, emissions levels would have stabilized or shown a slight decline in 1998. About one-half of the increase in emissions not associated with swine waste is the result of increased emissions from dairy cattle waste, which are attributable to a shift in the method used for handling the solid waste of dairy cattle in six States: Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas. Between 1990 and 1994, waste management techniques in those States shifted toward liquid systems, especially anaerobic lagoons. Solid waste managed in anaerobic lagoons³⁸ realizes a much larger share of its maximum potential

³⁶Swine populations are also being concentrated in larger facilities, which are more likely to manage waste in ways that promote methane generation. As better data and estimation methods become available, this phenomenon may be reflected in upward revisions of estimated emissions from this source.

³⁷U.S. Department of Agriculture, National Agricultural and Statistics Service, Livestock, Dairy and Poultry Branch, web site <http://usda.mannlib.cornell.edu>.

³⁸A liquid-based manure management system, characterized by waste residing in water to a depth of at least 6 feet for a period ranging between 30 and 200 days.

methane production than alternative methods. Growing poultry populations also contribute to the growth of emissions.

Rice Cultivation

Estimated 1998 methane emissions from rice cultivation were 0.47 million metric tons, up by 5.6 percent from the 0.44 million metric tons estimated for 1997. The 1998 estimate is 15.6 percent higher than the 1990 level due to a 14-percent increase in area harvested. In the estimate of methane emissions from rice cultivation appearing in the previous edition of *Emissions of Greenhouse Gases in the United States*, 1997 activity data for Florida were unavailable. The estimate in this report now includes 1997 data for Florida, which have also been extrapolated to provide a 1998 estimate. The area of land harvested has increased in 5 out of 7 rice growing States (Arkansas, Texas, Louisiana, Mississippi, and Missouri) compared with 1997 estimates. The area harvested, and thus emissions, rose by 19 percent in Missouri and 12 percent in Mississippi. The total area harvested in 1998 was 6.9 percent greater than in 1997.

Burning of Crop Residues

In 1998, modest increases in corn, soybean, wheat and sugar beet production accounted for a small increase in methane emissions from the burning of crop residues. Emissions grew to almost 0.042 million metric tons, up by 1 percent from 1997 levels. This total was 10 percent above the 1990 emissions level of 0.038 million metric tons. Crop residue burning, being the smallest contributor to agricultural greenhouse gas emissions, represents on the order of 0.1 percent of total U.S. methane emissions.

Inferred methane emissions from crop residue burning are caused by changes in crop production. Overall, 1998 crop production was up by 9 percent from 1997 levels and by 14 percent from 1990 levels. However, because residue from California rice fields is burned at a much higher ratio than residue in other States, it has a disproportionate effect on emissions levels. Emissions from California rice fields decreased steadily from 1990 to 1996 as the share of residue burned declined from 99 percent to 50 percent. From 1996 to the present, the share burned has remained steady at 50 percent (only about 3 percent of crops are assumed to be burned in

other States).³⁹ Crop production in California dropped by 23 percent from 1997 levels due primarily to climatic factors: a cold, wet spring delayed early-season crop development. The burning of the California crop represented about 5 percent of total methane emissions from crop residue burning in 1998.

Industrial Sources

U.S. Methane Emissions from Industrial Sources, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Methane)	0.13
Change Compared to 1997 (Million Metric Tons Methane)	*
Change from 1997 (<i>Percent</i>)	0.5%
Change Compared to 1990 (Million Metric Tons Methane)	0.02
Change from 1990 (<i>Percent</i>)	-4.5%

*Less than 0.005 million metric tons.

Chemical Production

U.S. methane emissions from chemical production in 1998 were 0.077 million metric tons, just 0.002 million metric tons higher than 1997 levels but about 0.02 million metric tons higher than 1990 (Table 21). Since 1990, emissions levels have increased along with production levels as a consequence of steady economic growth. Production of ethylene, ethylene dichloride, and styrene all have grown by about 40 percent since 1990. Methanol has experienced the largest growth in production, growing by approximately 50 percent during the same period.

Iron and Steel Production

Estimated methane emissions from iron and steel production in 1998 were 0.056 million metric tons, down by 0.002 million metric tons from 1997 levels and 9 percent below the 1990 level of 0.062 million metric tons (Table 21). This was the third consecutive year of decline, after emissions from iron and steel production grew between 1991 and 1995. The decline in emissions can be traced to a decrease in production of pig iron since 1995.

³⁹U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. 5-20.

Table 13. U.S. Methane Emissions from Anthropogenic Sources, 1990-1998
(Million Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Energy Sources									
Coal Mining	4.26	4.12	3.97	3.34	3.36	3.43	2.95	3.16	3.15
Oil and Gas	5.70	5.92	5.99	5.97	5.99	6.08	6.10	6.25	6.27
Stationary Combustion	0.56	0.59	0.62	0.54	0.53	0.58	0.58	0.44	0.43
Mobile Sources	0.25	0.23	0.24	0.24	0.24	0.25	0.24	0.24	0.24
Total Energy Sources	10.77	10.86	10.82	10.10	10.11	10.34	9.87	10.09	10.09
Waste Management									
Landfills	10.97	10.94	10.90	10.86	10.74	10.69	10.54	10.20	9.70
Wastewater Treatment	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.16
Total Waste Management	11.12	11.09	11.05	11.01	10.90	10.85	10.70	10.36	9.87
Agricultural Sources									
Enteric Fermentation	5.17	5.30	5.39	5.47	5.62	5.62	5.47	5.42	5.41
Animal Waste	2.57	2.67	2.69	2.71	2.77	2.78	2.68	2.79	2.83
Rice Paddies	0.40	0.39	0.44	0.40	0.47	0.44	0.40	0.44	0.47
Crop Residue Burning	0.04	0.04	0.04	0.03	0.04	0.03	0.04	0.04	0.04
Total Agricultural Sources	8.18	8.40	8.56	8.62	8.91	8.87	8.60	8.69	8.74
Industrial Processes									
Industrial Processes	0.12	0.11	0.12	0.12	0.13	0.13	0.13	0.13	0.13
Total	30.19	30.47	30.55	29.85	30.05	30.20	29.30	29.27	28.84

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter. Crop residue burning—U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (annual reports). Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.83-4.84, web site www.iea.org/ipcc/invs6.htm; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html.

Methane Emissions

Table 14. U.S. Methane Emissions from Coal Mining and Post-Mining Activities, 1990-1998
(Million Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Surface Mining									
Mining	0.43	0.42	0.42	0.42	0.45	0.45	0.46	0.47	0.49
Post-Mining	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Underground Mining									
Ventilation (Gassy Mines)	2.13	2.04	2.10	1.82	1.85	1.91	1.71	1.84	1.80
Ventilation (Nongassy Mines)	0.03	0.03	0.02	0.02	0.03	0.03	0.04	0.05	0.05
Degasification	1.26	1.23	1.17	1.05	1.06	1.21	1.02	1.06	1.16
Post-Mining	0.64	0.61	0.61	0.53	0.60	0.60	0.62	0.63	0.63
Methane Recovery for Energy (-)	0.25	0.25	0.39	0.53	0.67	0.80	0.94	0.94	1.02
Net Emissions	4.26	4.12	3.97	3.34	3.36	3.43	2.95	3.16	3.15

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Coal production numbers from Energy Information Administration, *Coal Production*, DOE/EIA-0118 (Washington, DC, various years), and *Coal Industry Annual*, DOE/EIA-0584 (Washington, DC, 1995-1997). Methane recovery rates from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress* (Washington, DC, April 1993), pp. 3-19-3-24; and U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997). Ventilation data for 1985, 1988, 1990, and 1993 provided by G. Finfinger, U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center. Ventilation data for 1994 and 1996-1998 provided by U.S. Environmental Protection Agency, Climate Protection Division, Coalbed Methane Outreach Program.

Table 15. U.S. Methane Emissions from Oil and Gas Operations, 1990-1998
(Million Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Natural Gas Systems									
Production	1.47	1.49	1.49	1.51	1.55	1.57	1.58	1.65	1.67
Processing	0.65	0.71	0.70	0.71	0.71	0.72	0.73	0.71	0.71
Transmission and Storage	2.10	2.21	2.23	2.15	2.11	2.14	2.11	2.20	2.20
Distribution	1.36	1.39	1.44	1.48	1.49	1.52	1.55	1.55	1.55
Total	5.58	5.80	5.86	5.85	5.86	5.95	5.97	6.12	6.14
Oil Wells	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Oil Refining and Transportation	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09
Total	5.70	5.92	5.99	5.97	5.99	6.08	6.10	6.25	6.27

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: 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), Appendix A; *World Oil* (February issue, various years); American Gas Association, *Gas Facts* (various years); Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (various years); Radian Corporation, *Global Emissions of Methane from Petroleum Sources* (February 1992); Energy Information Administration, *Annual Energy Review 1998*, DOE/EIA-0384(98) (Washington, DC, July 1999); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Table 16. U.S. Methane Emissions from Stationary Combustion Sources, 1990-1998
(Thousand Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Residential									
Coal	*	*	*	*	*	*	*	*	*
Distillate Fuel	4	4	4	5	4	4	5	5	5
Natural Gas	4	4	5	5	5	5	5	5	4
LPG	*	*	*	*	*	*	1	1	*
Wood	512	541	569	483	474	526	525	382	377
Total	521	550	578	493	483	535	535	392	387
Commercial									
Coal	1	1	1	1	1	1	1	1	1
Fuel Oil	1	1	1	1	1	1	1	*	*
Natural Gas	3	3	3	3	3	4	4	4	4
LPG	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*
Total	5	5	5	5	5	5	5	5	5
Industrial									
Coal	7	6	6	6	6	6	6	6	6
Fuel Oil	1	1	1	1	1	1	1	1	1
Natural Gas	11	12	12	13	13	14	14	14	14
LPG	2	2	3	2	3	3	3	3	3
Wood	4	4	4	4	5	5	5	5	5
Total	26	26	26	27	28	28	29	28	28
Electric Utility									
Coal	10	10	10	10	10	10	11	11	11
Fuel Oil	1	1	1	1	1	*	*	*	1
Natural Gas	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*
Total	11	11	11	11	11	11	12	12	12
Total All Fuels									
Coal	17	17	17	17	17	17	18	18	18
Fuel Oil	7	7	7	7	7	6	7	6	6
Natural Gas	19	20	20	21	21	22	23	23	22
LPG	3	3	3	3	3	3	4	4	3
Wood	517	545	573	488	478	530	530	387	383
Total	563	591	620	536	527	579	581	437	432

*Less than 500 metric tons of methane.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, web site www.epa.gov/ttn/chief; Energy Information Administration, *State Energy Data Report 1996*, DOE/EIA-0214(96) (Washington, DC, October 1998); *Monthly Energy Review*, DOE/EIA-0035(99/09) (Washington, DC, September 1999); and *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998), p. 267.

Methane Emissions

Table 17. U.S. Methane Emissions from Mobile Sources, 1990-1998
(Thousand Metric Tons of Methane)

Item	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Motor Vehicles									
Passenger Cars	142	132	131	126	117	109	107	105	104
Buses	1	1	1	1	1	1	1	1	1
Motorcycles	4	4	4	4	4	4	4	4	4
Light-Duty Trucks	63	63	63	75	85	99	92	91	92
Other Trucks	12	12	12	13	14	14	15	15	16
Total	222	212	212	219	221	228	219	217	217
Other Transport	23	23	24	22	22	23	23	21	21
Total Transport	245	235	235	241	243	251	242	238	238

P = preliminary data.

Sources: Calculations based on vehicle miles traveled from U.S. Department of Transportation, *Federal Highway Statistics*, various years, Table VM-1. Vehicle emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.65-1.75, web site www.iea.org/ipcc/invs6.htm. Distribution of passenger car and light duty truck fleet model years for 1983, 1985, 1988, 1991, and 1994 according to data in the Energy Information Administration's "Residential Transportation Energy Consumption Surveys" for those years. Distribution for passenger cars and light duty trucks in other years computed by interpolation. Distribution of bus and other truck fleet according to model year computed assuming 10-percent attrition per annum of pre-1983 fleet for each year after 1984.

Table 18. U.S. Methane Emissions from Landfills, 1990-1998
(Million Metric Tons of Methane)

Type	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Methane Generated	12.2	12.4	12.5	12.5	12.6	12.6	12.6	12.6	12.6
Methane Recovered for Energy	0.9	1.0	1.0	1.1	1.3	1.3	1.4	1.7	2.2
Methane Assumed Flared	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.7
Net Emissions	11.0	10.9	10.9	10.9	10.7	10.7	10.5	10.2	9.7

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Sources: Municipal solid waste landfilled from *Biocycle*, "Nationwide Survey: The State of Garbage in America" (1989-1996). Emissions calculations based on S.A. Thorneloe et al., "Estimate of Methane Emissions from U.S. Landfills," Prepared for the U.S. Environmental Protection Agency, Office of Research and Development, in departmental review (April 1994), and D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environmental Change* (December 1992), pp. 311-328. Methane recovered and flared from S.A. Thorneloe, "Landfill Gas Recovery Utilization—Options and Economics," presented at the Sixteenth Annual Conference by the Institute of Gas Technology on Energy from Biomass and Wastes, Orlando, Florida (March 5, 1992); J. Pacey, "Methane Recovery from Landfills," presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium, Washington, DC (June 27-29, 1995); and M. McGuigan and W.G. Vogt, SCS Engineers, "Greenhouse Gas Emission Reductions From U.S. Landfill Gas Utilization Projects: Landfills to the Rescue," presented at the 22nd Annual Landfill Gas Symposium (Orlando, FL, March 1999).

Table 19. U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-1998
(Million Metric Tons of Methane)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Cattle	4.88	5.01	5.11	5.19	5.35	5.36	5.22	5.17	5.16
Sheep	0.15	0.15	0.14	0.14	0.13	0.12	0.11	0.10	0.10
Pigs	0.08	0.09	0.09	0.09	0.09	0.09	0.08	0.09	0.09
Goats	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Horses	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05
Total	5.17	5.30	5.39	5.47	5.62	5.62	5.47	5.42	5.41

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Cattle, sheep, and pig population data provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Service. Goat and horse population figures extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982, 1987, and 1992. Emissions calculations based on U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), pp. 159-161, web site www.epa.gov/globalwarming/inventory/1999-inv.html; and 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), pp. 271-284.

Table 20. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1990-1998
(Thousand Metric Tons of Methane)

Type of Animal	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Cattle	1,163	1,184	1,196	1,208	1,230	1,232	1,216	1,212	1,216
Beef Cattle	249	264	271	278	288	287	277	276	274
Dairy Cattle	914	920	924	930	943	945	939	936	943
Swine	1,234	1,306	1,312	1,308	1,343	1,338	1,259	1,360	1,392
Market Swine	861	912	924	918	958	952	895	981	1,026
Breeding Swine	373	394	388	390	385	387	364	379	366
Poultry	157	161	167	179	184	189	193	197	203
Caged Layers	83	84	86	88	89	89	91	92	97
Broilers	73	77	81	91	95	100	102	105	107
Other Animals	18	17	17	17	17	17	17	17	18
Sheep	5	5	5	5	4	4	4	4	3
Goats	1	1	1	1	1	1	1	1	1
Horses	12	11	11	11	12	12	13	13	13
Total	2,571	2,669	2,692	2,712	2,774	2,776	2,684	2,786	2,829

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Population data for horses and goats extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982, 1987, and 1992. Population data for all other animals from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress* (Washington, DC, April 1993), p. 6-8. Cattle sizes adjusted by annual slaughter weight from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Maximum methane production, and waste management systems used from L.M. Safley, M.E. Casada, et al., *Global Methane Emissions from Livestock and Poultry Manure* (Washington, DC: U.S. Environmental Protection Agency, February 1992), pp. 24-27, and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1994*, EPA-230-496-006 (Washington, DC, November 1995), Appendix D. General methane conversion factors from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 4.25, web site www.iea.org/ipcc/invs6.htm. State methane conversion factors for dairy cattle from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), pp. 162-164, web site www.epa.gov/globalwarming/inventory/1999-inv.html.

Methane Emissions

Table 21. U.S. Methane Emissions from Industrial Processes, 1990-1998
(Thousand Metric Tons of Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Chemical Production									
Ethylene	17	18	19	19	20	19	21	22	23
Ethylene Dichloride	3	2	3	3	3	3	3	4	4
Styrene	15	15	16	18	20	21	22	21	21
Methanol	8	8	7	10	10	10	11	11	11
Carbon Black	14	13	15	16	16	17	17	17	18
Total	56	57	60	66	70	70	74	75	77
Iron and Steel Production									
Coke ^a	11	9	9	9	8	9	8	7	7
Sinter	6	5	6	6	6	6	6	6	6
Pig Iron	45	40	43	43	44	46	44	45	43
Total	62	54	57	58	59	61	59	58	56
Total Industrial Processes ...	117	111	117	124	129	131	132	132	133

^aBased on total U.S. production of metallurgical coke, including non-iron and steel uses.

P = preliminary data.

Note: Totals may not equal sum of components due to independent rounding.

Sources: American Iron and Steel Institute, *Annual Statistical Report* (Washington, DC, various years); Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years); and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.23, web site www.iea.org/ipcc/invs6.htm.

4. Nitrous Oxide Emissions

Overview

U.S. Anthropogenic Nitrous Oxide Emissions, 1990-1998

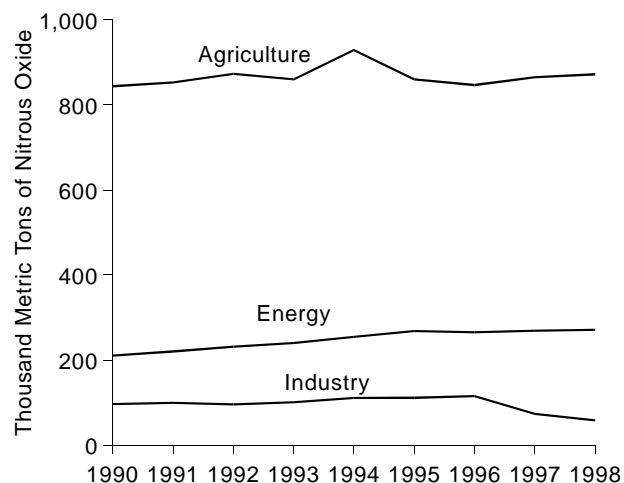
	Nitrous Oxide	Carbon Equivalent
Estimated 1998 Emissions (Million Metric Tons)	1.220	103.2
Change Compared to 1997 (Million Metric Tons)	-0.006	-0.5
Change from 1997 (Percent)	-0.5%	-0.5%
Change Compared to 1990 (Million Metric Tons)	0.052	4.4
Change from 1990 (Percent)	4.5%	4.5%

Estimated U.S. anthropogenic nitrous oxide emissions totaled 1.2 million metric tons in 1998, about 0.5 percent less than in 1997 but still 4 percent above 1990 levels (Table 22). Nearly all the increase from 1990 levels can be attributed to emissions from the nitrogen fertilization of agricultural soils, which for the first time included emissions from the biological fixation of nitrogen in agricultural soils, and emissions from mobile combustion, which grew by 33 percent between 1990 and 1995. Emissions of nitrous oxide from mobile combustion stabilized from 1995 through 1998, as growth in the light-duty truck fleet slowed and the next generation of lower-emitting catalytic converters was introduced. These trends in emissions from mobile combustion can be expected to lead to lower emissions from this source over the next few years.

Agricultural activities are the largest source of U.S. anthropogenic nitrous oxide emissions—primarily, the nitrogen fertilization of agricultural soils. Small quantities of nitrous oxide are also released from the burning of crop residues. Estimated emissions of nitrous oxide from agricultural sources were 0.9 million metric tons in 1998, about 1 percent above 1997 levels and 3 percent above 1990 levels (Figure 7). There are, however, large

uncertainties connected with the emissions consequences of adding nitrogen to agricultural soils (see box on page 42).

Figure 7. U.S. Emissions of Nitrous Oxide by Source, 1990-1998



Source: Estimates presented in this chapter.

Principal Sources of U.S. Anthropogenic Nitrous Oxide Emissions, 1990-1998

Source	Thousand Metric Tons Nitrous Oxide		Percent Change	
	1990	1998	1990-1998	1997-1998
Energy Use	210	271	28.7%	0.8%
Agriculture	844	872	3.3%	0.8%
Industrial	96	58	-39.5%	-20.2%

The second-largest source of anthropogenic nitrous oxide emissions is energy consumption, which includes mobile source combustion from passenger cars, buses, motorcycles, and trucks and stationary source combustion from commercial, residential, industrial, and

**Inclusion of Additional Sources
Produces Higher Estimates of U.S. Nitrous Oxide Emissions**

This edition of *Emissions of Greenhouse Gases in the United States* provides annual estimates of U.S. nitrous oxide emissions from the nitrogen fertilization of agricultural soils that are approximately 50 percent larger than those in previous editions. For 1998, the additional 0.232 million metric tons of nitrous oxide are equivalent to 20 million metric tons of carbon or 1.1 percent of all U.S. greenhouse gas emissions. For 1990, the additional 0.198 million metric tons of nitrous oxide are equivalent to 17 million metric tons of carbon or 1.0 percent of all U.S. Greenhouse gases (see Table ES2). For a discussion on the estimation method used, see Appendix A.

Previously, estimated emissions from nitrogen fertilization of agricultural soils included direct emissions from the use of commercial synthetic fertilizers, the application of animal manure, crop residues, and emissions from soil mineralization. In addition, previous emissions estimates included indirect emissions from leaching and atmospheric deposition. The

addition of nitrous oxide emissions from the biological fixation of nitrogen in agricultural soils to this year's estimates increases total emissions of nitrous oxide from the nitrogen fertilization of soils by 48 percent in 1990 and 57 percent in 1998 (see Table 25).

Estimates of emissions from fertilizer use are highly uncertain. Models used for estimation are based on limited sources of experimental data. The uncertainty increases when moving from emissions associated with animal manure to soil mineralization and atmospheric deposition, where both estimating emissions and partitioning emissions between anthropogenic and biogenic sources become increasingly difficult.

In addition, this year's report has been revised to include nitrous oxide emissions from the consumption of wood in the residential, industrial, and electric utility sectors, pursuant to the *1996 Revised IPCC Guidelines for National Greenhouse Gas Inventories*.

electric utility energy use. Energy use was responsible for the release of 0.3 about million metric tons of nitrous oxide in 1998, about 2 percent higher than in 1997 but 29 percent higher than in 1990.

Industrial production of adipic acid and nitric acid, which releases nitrous oxide as a byproduct, accounted for emissions of about 0.06 million metric tons of nitrous oxide in 1998, a 39-percent decrease from 1990 levels and a 20-percent decline from 1997 levels (Table 22).

Energy Use

Nitrous oxide emissions from both mobile and stationary sources are byproducts of fuel combustion. Estimated 1998 energy-related emissions were about 0.3 million metric tons, 22 percent of total U.S. anthropogenic nitrous oxide emissions (Table 22). Emissions from energy use are dominated by mobile combustion (82 percent of 1998 totals).

Mobile Combustion

Nitrous oxide emissions from mobile source combustion in 1998 were 0.2 million metric tons, about 1 percent above 1997 levels (Table 23). In addition to emissions from passenger cars and light-duty trucks,

U.S. Nitrous Oxide Emissions from Energy Use, 1990-1998

Estimated 1998 Emissions (Thousand Metric Tons Nitrous Oxide)	270.9
Change Compared to 1997 (Thousand Metric Tons Nitrous Oxide)	2.1
Change from 1997 (Percent)	0.8%
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	60.4
Change from 1990 (Percent)	28.7%

emissions from air, rail, and marine transportation and from farm and construction equipment are also included in the estimates. Ninety-five percent of the emissions can be attributed to motor vehicles. The rapid growth in emissions between 1990 and 1995 is a function of increasing motor vehicle use, the shifting composition of the light-duty vehicle fleet toward light trucks, and the gradual replacement of low emitting pre-1983 vehicles in the fleet with higher emitting post-1983 vehicles. The shift to advanced three-way catalytic converters in 1996, 1997, and 1998 model year cars has stabilized emissions from this source.

Nitrous oxide emissions from motor vehicles are caused primarily by the conversion of pollutant nitrogen oxides (NO_x) into nitrous oxide (N₂O) by vehicle catalytic converters. The normal operating temperature of catalytic converters is high enough to cause the thermal decomposition of nitrous oxide. Consequently, it is probable that nitrous oxide emissions result primarily from “cold starts” of motor vehicles and from catalytic converters that are defective or operating under abnormal conditions. This implies that the primary determinant of the level of emissions is motor vehicle operating conditions; however, different types of catalytic converters appear to differ systematically in their emissions, and emissions probably vary with engine size. Consequently, emissions also depend on the “mix” of vehicle age and type on the road.

Stationary Combustion

During combustion, nitrous oxide is produced as a result of chemical interactions between nitrogen oxides (mostly NO₂) and other combustion products. With most conventional stationary combustion systems, high temperatures destroy almost all nitrous oxide, limiting the quantity that escapes; therefore, emissions from these systems are typically low. In 1998, estimated nitrous oxide emissions from stationary combustion sources were 0.05 million metric tons, about 1 percent higher than in 1997 and 10 percent higher than in 1990 (Table 24). Nearly all the emissions increase from this source between 1990 and 1998 can be attributed to coal-fired electricity generation, which grew in response to the growing demand for electricity and improved operations at coal-fired power plants. Coal-fired combustion systems produced 61 percent of the 1998 emissions of nitrous oxide from stationary combustion, and electric utilities accounted for 56 percent of all stationary combustion emissions.

Agriculture

On a global scale, agricultural practices contribute approximately 70 percent of anthropogenic nitrous oxide emissions.⁴⁰ Similarly, in the United States, agricultural activities were responsible for 71 percent of 1998 nitrous oxide emissions. About three-quarters of agricultural emissions are associated with the application of commercial and animal-manure-based fertilizers. Nearly all the remaining agricultural emissions can be

U.S. Nitrous Oxide Emissions from Agriculture, 1990-1998

Estimated 1998 Emissions (Thousand Metric Tons Nitrous Oxide)	872.0
Change Compared to 1997 (Thousand Metric Tons Nitrous Oxide)	6.9
Change from 1997 (Percent)	0.8%
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	28.1
Change from 1990 (Percent)	3.3%

traced to the management of the solid waste of domesticated animals. The disposal of crop residues by burning also produces nitrous oxide that is released into the atmosphere; however, the amount is relatively minor, at 0.002 million metric tons or 0.2 percent of total U.S. emissions of nitrous oxide from agricultural sources in 1998. Nitrous oxide emissions from agricultural activities grew by 3 percent between 1990 and 1998.

Nitrogen Fertilization of Agricultural Soils

Nitrogen uptake and nitrous oxide emissions occur naturally as a result of nitrification and denitrification processes in soil and crops, generally through bacterial action. When nitrogen compounds are added to the soil, bacterial action is stimulated, and emissions generally increase, unless the application precisely matches plant uptake and soil capture.⁴¹ Nitrogen may be added to the soil by synthetic or organic fertilizers, nitrogen-fixing crops, and crop residues. Nitrogen-rich soils, called “histosols,” may also stimulate emissions.

Adding excess nitrogen to the soil also enriches ground and surface waters, such as rivers and streams, which generate indirect emissions of nitrous oxide. Additional indirect emissions occur from “atmospheric deposition,” in which soils emit other nitrogen compounds that react to form nitrous oxide in the atmosphere. EIA estimates that a total of 0.6 million metric tons of nitrous oxide were released into the atmosphere as a result of direct and indirect emissions associated with fertilization

⁴⁰A.R. Mosier, “Nitrous Oxide Emissions from Agricultural Soils,” in A.R. van Amstel (ed.), *International IPCC Workshop Proceedings: Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control* (Bilthoven, Netherlands: RIVM, 1993), p. 277.

⁴¹A.F. Bouwman, “Exchange of Greenhouse Gases Between Terrestrial Ecosystems and the Atmosphere,” in A.F. Bouwman (ed.), *Soils and the Greenhouse Effect* (New York, NY: John Wiley and Sons, 1990).

Nitrous Oxide Emissions

practices in 1998 (Table 25). Estimated emissions increased by 4 percent compared with 1990 and 2 percent compared with 1997.

For the first time, this year's edition of *Emissions of Greenhouse Gases in the United States* includes estimates of nitrous oxide emissions from biological fixation of nitrogen in agricultural soils, which added about 0.2 million metric tons of nitrous oxide emissions to 1998 estimates. The addition of this emissions source raised the 1990 estimates of emissions from the nitrogen fertilization of agricultural soils by 48 percent and the 1998 estimate by 57 percent.

Crop Residue Burning

When crop residues are burned, the incomplete combustion of agricultural waste results in the production of nitrous oxide as well as methane (discussed in Chapter 3). In 1998, estimated emissions of nitrous oxide from crop residue burning were 0.002 million metric tons, up by 1 percent from 1997 levels (Table 22). As with methane emissions from crop residue burning, the increase from the previous year's emissions level was negligible due to a very small increase in crop production. Although emissions from this source remain very small, at about 0.2 percent of all U.S. nitrous oxide emissions, they have grown by 21 percent since 1990, largely because of a 43-percent increase in soybean production and a 19-percent increase in corn production since 1990.

Solid Waste of Domesticated Animals

Estimated 1998 nitrous oxide emissions from animal waste were about 0.2 million metric tons, down by 1 percent from 1997 levels but still 2 percent higher than 1990 levels (Table 26), making animal waste the second-largest U.S. agricultural source of nitrous oxide emissions, after nitrogen fertilization of soils. Nitrous oxide emissions from animal waste are dominated by emissions from cattle waste, which account for 94 percent of emissions from the solid waste of domesticated animals. Thus, changes in estimated emissions have largely been caused by changes in cattle populations, growing between 1990 and 1994, stabilizing in 1995, and declining in 1996, 1997, and 1998. The decrease in cattle populations in 1998, however, was largely offset by an increase in average cattle size. The increase in animal size resulted in the production of more waste per animal and a slightly lower overall emission rate for 1998.

Nitrous oxide is released as part of the microbial denitrification of animal manure. The total volume of

nitrous oxide emissions is a function of animal size and manure production, the amount of nitrogen in the animal waste, and the method of managing the animal waste. Waste managed by a solid storage or pasture range method may emit 20 times the nitrous oxide per unit of nitrogen content than does waste managed in anaerobic lagoon and liquid systems. Generally, solid waste from feedlot beef cattle is managed with the solid storage or pasture range method, accounting for the majority of nitrous oxide emissions. Over the past few years, the solid waste of dairy cattle in Arizona, Florida, Nevada, North Carolina, North Dakota, and Texas has been managed in anaerobic lagoon and liquid systems, helping to decrease nitrous oxide emissions to near-1990 levels. Solid waste from swine is generally managed in anaerobic lagoons and other liquid systems. Anaerobic digestion yields methane emissions but only negligible amounts of nitrous oxide.

Waste Management

U.S. Nitrous Oxide Emissions from Waste Management, 1990-1998

Estimated 1998 Emissions (Thousand Metric Tons Nitrous Oxide)	18.4
Change Compared to 1997 (Thousand Metric Tons Nitrous Oxide)	0.1
Change from 1997 (Percent)	0.6%
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	1.8
Change from 1990 (Percent)	11.1%

Nitrous oxide emissions from waste management are estimated at about 0.2 million metric tons for 1998, or 2 percent of all U.S. anthropogenic nitrous oxide emissions (Table 22). During 1998, emissions from human sewage in wastewater were responsible for 96 percent of the estimated emissions from this source, and the remainder was associated with waste combustion. Estimated emissions from waste management grew by 11 percent between 1990 and 1998 and by 1 percent between 1997 and 1998. Because of the lack of reliable data and an effective estimation method, no estimate of emissions from industrial wastewater was calculated, leaving estimated emissions from waste management lower than they otherwise would be had estimation methods been available.

Industrial Wastewater Treatment

Nitrous oxide emissions from industrial wastewater treatment are the result of nitrification and denitrification, with denitrification having the largest effect. Denitrification is inhibited by the presence of oxygen. A carbon source is also required for denitrification.

Because data on volumes of wastewater generated and the methods for treating wastewater are limited, EIA does not present estimates of nitrous oxide emissions from industrial wastewater. There are, however, ongoing research efforts to characterize the volume of wastewater generated by key industries and the typical methods of treatment.

In September 1997, the U.S. Environmental Protection Agency's Office of Research and Development published the report, *Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment*. The report provides nitrous oxide emissions factors for wastewater degrading under anaerobic conditions, based on field tests at three meat processing plants; however, it does not provide an overall national estimate of nitrous oxide emissions from industrial wastewater. There is anecdotal evidence that very little industrial wastewater is treated anaerobically, thus limiting the potential size of emissions from this source.

Waste Combustion

In 1998, estimated nitrous oxide emissions from waste combustion were 0.001 million metric tons, down by 8 percent from 1997 levels and 12 percent below 1990 levels. The total volume of waste generated in the United States increased by 28 percent between 1990 and 1998. In 1990, the share of waste burned was 11 percent. After dropping to 10 percent in 1991, the share of waste that was incinerated in the United States remained relatively stable through 1996. Thus, increasing levels of waste generation led to an increase in the total volume of waste incinerated and higher nitrous oxide emissions. The share of waste incinerated dropped from 10 percent in 1996 to 8 percent in 1998 as the share of waste recycled increased, with a corresponding drop in estimated nitrous oxide emissions.⁴²

Human Sewage in Wastewater

Nitrous oxide is emitted from wastewater that contains nitrogen-based organic materials, such as those found

in human or animal waste. It is produced by two natural processes: nitrification and denitrification. Nitrification, an aerobic process, converts ammonia into nitrate; denitrification, an anaerobic process, converts nitrate to nitrous oxide. Factors that influence the amount of nitrous oxide generated from wastewater include temperature, acidity, biochemical oxygen demand (BOD),⁴³ and nitrogen concentration.

In 1998, nitrous oxide emissions from wastewater were about 0.02 million metric tons, a 1-percent increase from 1997 levels and a 12-percent increase from the 1990 level (Table 22). Estimates of nitrous oxide emissions from human waste correspond to population size and per capita protein intake. U.S. per capita protein intake rose steadily between 1980 and 1994, before leveling out. Data on protein intake are taken from the United Nations Food and Agriculture Organization (FAO). The FAO ended its time-series on protein intake with 1996 data. EIA has assumed that protein intake levels have been stable since then but trends seem to indicate that protein intake increases with economic growth and may now be above 1996 levels. The growth in emissions from this source since 1990 is attributable to a 9-percent increase in population and a 3.7-percent increase in per capita protein intake.⁴⁴

Industrial Processes

U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-1998

Estimated 1998 Emissions (Thousand Metric Tons Nitrous Oxide)	58.4
Change Compared to 1997 (Thousand Metric Tons Nitrous Oxide)	-14.8
Change from 1997 (Percent)	-20.2%
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	-38.1
Change from 1990 (Percent)	-39.5%

Nitrous oxide is emitted as a byproduct of certain chemical production processes. Table 27 provides estimates of emissions from the production of adipic acid and nitric acid, the two principal known sources. Emissions from the combination of these two processes were 0.058 million metric tons in 1998, a decrease of 0.038 million metric tons (39 percent) since 1990 and

⁴²"Nationwide Survey: The State of Garbage In America," *Biocycle Magazine* (1988-1999).

⁴³Biochemical oxygen demand is a measure of the organic content within the wastewater that is subject to decomposition.

⁴⁴Food and Agriculture Organization of the United Nations, web site apps.fao.org/lim500/nph-wrap.pl.

0.015 million metric tons (20 percent) since 1997. All the decline can be traced to decreased emissions from adipic acid production, which dropped as emissions controls added to the third of four manufacturing plants during early 1997 were in place for the entire year in 1998.

Adipic Acid Production

Adipic acid is a fine white powder that is used primarily in the manufacture of nylon fibers and plastics, such as carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizers for polyvinyl chloride and polyurethane resins, lubricants, insecticides, and dyes.

In the United States, three companies, which operate a total of four plants, manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid. Nitrous oxide is an intrinsic byproduct of this chemical reaction. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.⁴⁵ Between 1990 and 1994, emissions from adipic acid manufacture grew slowly until they reached 0.067 million metric tons (Table 27). After remaining relatively stable in 1995 and 1996, emissions dropped sharply to just 0.012 million metric tons in 1998. Through 1996, two of the four plants that manufacture adipic acid controlled emissions by thermally decomposing the nitrous oxide. This technique eliminates 98 percent of potential emissions from the plants.⁴⁶

During the first quarter of 1997, a third plant had installed emissions controls, increasing the share of adipic acid production employing emissions abatement controls from 74 percent in 1996 to an annual average of 92 percent in 1997. Emissions from 97 percent of 1998 U.S. adipic acid production were controlled.⁴⁷ Consequently, estimated emissions of nitrous oxide from uncontrolled adipic acid production plants decreased from 0.021 million metric tons in 1997 to 0.007 million metric tons in 1998, while 1998 emissions of nitrous oxide from controlled plants remained constant at 0.005 million metric tons.

Nitric Acid Production

Nitric acid, a primary ingredient in fertilizers, usually is manufactured by oxidizing ammonia (NH_3) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation. The 9.4 million short tons of nitric acid manufactured in 1998 resulted in estimated emissions of 0.047 million metric tons of nitrous oxide (Table 27). This estimate was 1 percent lower than 1997 levels but 18 percent higher than 1990 levels. The emissions factor used to make this estimate was based on measurements at a single DuPont plant, which indicated an emissions factor of 2 to 9 grams of nitrous oxide emitted per kilogram of nitric acid manufactured, an uncertainty of about 50 percent (see Appendix A).

⁴⁵M.H. Thiemens and W.C. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 1991).

⁴⁶Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

⁴⁷R.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).

Table 22. Estimated U.S. Emissions of Nitrous Oxide, 1990-1998
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Agriculture									
Nitrogen Fertilization of Soils	614	620	638	621	686	616	607	628	637
Crop Residue Burning	1	1	2	1	2	1	2	2	2
Solid Waste of Domesticated Animals	229	231	234	238	241	243	239	235	233
Total	844	853	873	860	929	860	847	865	872
Energy Use									
Mobile Sources	166	176	186	195	209	222	217	220	222
Stationary Combustion	44	44	44	45	46	46	48	48	49
Total	210	220	231	240	255	268	265	269	271
Waste Management									
Waste Combustion	1	1	1	1	1	1	1	1	1
Human Sewage in Wastewater	16	16	16	16	17	17	17	17	18
Total	17	17	17	17	18	18	18	18	18
Industrial Sources	96	99	95	100	110	111	115	73	58
Total	1,167	1,189	1,217	1,218	1,312	1,257	1,245	1,225	1,220

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Crop residue burning—U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (annual reports). Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.81-4.94, web site www.iea.org/ipcc/invs6.htm; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html. Emissions from human sewage—Food and Agriculture Organization of the United Nations, web site, apps.fao.org/lim500/nph-wrap.pl; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html.

Table 23. U.S. Nitrous Oxide Emissions from Mobile Sources, 1990-1998
(Thousand Metric Tons of Nitrous Oxide)

Item	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Motor Vehicles									
Passenger Cars	99	107	115	112	111	108	109	109	109
Buses	*	*	*	*	*	*	*	*	*
Motorcycles	*	*	*	*	*	*	*	*	*
Light-Duty Trucks	49	51	53	64	79	94	88	91	93
Other Trucks	6	6	6	6	7	7	7	8	8
Total	154	164	174	183	197	210	205	208	210
Other Mobile Sources	12	12	12	12	12	12	13	12	12
Total Mobile Sources	166	176	186	195	209	222	217	220	222

*Less than 500 metric tons of nitrous oxide.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Calculations based on vehicle miles traveled from U.S. Department of Transportation, *Federal Highway Statistics* (various years), Table VM-1. Passenger car and light-duty truck emissions coefficients from U.S. Environmental Protection Agency, Office of Air and Radiation, *Emissions of Nitrous Oxide From Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996*, EPA-420-R-98-009 (Washington DC, August 1998). Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.64-1.68, web site www.iea.org/ipcc/invs6.htm.

Nitrous Oxide Emissions

Table 24. U.S. Nitrous Oxide Emissions from Stationary Combustion Sources, 1990-1998
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Commercial	1	1	1	1	1	1	1	1	1
Coal	*	*	*	*	*	*	*	*	*
Fuel Oil	1	1	*	*	*	*	*	*	*
Natural Gas	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*
Residential	4	4	4	4	3	4	4	3	3
Coal	*	*	*	*	*	*	*	*	*
Fuel Oil	1	1	1	1	1	1	1	1	1
Natural Gas	*	*	*	*	*	*	1	*	*
Industrial	10	9	10	10	10	10	10	10	10
Coal	4	4	4	4	4	4	3	3	3
Fuel Oil	5	5	5	5	5	5	5	6	6
Natural Gas	1	1	1	1	1	1	1	1	1
Electric Utility	24	24	24	25	25	25	26	27	27
Coal	23	23	23	24	24	24	25	26	26
Fuel Oil	1	1	1	1	1	*	*	*	1
Natural Gas	*	*	*	*	*	*	*	*	*
Fuel Totals									
Coal	27	26	27	27	27	28	29	30	30
Fuel Oil	7	7	7	7	7	7	7	7	8
Natural Gas	2	2	2	2	2	2	2	2	2
Wood	9	9	9	9	9	10	10	9	9
Total (All Fuels)	44	44	44	45	46	46	48	48	49

*Less than 500 metric tons of nitrous oxide.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.50, web site www.iaa.org/ipcc/invs6.htm. Energy consumption data from Energy Information Administration, *State Energy Data Report 1996*, DOE/EIA-0214(96) (Washington, DC, October 1998); and *Monthly Energy Review*, DOE/EIA-0035(99/09) (Washington, DC, September 1999).

Table 25. U.S. Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils, 1990-1998
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Direct Emissions									
Nitrogen Fertilizers	179	182	183	193	195	173	159	159	159
Animal Manure	6	6	6	6	6	6	6	6	6
Crop Residues	92	90	104	83	112	93	106	114	116
Soil Mineralization	7	7	7	7	7	7	7	7	7
Biological Fixation in Crops . . .	198	201	203	190	222	210	212	224	232
Total	482	486	503	480	543	488	489	510	520
Indirect Emissions									
Soil Leaching	112	114	115	121	122	109	100	101	100
Atmospheric Deposition	19	20	20	21	21	19	17	17	17
Total	132	134	135	142	143	128	118	118	118
Total	614	620	638	621	686	616	607	628	637

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.89-4.107, web site www.iea.org/ipcc/invs6.htm. Total nitrogen content of U.S. commercial fertilizer consumption—1988-1994, Tennessee Valley Authority; 1995-1998, Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, DC, various years). Manure application based on cattle population data provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Service. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993). Manure production and waste management systems used from L.M. Safley, M.E. Casada et al., *Global Methane Emissions From Livestock and Poultry Manure* (Washington, DC, February 1992), and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1994* (Washington, DC, November 1995).

Nitrous Oxide Emissions

Table 26. U.S. Nitrous Oxide Emissions from Solid Waste of Domesticated Animals, 1990-1998
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Cattle	215	217	219	223	226	228	225	221	218
Swine	5	5	5	5	6	6	5	6	6
Poultry	3	3	3	4	4	4	4	4	4
Sheep	3	3	3	3	3	3	3	2	2
Goats	1	1	1	1	1	1	1	1	1
Horses	1	1	1	1	1	1	1	1	1
Total	229	231	234	238	241	243	239	235	233

P = preliminary data.

Notes: Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Nitrogen content of waste by species, manure management systems, and emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.89-4.107, web site www.iea.org/ipcc/invs6.htm. Animal populations from U.S. Department of Agriculture, National Agricultural Statistics Service, web site www.mannlib.usda.edu.

Table 27. U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-1998
(Thousand Metric Tons of Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Adipic Acid									
Controlled Sources	3	4	3	3	4	4	4	5	5
Uncontrolled Sources	54	56	52	56	63	63	65	21	7
Total	57	60	55	59	67	67	69	26	12
Nitric Acid	40	40	41	41	43	44	46	47	47
Total Known Industrial Sources	96	99	95	100	110	111	115	73	58

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Sources: Data sources and methods documented in Appendix A.

5. Halocarbons and Other Gases

Overview

Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Carbon Equivalent)	39.5
Change Compared to 1997 (Million Metric Tons Carbon Equivalent)	1.1
Change from 1997 (<i>Percent</i>)	3.0%
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	17.1
Change from 1990 (<i>Percent</i>)	76.1%

Beyond the three principal gases (carbon dioxide, methane, and nitrous oxide) that account for some 98 percent of U.S. greenhouse gas emissions weighted by global warming potential (GWP), there are an array of gases that affect climate in diverse ways. Some are engineered chemicals that do not occur in nature. The consequences of their emissions for the climate are considerably less than those of the principal greenhouse gases, for various reasons. In some cases, the quantities emitted are small; in other cases, the impact of a particular gas on the climate may be difficult to quantify or measure.

The Kyoto Protocol has crystallized these ambiguities by defining three classes of gases that “count” for emissions estimation: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). This chapter describes emissions sources and estimates emissions for HFCs, PFCs, and sulfur hexafluoride. Emissions are also estimated for two other categories of gases that *do not* “count” under the Kyoto Protocol but do have indirect and difficult-to-measure effects on climate:

- Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and bromofluorocarbons (sometimes called by their trade name, “halons”), which

are ozone-depleting substances controlled under the Montreal Protocol

- Gases that indirectly affect climate through their effects on tropospheric ozone, which are controlled as “criteria pollutants” in the United States under the authority of the Clean Air Act.

As a group, emissions of HFCs, PFCs, and sulfur hexafluoride are rising. In the case of HFCs, the rise in emissions reflects the introduction of HFCs specifically as replacements for CFCs, whose use is being phased out under the Montreal Protocol because they damage the Earth’s ozone layer. CFCs have been widely used as refrigerants, aerosol propellants, and foam blowing agents for many years, but with CFC production virtually ceasing by 1996, HFCs have been introduced into the market to fill the void in many key applications. Emissions of PFCs and perfluoropolyethers (PFPEs) have also been rising in the 1990s (although not as rapidly as HFC emissions), mainly because of the recent commercial introduction of new PFCs and PFPEs both as CFC substitutes and for use in various applications in the semiconductor manufacturing industry.

HFCs, PFCs, and sulfur hexafluoride are emitted in small quantities, but they have disproportionate effects because their long atmospheric lifetimes and extreme scarcity in the atmosphere give them extremely large GWPs. Sulfur hexafluoride is the most potent of the greenhouse gases, with a GWP of 23,900. PFCs also tend to have particularly high GWPs, falling in the range of 7,000 to 9,000. Among HFCs, HFC-23 is the most potent greenhouse gas, with a GWP of 11,700.

Table 28 summarizes U.S. emissions of halocarbons and other gases from 1990 to 1998, and Table 29 shows U.S. emissions of HFCs, PFCs, and sulfur hexafluoride in million metric tons carbon equivalent. As Table 29 indicates, throughout the 1990s HFC emissions have accounted for roughly one-half of the total carbon-equivalent emissions of HFCs, PFCs, and sulfur hexafluoride combined.

The emissions estimates presented in Tables 28 and 29 are taken primarily from the U.S. Environmental Protection Agency (EPA) report, *Inventory of U.S.*

*Greenhouse Gas Emissions and Sinks 1990-1997.*⁴⁸ The 1998 preliminary estimates for HFC-23, PFCs, and sulfur hexafluoride represent advance estimates developed by EPA and provided to EIA. The 1998 preliminary estimates for the remaining HFCs were developed primarily by extrapolating the trends shown in the EPA estimates through 1997. More information on methodologies and data sources for emissions of halocarbons and related gases is presented in Appendix A.

Hydrofluorocarbons (HFCs)

U.S. Emissions of Hydrofluorocarbons, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Carbon Equivalent)	22.6
Change Compared to 1997 (Million Metric Tons Carbon Equivalent)	1.3
Change from 1997 (Percent)	6.0%
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	12.8
Change from 1990 (Percent)	130.3%

HFCs are compounds containing carbon, hydrogen, and fluorine. They do not destroy ozone. The market for HFCs is expanding as CFCs are being phased out. It is difficult to keep pace with the variety of HFCs that are being developed and the quantities being produced. Consequently, accurate data are difficult to obtain.

HFC-23

Although emissions of HFC-23 are relatively small, its high GWP gives it a substantial direct effect. HFC-23 is created as a byproduct in the production of HCFC-22. Small amounts are also used in semiconductor manufacture and as a fire-extinguishing agent.

The EPA has developed its most recent emissions estimates on the basis of actual measurements of feed

components and HFC-23 process stream concentrations at HCFC-22 production plants. Using this approach, the EPA estimates 1997 HFC-23 emissions at 2,570 metric tons.⁴⁹ Annual emissions dropped by 22 percent between 1992 and 1995 but increased by 11 percent in 1997. Demand for HCFC-22 as a chemical feedstock is growing at a 7-percent annual rate, and HCFC-22 is continuing to make inroads in refrigeration applications as a replacement for CFCs.⁵⁰ The Climate Change Action Plan (CCAP) includes a voluntary program with HCFC-22 producers to reduce HFC-23 emissions, which may help to offset the rising demand for HCFC-22 in the short term. HCFC-22 production (except for use as a feedstock) is scheduled to be eliminated by 2020 under the Copenhagen Amendments.⁵¹

1,2,2,2-Tetrafluoroethane (HFC-134a)

HFC-134a, with a GWP of 1,300, is gaining importance as a replacement for CFCs, especially in automotive air conditioners. Emissions in 1990 were estimated at 560 metric tons, but they are growing rapidly (by 3,400 percent since 1990) (Table 28). In 1993, Ford Motor Company sold nearly 40,000 vehicles, each of which used approximately 2 pounds of HFC-134a in its air conditioner.⁵² Previous models used about 2.5 pounds of CFC-12. Nearly all 1994 and subsequent model year automobiles use HFC-134a as their air conditioner refrigerant. In addition, HFC-134a conversion packages are now available for older cars.

Automobile air conditioners are subject to leakage, with sufficient refrigerant leaking (15 to 30 percent of the charge) over a 5-year period to require servicing. On its Form EIA-1605, General Motors (GM) reported total HFC-134a emissions of about 2,150 metric tons from GM-made vehicles on the road in 1998.⁵³ GM based its estimate on an assumed annual leakage rate of 10 percent per year. With GM vehicles accounting for about one-third of the U.S. light-duty fleet,⁵⁴ the GM emissions estimate implies that total U.S. HFC-134a emissions from mobile air conditioners were equal to about 6,500 metric tons in 1998. Emissions from this source are expected to continue to increase in the near future, as the replacement of vehicles using CFCs proceeds at a rapid pace.

⁴⁸U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999).

⁴⁹U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999).

⁵⁰"Fluorocarbon Outlook Turns Bullish," *Chemical Market Reporter* (May 25, 1998).

⁵¹See web site www.epa.gov/oiamount/egei3.htm.

⁵²Information obtained during oral communication with Ford Motor Company representatives.

⁵³Form EIA-1605 is a greenhouse gas emissions and emissions reductions reporting form, which is submitted to EIA on a voluntary basis by entities interested in creating a public record of their emissions reduction activities.

⁵⁴American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures 96* (Detroit, MI, 1999).

In addition to its use in all new automobiles, an automotive aftermarket for HFC-134a has been developing. Spurred by rising prices for CFC-12, 5 million cars were retrofitted for HFC-134a use in 1997.⁵⁵ Furthermore, many of the air conditioners in mid-1990s models (which were among the first automobiles to use HFC-134a) are now due to be serviced. A spokesperson for Elf Atochem North America estimates the U.S. aftermarket for HFC-134a at 45 to 50 million pounds, or roughly 35 percent of total annual demand. He believes that, as the market for HFC-134a matures, the aftermarket will eventually be about twice the size of the original equipment market.⁵⁶

HFC-134a is also used as a refrigerant in most new refrigerators built in the United States and in commercial chillers, but leakage from these sources is much less than from automotive air conditioners. Leakage occurs primarily during servicing of the units rather than during normal operation. Short-term uses of HFC-134a, on the other hand, are becoming an important source of emissions. Such uses include aerosols and open-cell foam blowing, which are denoted as short term because most of the HFC-134a used will be emitted to the atmosphere within a short period of time. According to the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), worldwide sales of HFC-134a for short-term applications jumped almost fourfold between 1994 and 1995. However, sales for short-term uses leveled off at 10,000 metric tons in 1996 and then dropped to 7,400 metric tons (or 7 percent of sales for all uses) in 1997.⁵⁷ New developments in the U.S. market may, however, reverse this recent downward trend. Beginning in September 1998, U.S. regulations require aerosol manufacturers to use propellants with a maximum volatile organic compound (VOC) level of 45 to 55 percent. HFC-134a is one of only two chemicals that meet this requirement (the other being HFC-152a). Also, in January 1999, the major marketers of tire inflators began requiring the use of nonflammable material, creating additional demand for HFC-134a.

With global consumption of HFC-134a rising at an annual rate of 10 to 15 percent, there is some concern that demand will surpass supply in the near future. For many years, the HFC-134a market was characterized by excess capacity and low prices, but since November

1998 there have been three price increases, indicating a tightening of the market.⁵⁸ Elf Atochem estimates that in 1999 global demand for HFCs will be roughly equal to the total world production capacity of 120,000 metric tons. Yet neither Elf Atochem nor the global market leader, ICI, is planning to build new capacity, in part because of concerns about the possibility of new regulations stemming from the Kyoto Protocol. Demand is thus expected to exceed production starting in 2000.⁵⁹ It is possible that capacity constraints will act as a brake on HFC-134a consumption and emissions in the future. The recent tightening of supply in the United States has already caused producers to divert HFC-134a from the export to the domestic market.⁶⁰

1,1-Difluoroethane (HFC-152a)

As a non-ozone-depleting substance with a GWP of 140, HFC-152a is an attractive potential replacement for CFCs. It can be used as a blowing agent, an ingredient in refrigerant blends (e.g., in R-500), and in fluoropolymer manufacturing applications. It is also compatible with the components used in aerosol products. Unlike CFCs, however, HFC-152a is flammable.

Only one U.S. company (DuPont) produces HFC-152a, using the trade name Dymel-152a. In 1995 the company reported having doubled its production capacity from 1992 levels, to 35 million pounds.⁶¹ DuPont probably was producing HFC-152a at nearly full capacity in 1994, corresponding to production of about 8,000 metric tons. The company reported 1994 HFC-152a emissions of 180 metric tons on its Form EIA-1605. In 1997, however, DuPont's reported emissions dropped to only 36 metric tons. The EPA estimated 1990 emissions of HFC-152a at 1,500 metric tons, and they are believed to have been somewhat lower in 1998.

Other HFCs

Other hydrofluorocarbons with considerable radiative forcing potential include HFC-125 (C₂HF₅), HFC-143a (C₂H₃F₃), HFC-227ea (C₃HF₇), and HFC-236fa (C₃H₂F₆), with 100-year GWPs of 2,800, 3,800, 2,900, and 6,300, respectively. Emissions of these HFCs are small but growing rapidly, as they continue to find applications as substitutes for CFCs. The EPA estimated 1997

⁵⁵"Fluorocarbon Outlook Turns Bullish," *Chemical Market Reporter* (May 25, 1998).

⁵⁶"HFC-134a Prices Rise as Market Tightens," *Chemical Market Reporter* (March 15, 1999).

⁵⁷Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of Fluorocarbons Through 1997*, web site www.afeas.org/prodsales_download.html.

⁵⁸"HFC-134a Prices Rise as Market Tightens," *Chemical Market Reporter* (March 15, 1999).

⁵⁹"HFC Shortage Looms Because of Producers' Fears," *Chemical Market Reporter* (April 26, 1999).

⁶⁰"HFC-134a Prices Rise as Market Tightens," *Chemical Market Reporter* (March 15, 1999).

⁶¹"DuPont Set To Expand Markets for Ozone-Safe HFC-152a Product," *Ozone Depletion Online Today* (Alexandria, VA, June 9, 1995).

emissions at 3,570 metric tons for HFC-125, 430 metric tons for HFC-143a, and 170 metric tons for HFC-236fa.

Perfluorocarbons (PFCs)

U.S. Emissions of Perfluorocarbons, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Carbon Equivalent)	7.0
Change Compared to 1997 (Million Metric Tons Carbon Equivalent)	-0.1
Change from 1997 (Percent)	-2.0%
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	1.6
Change from 1990 (Percent)	30.7%

Perfluorocarbons are compounds composed of carbon and fluorine. PFC emissions are not regulated or reported, although their high GWPs (6,500 for perfluoromethane and 9,200 for perfluoroethane) have drawn the attention of the CCAP. PFCs are also characterized by long atmospheric lifetimes (up to 50,000 years); hence, unlike HFCs, they are essentially permanent additions to the atmosphere. As byproducts of aluminum production, they arise during discrete periods of process inefficiency. Emissions can be reduced by improving process efficiency. The Voluntary Aluminum Industrial Partnership, aimed at reducing PFC emissions from the aluminum industry, is a CCAP initiative.

The principal quantifiable source of PFCs is as a byproduct of aluminum smelting. The EPA estimates U.S. emissions at 1,430 metric tons of perfluoromethane and 140 metric tons of perfluoroethane in 1997. U.S. primary aluminum production has been increasing since 1994, and the trend is expected to continue as the automobile industry expands its use of aluminum.⁶²

⁶²U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, Review Draft (Washington, DC, March 1999), pp. 87-88, web site www.epa.gov/globalwarming/inventory/1999-inv.html.

⁶³"PFCs Can Be Recycled with New Technology," American Institute of Chemical Engineers, Press Release (March 12, 1997).

⁶⁴U.S. Environmental Protection Agency, Office of Air and Radiation, Climate Protection Division, personal communication, August 29, 1996.

⁶⁵U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html.

⁶⁶On the other hand, 3M has begun to market C₃F₈ to the semiconductor industry as a substitute for CF₄ and C₂F₆.

⁶⁷"Environmental Protection Drives Emissions Reduction Effort," *Electronic Design* (December 1, 1997).

⁶⁸"EPA Launches PFC Reduction Program," *Chemical Week* (July 31, 1996). Without emissions control efforts, PFC emissions would be expected to rise as the use of PFCs in the semiconductor industry increases.

⁶⁹D. Schiff and M. Sciannamea, "Greenlook," *Electronic Design* (December 15, 1997).

Another source of PFC emissions is semiconductor manufacturing. Perfluoromethane and perfluoroethane are used as etchants and cleaning agents in semiconductor manufacturing. Although anywhere from 5 to 95 percent of the CF₄ and C₂F₆ is destroyed, the process produces fugitive emissions of perfluoroethane, perfluoromethane, and sulfur hexafluoride. The United States consumed an estimated 800 tons of perfluoroethane and perfluoromethane in 1995.⁶³ The EPA's Climate Protection Division estimates that emissions of PFCs, HFC-23, and sulfur hexafluoride from the semiconductor industry totaled about 1 million metric tons carbon equivalent in 1994, with about 60 to 70 percent of GWP-weighted emissions consisting of perfluoroethane.⁶⁴ For 1996, the EPA estimates total emissions of all greenhouse gases from semiconductor manufacturing at 1.3 million metric tons carbon equivalent.⁶⁵

It is difficult to assess trends in PFC emissions from the semiconductor industry. On the one hand, the continued rapid expansion of the worldwide semiconductor market may lead to increased PFC use and emissions. On the other hand, industry efforts to curb emissions may help to offset these market forces to some extent. Since 1992, DuPont—the sole manufacturer of perfluoroethane—has been asking its customers to limit PFC use.⁶⁶

A number of semiconductor manufacturing firms have joined an EPA program to reduce PFC emissions voluntarily.⁶⁷ In 1999, the World Semiconductor Council, comprising manufacturers from Europe, the United States, Japan, and Korea, has voluntarily committed to reduce emissions of PFCs by 10 percent from 1990 levels. In addition, a number of PFC distributors are developing PFC emissions control equipment.⁶⁸ Recycling, abatement, and other control options remain in the early stages of development, however, and PFC substitutes are not yet available.⁶⁹

A variety of other perfluorinated compounds are beginning to be used in the semiconductor industry, including C₃F₈ (manufactured by 3M), C₄F₁₀ (with a GWP of 7,000), C₆F₁₄ (with a GWP of 7,400), NF₃ (manufactured by Air Products), and CHF₃.

Sulfur Hexafluoride

U.S. Emissions of Sulfur Hexafluoride, 1990-1998

Estimated 1998 Emissions (Million Metric Tons Carbon Equivalent)	10.0
Change Compared to 1997 (Million Metric Tons Carbon Equivalent)	*
Change from 1997 (Percent)	**
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	2.7
Change from 1990 (Percent)	36.6%

*Less than 0.05 million metric tons carbon equivalent.

**Less than 0.05 percent.

Sulfur hexafluoride (SF₆) is used as an insulator for circuit breakers, switch gear, and other electrical equipment. In addition, its extremely low atmospheric concentration makes it a useful atmospheric tracer gas for a variety of experimental purposes. It is also a fugitive emission from certain semiconductor manufacturing processes, and it is used as a cover gas during magnesium production and processing, to prevent the violent oxidation of molten magnesium in the presence of air.

Sulfur hexafluoride has a high GWP of 23,900, but it is not produced or used in large quantities. In 1989, global production and emissions were estimated at 5,000 metric tons.⁷⁰ The EPA's estimates indicate a gradual increase in U.S. emissions between 1990 and 1995, from 1,120 metric tons to 1,530 metric tons and holding steady thereafter.⁷¹

Ozone-Depleting Substances

The impact of ozone-depleting substances on global climate is ambiguous, and they are not included among the greenhouse gases to be controlled under the Kyoto Protocol. Emissions of CFCs, HCFCs, halons, and other chlorine-containing gases are therefore considered separately in this report.

⁷⁰M.K.W. Ko, N.D. Sze, W.C. Wang, G. Shia, A. Goldman, F.J. Murcray, D.G. Murcray, and C.P. Rinsland, "Atmospheric Sulfur Hexafluoride: Sources, Sinks, and Greenhouse Warming," *Journal of Geophysical Research*, Vol. 98 (1993), p. 10,500.

⁷¹U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html.

⁷²The current (amended) text of the Montreal Protocol can be found at web site www.unep.org/unep/secretar/ozone/treaties.htm.

⁷³U.S. International Trade Commission, *Synthetic Organic Chemicals: United States Production and Sales, 1993* (Washington, DC, November 1994), p. 3-21.

⁷⁴U.S. International Trade Commission, *Synthetic Organic Chemicals: United States Production and Sales, 1994* (Washington, DC, March 1995), p. 3-21.

Chlorofluorocarbons (CFCs)

CFCs are derivatives of hydrocarbons. Hydrocarbons are composed of hydrogen and carbon atoms. In CFCs, the hydrogen atoms are replaced with chlorine and fluorine atoms, yielding an array of usually nontoxic, nonflammable gases useful in a wide variety of applications. CFCs have no natural source, and their high molecular stability allows them to migrate to the stratosphere, where they destroy ozone. Although molecule for molecule they absorb thousands of times more infrared radiation than does carbon dioxide, their net warming effect is reduced because of their effect on ozone. Ozone (O₃), beneficial in the stratosphere for its ability to absorb harmful ultraviolet radiation, is also a potent greenhouse gas. Thus, while the direct warming potential of CFCs is far greater than that of carbon dioxide, their indirect effect on ozone reduces their net radiative forcing effects by half (see discussion in Chapter 1).

The Copenhagen Amendments of the Montreal Protocol requires the phaseout of CFC production by 1996.⁷² The United States is implementing these provisions through the Clean Air Act Amendments of 1990 and subsequent EPA regulations, which specify allowable production quotas and taxes on inventories and stocks. All production ceased in January 1996, with the exception of small amounts used in metered dose inhalers for asthma patients, for which no substitutes are available. Emissions of CFCs contained in mobile air conditioners, chillers, and other equipment built prior to the regulations will continue at least into the next decade.

CFC-11 is used principally as a blowing agent for foams and packaging materials and as a refrigerant in large commercial chillers. Sales have been declining steadily since 1989, with production following roughly the same trend, except for a spike in 1992.⁷³ In 1994, production and sales declined by nearly 80 percent, to only 7,000 metric tons,⁷⁴ implying that CFC-11 has been phased out of the blowing agent market completely, with residual CFC-11 probably used only to recharge existing chillers.

CFC-12 is often known by its trade name, "freon-12." Exceedingly versatile, its end uses include air conditioning (both automotive and commercial); refrigeration (refrigerators and freezers of varying scales); and as a

blowing agent for foams, insulations, and packaging. Pursuant to the Montreal Protocol, production and sales dropped dramatically in 1990 and 1991, falling below estimates of end-use applications and emissions. In recent years, end use has gradually declined with the ongoing phaseout of CFCs.⁷⁵

AFEAS data suggest that use of CFC-12 as a blowing agent dropped by more than 90 percent between 1988 and 1996.⁷⁶ The use of CFC-12 in refrigeration, however, declined more slowly until 1994. In 1994, automobile, refrigerator, and commercial chiller manufacturers essentially ceased using CFC-12 in their products. At present, emissions are being sustained by the existing stock of CFC-using equipment.

Other CFCs include CFC-113, CFC-114, and CFC-115. CFC-113 and CFC-114 are used principally as solvents. EPA-estimated emissions of both of these CFCs have been declining rapidly since 1989, although small CFC-114 emissions from metered dose inhalers are likely to continue for a few more years. The EPA granted the International Pharmaceutical Aerosol Consortium 338 metric tons of CFC-114 essential use allowances for 1998.⁷⁷ CFC-115 is used primarily as a blending agent for some specialty refrigerants. CFC-115 emissions have also declined during the 1990s, although not as rapidly as CFC-113 and CFC-114 emissions.

Hydrochlorofluorocarbons (HCFCs)

HCFCs are essentially CFCs that include one or more hydrogen atoms. The presence of hydrogen makes the resulting compounds less stable, and as a result they are more susceptible to photodecomposition, have much shorter atmospheric lifetimes than CFCs, and are less likely to migrate to the stratosphere where they would destroy ozone. They are therefore popular interim substitutes for CFCs. The Copenhagen Amendments placed HCFCs under control, with HCFC-22 slated for elimination by 2020 and all others by 2030.

HCFC-22 is the most commonly used refrigerant for home air conditioning systems. It is the most widely available and least expensive potential substitute for CFCs in a variety of applications; however, the available evidence suggests that HCFC-22 gained most of its market share at the expense of CFCs in the late 1980s. Nonetheless, use of HCFC-22 for long- and medium-

lifetime applications has created a “banked” inventory of the compound that is now being emitted at a rate of 70,000 to 80,000 metric tons per year.

A number of other HCFCs are gaining importance as CFCs are phased out. HCFC-141b is used primarily as a solvent and as a blowing agent for closed-cell foams, and HCFC-142b is used mainly for long-lifetime applications—particularly as a blowing agent for closed-cell foams. HCFC-123 is a replacement for CFC-11 in refrigeration applications, and HCFC-124 is a potential replacement for CFC-12 in sterilizers. EPA-estimated emissions of all these HCFCs have risen from zero in the early 1990s to 60,000 metric tons total in 1998.

Bromofluorocarbons (Halons)

Bromofluorocarbons are similar to CFCs except that they contain at least one bromine atom. They are inert, nontoxic, and evaporate without leaving any residue, making them popular for use as fire suppressants for high-value equipment, such as computer centers and aircraft. The trade name “halon” is applied to several of these chemicals, which are used as fire suppressants. Halons are particularly destructive to stratospheric ozone; consequently, production ceased in 1996 pursuant to the Montreal Protocol. However, attempts to smuggle halon-1301 into the United States have been reported.⁷⁸ Emissions of halons are low, although the exact figure is uncertain.

Other Chemicals

Several other chemicals, including carbon tetrachloride, methyl chloroform, chloroform, and methylene chloride, combine high GWPs and sufficiently high emissions levels to produce potential effects on global climate. Several of these chemicals are regulated under the Clean Air Act Amendments of 1990.

Most carbon tetrachloride is used as a feedstock in the production of CFC-11 and CFC-12. Carbon tetrachloride is regulated by the Clean Air Act Amendments as a known carcinogen and under the Montreal Protocol as an ozone-depleting chemical. Production ceased in January 1996. Emissions declined rapidly in the 1990s and, according to the EPA, reached negligible levels in 1996. Emissions remained negligible in 1997.

⁷⁵U.S. International Trade Commission, *Synthetic Organic Chemicals: United States Production and Sales, 1993* (Washington, DC, November 1994), p. 3-21.

⁷⁶Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of Fluorocarbons Through 1996* (Washington, DC, January 1998), p. 10.

⁷⁷U.S. Environmental Protection Agency, *Ozone Depleter Compliance Guide* (Washington, DC, March 1998).

⁷⁸“Justice Department Adds to CFC Indictments,” *Ozone Depletion Today* (Alexandria, VA, February 27, 1998).

Like carbon tetrachloride, methyl chloroform is regulated under the Clean Air Act Amendments as an ozone-depleting chemical covered by the Montreal Protocol. Used primarily as a solvent, it was required to be phased out by 1996. Emissions have declined rapidly, from about 160,000 metric tons in 1990 to negligible levels in 1996 and 1997. For 1998, the EPA granted the National Aeronautics and Space Administration and the Air Force a total of 60 metric tons of essential use allowances for the use of methyl chloroform in cleaning, bonding, and surface activation applications on the space shuttle and the Titan rocket.⁷⁹

Chloroform is used primarily as a feedstock for HCFC-22, with secondary use as a solvent. It is a weak greenhouse gas with a GWP of 5. Total emissions should be low, because most chloroform is incorporated into HCFC-22 during its production. As a carcinogen, chloroform is reported to the EPA's Toxics Release Inventory (TRI). The TRI indicates that emissions have been decreasing and were only 3,365 metric tons in 1997.⁸⁰

Like chloroform, methylene chloride is a weak greenhouse gas (GWP of 9). Its short atmospheric lifetime of less than 1 year probably prevents it from reaching the stratosphere where it would be damaging to ozone. As a result, its indirect cooling effects are likely to be small. A potential carcinogen, methylene chloride emissions are regulated and included in the TRI, with 1997 emissions of almost 22,000 metric tons, down from 46,000 metric tons in 1990.⁸¹

Criteria Pollutants That Affect Climate

Overview

Certain criteria pollutants also affect climate: carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs).⁸² The Clean Air Act of 1970 required that air quality standards be established for pollutants with adverse

U.S. Emissions of Criteria Pollutants, 1990-1997

Source	Million Metric Tons of Gas		Percent Change	
	1990	1997	1990-1997	1996-1997
Carbon Monoxide	86.8	79.2	-8.7%	-3.8%
Nitrogen Oxides	21.2	21.4	0.6%	0.5%
Nonmethane Volatile Organic Compounds	18.9	17.3	-8.2%	-0.4%

effects on public health or welfare. They are termed "criteria pollutants" because the EPA based each National Ambient Air Quality Standard (NAAQS) on health-based criteria from scientific studies. Although these gases are not considered to be greenhouse gases themselves, estimates of their emissions are presented here because of their indirect effects on atmospheric concentrations of greenhouse gases, including carbon dioxide, methane, and ozone.

Ozone is produced largely from atmospheric chemical reactions involving the criteria pollutants. Ozone is highly reactive with other atmospheric gases, and its concentration is influenced by meteorological conditions. As a result, it remains in the troposphere for only hours or days. Hence, concentrations of tropospheric ozone tend to be centered around cities where high levels of criteria pollutants are found. Ozone concentrations are measured at individual urban sites throughout the United States. The EPA reported that the composite average ozone concentration for its 660 U.S. testing sites has declined by 19 percent since 1988.⁸³

The EPA Office of Air Quality Planning and Standards has compiled emissions data for the various criteria pollutants in the document *National Air Pollutant Emission Trends Update, 1990-1997*.⁸⁴ The emissions estimates in this report are taken from that document.

⁷⁹U.S. Environmental Protection Agency, *Ozone Depleter Compliance Guide* (Washington, DC, March 1998).

⁸⁰U.S. Environmental Protection Agency, *1997 Toxics Release Inventory* (Washington, DC, April 1999), p. 2-66, web site www.epa.gov/opptintr/tri/pdr99/drhome.htm.

⁸¹U.S. Environmental Protection Agency, *1997 Toxics Release Inventory* (Washington, DC, April 1999), p. 2-70, web site www.epa.gov/opptintr/tri/pdr99/drhome.htm.

⁸²All estimates and projections presented in this chapter are taken directly from U.S. Environmental Protection Agency, *National Air Pollutant Emission Trend Update, 1990-1997*, EPA-454-E-98-007 (Research Triangle Park, NC, December 1998), web site www.epa.gov/ttn/chief/trends97/emtrnd.html.

⁸³U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Quality and Emissions Trends Report, 1997*, EPA-454-R-98-016 (Research Triangle Park, NC, December 1998), p. 110, Table A-1, web site www.epa.gov/oar/aqtrnd97.

⁸⁴U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends Update, 1990-1997*, EPA-454-E-98-007 (Research Triangle Park, NC, December 1998), web site www.epa.gov/ttn/chief/trends97/emtrnd.html.

The EPA continues to modify emissions data with improved estimation methods and updated information.

Since the passage of the Clean Air Act of 1970 and subsequent amendments, implementation of pollution control measures and replacement of older, less fuel-efficient vehicles have restrained potential growth in criteria pollutant emissions that otherwise would have been expected from growth in the economy, increased driving, and expansion of industrial output. Current emissions of both carbon monoxide and NMVOCs are well below peak levels seen in the early 1970s, despite year-to-year fluctuations. Although emissions of nitrogen oxides are now higher than in 1970, the level of emissions has been relatively stable in the 1990s.

Carbon Monoxide

Most emissions of carbon monoxide result from incomplete oxidation during combustion of fuels used for transportation. Transportation emissions, primarily from highway vehicles, accounted for about 77 percent of 1997 emissions. Total emissions of carbon monoxide in 1997 amounted to 79.2 million metric tons (Table 30). Between 1990 and 1997, carbon monoxide emissions decreased by 7.6 million metric tons (9 percent), due largely to decreases in emissions of approximately 6.9 million metric tons from highway vehicles (down by 13 percent).

Carbon monoxide emissions from residential fuel use and forest fires also declined in 1997, by 0.9 million (25 percent) and 1.9 million (35 percent) metric tons, respectively, compared with 1990. Otherwise, 1997 emissions were generally the same as or slightly above 1990 levels. One exception was emissions from "other off-highway vehicles," which were not as well controlled as other sources. Emissions from this source during 1996 were 1.2 million metric tons (9 percent) higher than in 1990. Carbon monoxide emissions are expected to decrease through the year 2000 as a result of more stringent tailpipe standards and other factors.

Nitrogen Oxides

Nitrogen oxide emissions are related to air-fuel mixes and combustion temperatures during the burning of fuels. Emissions are reduced by the use of pollution control equipment, such as catalytic converters. Total U.S. emissions of nitrogen oxides between 1990 and 1997, have ranged between 21 and 22 million metric

tons per year (Table 31). Although this does not represent a decline (as seen with the other criteria pollutants), it is much lower than the rate of growth in fuel consumption (such as consumption of gasoline by motorists and coal by electric utilities).

Total U.S. emissions of nitrogen oxide during 1997 (21.4 million metric tons) were about 1 percent higher than their 1990 level of 21.2 million metric tons. In the United States, the majority of nitrogen oxide emissions are from transportation and stationary fuel combustion sources. During 1997, nitrogen oxide emissions from transportation sources accounted for 10.5 million metric tons (49 percent) of total U.S. emissions of this gas, followed by stationary fuel combustion sources, which accounted for 9.7 million metric tons (45 percent) of total U.S. emissions of nitrogen oxide. Emissions are expected to decline with implementation of various additional emissions control measures.

Nonmethane Volatile Organic Compounds

NMVOCs are a principal component in the chemical and physical atmospheric reactions that form ozone and other photochemical oxidants. Nearly half (49 percent) of the 17.3 million metric tons of NMVOC emissions during 1997 came from industrial processes (Table 32), of which solvent use was the largest source. Most (79 percent) of the remaining 8.8 million metric tons of emissions were from combustion of transportation fuels.

Emissions of NMVOCs declined by some 10.5 million metric tons (38 percent) from 1970 to 1997, while fuel consumption in the transportation sector increased and activity in the industrial sector expanded.⁸⁵ This improvement was accomplished by some reformulation of petroleum products, implementation of pollution abatement measures, and changes in industrial processes. Emissions from solvent utilization declined as a result of the substitution of water-based emulsified asphalt for asphalt liquefied with petroleum distillates.

Emissions of NMVOCs were 17.3 million metric tons in 1997, down by 0.1 million metric tons (0.4 percent) from their level in 1996, and down by 1.6 million metric tons (8.2 percent) from 1990 levels. Energy-related emissions have declined by 1.1 million metric tons (13 percent) since 1990, while emissions associated with solid waste disposal have declined by 0.5 million metric tons (55 percent) since 1990.

⁸⁵U.S. Environmental Protection Agency, *National Air Pollutant Emission Trends, 1900-1996*, EPA-454-R-97-011 (Research Triangle Park, NC, December 1997), web site www.epa.gov/oar/emtrnd.

Table 28. U.S. Emissions of Halocarbons and Miscellaneous Greenhouse Gases, 1990-1998
(Thousand Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Chlorofluorocarbons (CFCs)									
CFC-11	54	48	45	45	37	36	27	25	20
CFC-12	113	104	81	79	58	52	36	23	9
CFC-113	26	21	17	17	9	9	*	*	*
Other CFCs	9	8	7	7	5	5	4	3	3
Halons	3	3	3	3	2	3	3	2	2
Hydrochlorofluorocarbons (HCFCs)									
HCFC-22	80	80	80	71	71	74	77	80	78
HCFC-141b	0	0	0	2	7	12	14	12	15
HCFC-142b	0	0	4	9	15	21	28	28	36
Other HCFCs	0	0	1	3	6	7	7	8	9
Hydrofluorocarbons (HFCs)									
HFC-23	3	3	3	3	3	2	3	3	3
HFC-134a	1	1	1	3	5	10	14	18	19
Other HFCs	2	1	0	2	5	9	11	13	15
Perfluorocarbons (PFCs)	3	3	2	2	2	3	3	3	3
Other Chemicals									
Carbon Tetrachloride	32	31	22	19	16	5	*	*	*
Methyl Chloroform	158	155	108	93	77	46	0	*	*
Sulfur Hexafluoride	1	1	1	1	1	2	2	2	2

*Less than 500 metric tons of gas.

P = preliminary data.

Sources: **1990-1997:** U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html. **1998:** U.S. Environmental Protection Agency, unpublished data, courtesy of the Office of Air and Radiation; and EIA estimates.

Table 29. GWP-Weighted U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-1998
(Million Metric Tons Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Hydrofluorocarbons (HFCs)									
HFC-23	9.54	8.46	9.70	8.97	8.97	7.85	9.06	8.78	8.65
HFC-134a	0.20	0.20	0.22	1.02	1.92	3.39	4.83	6.37	6.82
HFC-125	0.00	0.00	0.18	0.37	1.24	2.15	2.42	2.73	3.01
HFC-227	0.00	0.00	0.00	0.00	0.70	1.49	1.63	2.09	2.39
HFC-143a	0.00	0.00	0.00	0.01	0.04	0.09	0.24	0.44	0.62
HFC-4310	0.00	0.00	0.00	0.00	0.00	0.22	0.37	0.52	0.68
Other HFCs	0.06	0.03	0.01	0.03	0.03	0.04	0.18	0.36	0.39
Total	9.80	8.68	10.12	10.39	12.91	15.23	18.72	21.28	22.56
Perfluorocarbons (PFCs)									
CF ₄	4.61	4.46	4.03	3.59	3.01	2.95	3.22	3.18	3.09
C ₂ F ₆	0.73	0.83	0.88	0.95	1.00	1.10	1.25	1.18	1.13
C ₄ F ₁₀	0.00	0.00	0.00	0.00	0.00	0.05	0.15	0.25	0.25
PFCs/PFPEs	0.00	0.00	0.00	0.00	0.08	2.48	2.48	2.51	2.51
Total	5.34	5.29	4.91	4.55	4.09	6.59	7.11	7.12	6.98
Sulfur Hexafluoride	7.30	7.82	8.34	8.93	9.45	9.97	9.97	9.97	9.97
Total Emissions	22.44	21.79	23.37	23.87	26.45	31.80	35.80	38.38	39.51

P = preliminary data.

Sources: **1990-1997:** U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html. **1998:** Estimated from methods described in Appendix A. Global warming potentials used to convert emissions to carbon-equivalent basis from Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), pp. 119 and 121.

Table 30. U.S. Carbon Monoxide Emissions, 1990-1998
(Million Metric Tons)

Source	1990	1991	1992	1993	1994	1995	1996	P1997	1998
Transportation									
Highway Vehicles	52.48	56.31	54.30	54.61	56.09	49.08	48.32	45.59	NA
Aircraft	0.82	0.81	0.82	0.82	0.83	0.85	0.86	0.92	NA
Railroads	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	NA
Vessels	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.08	NA
Other Off-Highway	12.94	12.95	13.19	13.36	13.55	13.73	13.85	14.10	NA
Total	66.43	70.25	68.50	68.97	70.65	63.85	63.20	60.79	NA
Stationary Source Fuel Combustion									
Electric Utilities	0.33	0.32	0.32	0.33	0.34	0.34	0.36	0.37	NA
Industrial	0.80	0.83	0.87	0.95	0.94	0.96	0.97	1.01	NA
Commercial-Institutional	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08	NA
Residential	3.67	3.97	4.20	3.59	3.51	3.88	3.87	2.76	NA
Total	4.86	5.18	5.45	4.94	4.87	5.25	5.28	4.22	NA
Total Energy-Related Emissions .	71.29	75.44	73.96	73.91	75.53	69.10	68.48	65.01	NA
Industrial Processes	4.33	4.19	4.12	4.22	4.19	4.18	4.19	4.36	NA
Solid Waste Disposal									
Incineration	0.34	0.36	0.37	0.45	0.42	0.39	0.40	0.42	NA
Open Burning	0.64	0.66	0.66	0.68	0.68	0.68	0.69	0.70	NA
Total	0.98	1.01	1.03	1.13	1.11	1.07	1.09	1.12	NA
Miscellaneous									
Forest Fires	5.38	3.11	1.52	1.44	3.73	1.33	3.50	3.50	NA
Other Burning	4.79	4.83	4.88	4.92	4.99	5.06	5.08	5.18	NA
Total	10.17	7.94	6.40	6.36	8.72	6.39	8.58	8.68	NA
Total All Sources	86.77	88.58	85.51	85.62	89.54	80.74	82.34	79.18	NA
Carbon Content of Carbon Monoxide .	37.21	37.99	36.67	36.71	38.40	34.62	35.31	33.95	NA
Carbon Content of Energy-Related Carbon Monoxide	30.57	32.35	31.71	31.69	32.39	29.63	29.36	27.88	NA

P = preliminary data. NA = not available.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends Update, 1900-1997*, EPA-454-R-98-007 (Research Triangle Park, NC, December 1998), Table A-1, pp. A-2-A-6, web site www.epa.gov/ttn/chief/trends97/emtmd.html.

Halocarbons and Other Gases

Table 31. U.S. Nitrogen Oxide Emissions, 1990-1998
(Million Metric Tons)

Source	1990	1991	1992	1993	1994	1995	1996	P1997	1998
Transportation									
Highway Vehicles	6.39	6.69	6.75	6.81	6.96	6.64	6.57	6.38	NA
Aircraft	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.16	NA
Railroads	0.84	0.84	0.86	0.86	0.86	0.90	0.84	0.86	NA
Vessels	0.21	0.22	0.21	0.20	0.20	0.21	0.21	0.21	NA
Other Off-Highway	2.65	2.67	2.70	2.74	2.78	2.84	2.87	2.90	NA
Total	10.23	10.56	10.66	10.75	10.95	10.73	10.64	10.52	NA
Stationary Source Fuel Combustion									
Electric Utilities	6.04	5.91	5.90	6.03	5.96	5.79	5.50	5.60	NA
Industrial	2.75	2.70	2.79	2.86	2.85	2.85	2.88	2.97	NA
Commercial-Institutional	0.31	0.30	0.32	0.33	0.34	0.34	0.34	0.35	NA
Residential	0.75	0.83	0.88	0.83	0.82	0.81	0.80	0.78	NA
Total	9.85	9.75	9.89	10.05	9.96	9.79	9.52	9.70	NA
Total Energy-Related Emissions .	20.08	20.31	20.55	20.80	20.91	20.53	20.15	20.22	NA
Industrial Processes	0.73	0.65	0.69	0.67	0.69	0.70	0.71	0.74	NA
Solid Waste Disposal									
Incineration	0.04	0.05	0.05	0.07	0.06	0.05	0.05	0.05	NA
Open Burning	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	NA
Total	0.08	0.08	0.09	0.11	0.10	0.09	0.09	0.09	NA
Miscellaneous									
Forest Fires	*	*	*	*	*	*	*	*	NA
Other Burning	0.34	0.26	0.23	0.20	0.35	0.21	0.31	0.31	NA
Total	0.34	0.26	0.23	0.20	0.35	0.21	0.31	0.31	NA
Total All Sources	21.23	21.31	21.55	21.78	22.05	21.53	21.26	21.36	NA

*Less than 5,000 metric tons of nitrous oxide.

P = preliminary data. NA = not available.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends Update, 1900-1997*, EPA-454-R-98-007 (Research Triangle Park, NC, December 1998), Table A-2, pp. A-7-A-11, web site www.epa.gov/ttn/chief/trends97/emtmd.html.

Table 32. U.S. Emissions of Nonmethane Volatile Organic Compounds, 1990-1998
(Million Metric Tons)

Source	1990	1991	1992	1993	1994	1995	1996	P1997	1998
Transportation									
Highway Vehicles	5.73	5.90	5.51	5.54	5.81	5.17	4.98	4.74	NA
Aircraft	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.17	NA
Railroads	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.05	NA
Vessels	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.05	NA
Other Off-Highway	1.97	1.98	2.01	2.03	2.05	1.93	1.93	1.94	NA
Total	7.95	8.13	7.77	7.82	8.11	7.35	7.16	6.95	NA
Stationary Source Fuel Combustion									
Electric Utilities	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	NA
Industrial	0.17	0.18	0.17	0.17	0.18	0.19	0.19	0.20	NA
Commercial-Institutional	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	NA
Residential	0.69	0.74	0.78	0.67	0.66	0.73	0.72	0.52	NA
Total	0.90	0.97	1.00	0.89	0.89	0.97	0.97	0.77	NA
Total Energy-Related Emissions .	8.86	9.10	8.78	8.71	9.00	8.32	8.13	7.72	NA
Industrial Processes	8.18	8.33	8.50	8.65	8.79	8.81	8.21	8.52	NA
Solid Waste Disposal									
Incineration	0.04	0.05	0.05	0.07	0.06	0.05	0.05	0.05	NA
Open Burning	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.19	NA
Other	0.67	0.68	0.69	0.69	0.70	0.73	0.15	0.16	NA
Total	0.89	0.91	0.92	0.95	0.95	0.97	0.39	0.41	NA
Miscellaneous									
Forest Fires	0.68	0.40	0.15	0.19	0.34	0.16	0.38	0.38	NA
Other Burning	0.29	0.29	0.29	0.29	0.30	0.31	0.31	0.32	NA
Total	0.97	0.69	0.44	0.49	0.64	0.46	0.69	0.70	NA
Total All Sources	18.89	19.02	18.63	18.79	19.39	18.56	17.42	17.34	NA

P = preliminary data. NA = not available.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998). Totals may not equal sum of components due to independent rounding.

Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends Update, 1900-1997*, EPA-454-R-98-007 (Research Triangle Park, NC, December 1998), Table A-3, pp. A-12-A-18, web site www.epa.gov/ttn/chief/trends97/emtrnd.html.

6. Land Use Issues

Overview

Land use and forestry issues are important to the global and national inventories of greenhouse gases in two ways:

- Vegetation can remove carbon dioxide from the atmosphere and store it for potentially long periods in above-ground and below-ground biomass and in soils.
- Humans can intervene in the natural carbon cycle through changes in land use, which can affect the quantities of both atmospheric and terrestrial carbon stocks.

Land use issues are of particular interest to the United States because U.S. forests and soils annually sequester large amounts of carbon dioxide. Much of the forest land in the United States was cleared for agriculture, lumber, or fuel in the hundred years prior to 1920. Since then, much agricultural and pastureland has reverted to forest land, and is now covered with relatively young, rapidly growing trees.

The amount of carbon being sequestered annually is uncertain. In part, this uncertainty is due to the absence of data or difficulties in measuring sequestration. In addition to the technical uncertainty, however, there is also policy or accounting ambiguity about which aspects of the biological carbon cycle ought to be included in national inventories as anthropogenic emissions and removals.

The Intergovernmental Panel on Climate Change (IPCC) *Revised Guidelines for National Emissions Inventories*, promulgated pursuant to the Framework Convention on Climate Change, contains a set of rules governing the inclusion of carbon sequestration and land use in national inventories.⁸⁶ The U.S. Environmental Protection Agency (EPA), relying heavily on the work of U.S. Forest Service Researchers Richard Birdsey and Linda Heath, estimates annual U.S. carbon sequestration (generally defined according to the IPCC guidelines) at 209 million metric tons carbon equivalent (Table 33).⁸⁷ Under the IPCC guidelines, this quantity would be

treated as an offset to gross greenhouse gas emissions from other sources.

Land Use and the Kyoto Protocol

Articles 3.3 and 3.4 of the Kyoto Protocol include provisions for the inclusion of carbon sequestration from land use changes and forestry. The Protocol requires that national emissions and sequestration be estimated in accord with guidelines and methods promulgated by the IPCC. There are differences, however, between forestry accounting methods implied by the Kyoto Protocol and the IPCC Guidelines, which make it difficult to determine the amount of greenhouse gas emissions and reductions attributable to land use that should be included. For example, national estimates for annual greenhouse gas fluxes from grassland, pastureland, rangeland, and cropland are required by the IPCC Guidelines but are absent from the Kyoto Protocol. Table 34 highlights some of the key areas where the IPCC guidelines differ from the Kyoto Protocol in terms of the type of land use change and forestry data included in each.

The IPCC Guidelines recommend an inclusive “carbon cycle” approach to measuring net fluxes, which are then treated as an offset to emissions from other sources. This approach encourages reporting of all relevant sources and sinks, even if the data are poor or measurement is difficult. The IPCC guidelines also require identical accounting for all years, including 1990. In an “IPCC compliant” inventory, Table 33 would be deducted from gross emissions in Table ES2 (in the Executive Summary) to produce a net emissions figure for the United States. In addition, carbon sources and sinks from relevant sources not included in Table 33 (for example, carbon sequestered or released by agricultural soils) would also be eligible for inclusion in the inventory.

The Kyoto Protocol appears to limit the extent to which the array of sources and sinks listed in the IPCC guidelines would be counted for compliance purposes. The most fundamental difference is found in Articles

⁸⁶Intergovernmental Panel on Climate Change, *Revised Guidelines for National Emissions Inventories* (1996), available at web site www.iea.org/ipcc/envs1.htm.

⁸⁷Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. 6-2, web site www.epa.gov/globalwarming/1999-inv/landuse.pdf.

Table 33. Net Carbon Flux from Land Use Change and Forestry, 1990-1997
(Million Metric Tons Carbon Equivalent)

Description	1990	1991	1992	1993	1994	1995	1996	1997
Forests								
Trees	95.6	95.6	95.6	74.0	74.0	74.0	74.0	74.0
Understory	2.4	2.4	2.4	1.3	1.3	1.3	1.3	1.3
Forest Floor	20.8	20.8	20.8	9.8	9.8	9.8	9.8	9.8
Soil	155.2	155.2	155.2	86.3	86.3	86.3	86.3	86.3
Total Forests	274.2	274.2	274.2	171.3	171.3	171.3	171.3	171.3
Harvested Wood								
Wood Products	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9
Landfilled Wood	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4
Total Harvested Wood	37.3	37.3	37.3	37.3	37.3	37.3	37.3	37.3
Total Net Flux	311.5	311.5	311.5	208.6	208.6	208.6	208.6	208.6

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-R-236-99-003 (Washington, DC, April 1999), p. 6-2, drawing on the work of Richard Birdsey and Linda Heath of the U.S. Forest Service. See web site www.epa.gov/globalwarming/1999-inv/landuse.pdf.

3.3, 3.4, and 3.7 of the Protocol, which permit countries with net forestry sinks (like the United States) to exclude forestry sinks from their emissions. However, countries with net sinks are permitted to add a portion of their sequestration from land use change and forestry to their “assigned amount” in the 2008-2013 commitment period. Thus, land use change and forestry can still act as an offset to emissions under some circumstances.

The circumstances are listed in Article 3.3 of the Protocol:

*The net changes in greenhouse gas emissions from sources and removals by sinks resulting from direct human-induced land use change and forestry activities, limited to afforestation, deforestation, and reforestation since 1990, measured as verifiable changes in stocks shall be used to meet the Commitments under this Article of each party included in Annex I. The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner and reviewed in accordance with Articles 7 and 8.*⁸⁸

“Direct human-induced land use change and forestry activities” places increased emphasis on the anthropogenic nature of the activity, because not all carbon

sequestration may be considered “anthropogenic.” Also, the inclusion of the term “direct” may exclude carbon stored in or emitted from harvested wood.

“Afforestation, deforestation, and reforestation” may exclude changes in land use not affecting forest lands, such as grassland conversion or carbon sequestered in agricultural soils, and also may exclude unharvested forest land subject to forest management practices. Article 3.4 identifies emissions and sinks from “agricultural soils” as a different category from “land use change and forestry,” which would tend to reinforce the interpretation of this clause as excluding non-forestry activities.

“Since 1990” may limit coverage to only that portion of U.S. forests subject to “afforestation, deforestation, and reforestation since 1990” but not before that date. Specific tracts may need to be identified. Because much of the commercial forest in the United States is harvested regularly on a multi-decade cropping cycle, this would still be a large area, but it would exclude park and wilderness areas.

“Measured and verifiable” may exclude some or all changes in soil carbon, either because soil carbon may not be deemed measurable and verifiable, or because some of the accumulation is occurring on land that does not qualify for inclusion under the Protocol, or

⁸⁸United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, FCCC/CP/1997/L.7/Add.1 (1997), Article 3, Paragraph 3, web site www.unfccc.de/index.html.

Table 34. Comparison of Components of Forestry and Land Use Change Included in the Kyoto Protocol and IPCC Guidelines

IPCC Category	Category	1997 U.S. Carbon Sequestered (Million Metric Tons)	Included in the Kyoto Protocol? Reason	Included In IPCC Guidelines?
Changes in Forest and Other Woody Biomass Stocks	Carbon flux, timberland only	161, of which 92 in soil carbon.	Yes. Limited to the portion that is anthropogenic and subject to afforestation, reforestation, or deforestation since 1990.	Yes
	Carbon flux, reserved and other forest land (national parks, etc.)	36, of which 19 in soil carbon.	No. As above, but most parkland will not have been subject to afforestation, reforestation, or deforestation since 1990.	Yes
	Carbon stored in wood products	13	No. Emissions or sequestration away from the forest may not be considered "direct." Possible future inclusion under Article 3.4.	Yes
	Carbon stored in landfills	17	No. Emissions or sequestration away from the forest may not be considered "direct." Possible future inclusion under Article 3.4.	Yes
	Carbon emitted by wood burned for energy	-55	No. Emissions or sequestration away from the forest may not be considered "direct." Possible future inclusion under Article 3.4.	Yes
	Carbon emitted by decay and non-energy burning	-53	No. Emissions or sequestration away from the forest may not be considered "direct." Possible future inclusion under Article 3.4.	Yes
Forest and Grassland Conversion	Carbon emitted by forest conversion to agricultural uses	Not available.	Yes. Deforestation, if the conversion occurs after 1990.	Yes
	Carbon emitted by grassland conversion to agricultural uses	Not available.	No. Not afforestation, deforestation, or reforestation. Possible future inclusion under Article 3.4, if since 1990.	Yes
Abandonment of Managed Lands	Carbon sequestered on abandoned formerly managed lands that revert to forest	Not available.	Yes, if the conversion occurs after 1990. Afforestation or reforestation.	Yes
	Carbon sequestered on abandoned formerly managed lands that revert to grassland	Not available.	No. Not afforestation, deforestation, or reforestation. Possible future inclusion under Article 3.4, if since 1990.	Yes
Changes in Soil Carbon	Changes in soil carbon	92 timberland, 19 other forests. Otherwise, not available.	Yes, if the land otherwise qualifies and soil carbon is deemed "verifiable."	Yes for non-forest land, maybe for forests.

Note: The calculations in this table are based on an earlier estimate of sequestration than that shown in Table 33. Hence, both the totals and the distribution of tons into categories for 1997 differ by about 10 percent (209 million metric tons versus 227 million metric tons).

Sources: Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 5.1-5.50, web site www.iea.org/ipcc/invs6.htm. Sequestration from R.A. Birdsey and L.S. Heath, "Carbon Changes in U.S. Forests," in L.A. Joyce (ed.), *Productivity of America's Forests and Climate Change*, General Technical Report RM-GTR-271 (Fort Collins, CO: USDA Forest Service, 1995), pp. 64-65, 67.

both. More than 50 percent of the carbon in U.S. forest ecosystems is found in the soil; however, the IPCC guideline category "Change in Soil Content" includes only soil carbon on non-forest land. The Kyoto Protocol limits reporting to activities deemed "measurable and verifiable."

Some of what Article 3.3 takes away, Article 3.4 may potentially return. Article 3.4 requires the Conference of the Parties to ". . . decide upon modalities, rules and guidelines as to how, and which, additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories shall be added to, or subtracted from, the assigned amounts for Parties included in Annex I Such a decision shall apply in the second and subsequent commitment periods. A Party may choose to apply such a decision on these additional human-induced activities for its first commitment period, provided that these activities have taken place since 1990."⁸⁹

Thus, the development of better information about soil carbon emissions and sequestration and the development of internationally accepted practices for actions such as measuring carbon cycle emissions and sequestration and carbon sequestered in agricultural soils may ultimately open a pathway for their inclusion as a tool for managing greenhouse gas emissions. Recent research suggests that carbon sequestration in agricultural soils may be a useful method of offsetting carbon emissions from fossil fuels (see box on page 69).

Both the IPCC guidelines and the Kyoto Protocol approach present formidable complexities for the United States and other Framework Convention signatories in actually developing and collecting relevant information. Thus, Kyoto signatories have agreed to defer the negotiation of an agreed interpretation of the land use change and forestry provisions of the Kyoto Protocol. They commissioned a new IPCC study of the topic, to be completed before June 2000.⁹⁰

Land Use Data Issues

The Kyoto Protocol (if adopted) would require signatories to ". . . have in place, no later than one year prior to the start of the first commitment period [2007], a national system for the estimation of anthropogenic emissions by sources and removals by sinks of all greenhouse gases."⁹¹ In principle, land use and forestry data would form a portion of this work. Remote sensing technology may be helpful.

The United States would need better coverage of non-forest lands plus new analytical methods in order to prepare a national inventory under the Framework Convention that includes all of the land categories listed under the IPCC guidelines; however, this is not the only difficulty in applying the guidelines to available U.S. forestry data. The IPCC guidelines require that, in the event that land use changes (for example, from forest to pasture), the change in carbon stocks caused by that change be calculated. However, U.S. forestry data on national land use totals by land use type are available only at 5-year intervals, so that one can determine the net change of land use in a particular category but cannot ascertain how much land was converted from one use to another. Hence, a rigorous application of the IPCC guidelines would require, in effect, tracking individual plots of land rather than the sampling approach actually used.

In order to use carbon sequestration to help comply with the Kyoto Protocol, the United States would need information from which carbon emissions and sequestration of specific tracts of land subject to afforestation, deforestation, and reforestation since 1990 could be calculated. Even if only a few such tracts were identified ("activities" are defined as individual projects), the problem could become more manageable. In contrast, if the standard covered all qualifying tracts on a national basis, it would require much more detailed land use statistics than the United States currently collects.

⁸⁹United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, FCCC/CP/1997/L.7/Add.1 (1997), Article 3, Paragraph 4, web site www.unfccc.de/index.html.

⁹⁰The Subsidiary Body for Scientific and Technical Advice (SBSTA) made this decision at its eighth meeting, in Bonn Germany. See United Nations, *Report of the Subsidiary Body for Scientific and Technological Advice on its Eighth Session, Bonn, June 2-12, 1998*, FCCC/SBSTA/1998/6, Section 45(e), page 17, web site www.unfccc.de.

⁹¹United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, FCCC/CP/1997/L.7/Add.1 (1997), Article 5, Paragraph 1, web site www.unfccc.de/index.html.

More frequent data collection would be also necessary to ascertain U.S. carbon sequestration from land use during the Kyoto commitment period. At present, the most important statistics on forest and other land

necessary for estimates of greenhouse gas fluxes in the United States are updated by the USDA Forest Service only once every 5 years, and full reports containing the data are released once every 10 years.⁹²

Carbon Sequestered in Agricultural Soils

In previous years, research on the effects of land use on carbon emissions and sequestration and their incorporation into emissions inventories focused on forests, which were generally believed to be the most important potential biological carbon source or sink. Recent research has tended to suggest that agricultural soils can also be a potentially important carbon source or sink. Natural soils suitable for agriculture, whether grasslands or forests, tend to contain large amounts of mineral or biological carbon, the product of atmospheric carbon dioxide absorbed by plants in the past and left in the soil when they decay.^a

Farming practices before the 20th century tended to deplete soil carbon. Deep plowing (partly to discourage weeds) tended to expose soil carbon to natural weathering and oxidation, returning it to the atmosphere, and burning or removing crop residues prevented the soil from regaining the lost carbon. Before the introduction of chemical fertilizers, farming also tended to deplete soil nutrients, requiring farmers periodically to leave a portion of their lands fallow or temporarily abandon them.

Researchers believe that a combination of shallow plowing (also known as conservation tillage) and leaving crop residues to decay in the fields tends to replace soil carbon deleted in the 19th and early 20th centuries. Further, abandoned croplands, even if they revert to grasslands rather than forest, will also

sequester carbon in the soil, so long as the abandoned lands are not permitted to erode.

Researcher J.S. Kern has estimated that the soil carbon pool in "major field cropland" in the lower 48 United States is in the range of 5.3 to 8.7 billion metric tons of carbon, and that total carbon losses from this pool since the settlement of the United States total 1.0 to 1.7 billion metric tons of carbon. Extrapolating from this estimate to the total United States may imply a total of 5 billion metric tons of carbon lost to the atmosphere from U.S. agricultural soils over the past 200 years.^b

Estimating current carbon emissions and sequestration from agricultural soils is difficult, because it requires matching cultivation and crop residue handling practices with land use, soils, and cultivation practices. Work by the U.S. Department of Agriculture may yield additional information at the national level in the future. Department of Agriculture researchers believe that there are an array of low-cost methods to sequester carbon in agricultural soils, including increasing the incidence of conservation tillage, encouraging spreading agricultural residues on soils, controlling erosion, and an array of "improved cropping systems." They assert that the carbon sequestration potential of agricultural lands is on the order of 75 to 208 million metric tons of carbon per year.^c

^aThe following discussion draws on: R. Lal, J.M. Kimble, R.F. Follet, and C.V. Cole, *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Chelsea, MI: Sleeping Bear Press, 1998).

^bR. Lal et al., p. 20.

^cR. Lal et al., p. 81.

⁹²D.S. Powell, J.L. Faulkner, D.R. Darr, Z. Zhu, and D.W. MacCleery, *Forest Resources of the United States, 1992*, USDA Forest Service General Technical Report RM-234 (Washington, DC, September 1993), p. 122.

Appendix A

Estimation Methods

The organization of this appendix generally follows the organization of the body of the report: the discussion is divided by greenhouse gas and by emissions source.

Carbon Dioxide

Most U.S. anthropogenic carbon dioxide emissions result from energy consumption. Energy production contributes a small amount from the flaring of natural gas at oil and gas wells and the scrubbing of carbon dioxide from natural gas, and a number of industrial processes also 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. Lastly, some small adjustments are made to reach the total for national emissions. This appendix describes each carbon dioxide emissions source, the estimation methods used, and the data sources.

Several emissions sources are excluded from the carbon dioxide emissions presented in this report, due either to the uncertainty of estimates or because they are based on biomass combustion (which is assumed to be consumed sustainably 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).

Energy Consumption

Emissions Sources

Most U.S. commercial energy is produced through the combustion of fossil fuels, such as coal, natural gas, and petroleum. Chemically, the main components of fossil fuels are hydrocarbons, made up of 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 can reduce the precision of the estimate. These complexities are discussed further in this appendix. Nonetheless, energy-related carbon dioxide emissions are known with greater reliability than are other greenhouse gas emissions sources, and the uncertainty of the estimate is probably in the 3 to 5 percent range. Appendix C, "Uncertainty in Emissions Estimates," contains an extended discussion of the nature and sources of uncertainty in the estimates presented in this report.

One real-world complexity is that not all the carbon in fuel is perfectly combusted. 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 volatile organic compounds (including methane), 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.

Estimation Methods

Carbon emissions in this report were calculated by multiplying energy consumption for each fuel type by an associated carbon emissions coefficient. The result was then modified by subtracting carbon sequestered by nonfuel use. This section describes the derivation of information on energy consumption, emissions coefficients, and carbon sequestered by nonfuel use.

Consumption Data

The Energy Information Administration (EIA) collects a wide variety of information from primary suppliers on a frequent basis and from energy consumers less 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.⁹³ To estimate carbon dioxide emissions, EIA uses annual data from the four end-use sectors (residential, commercial, industrial, and transportation) and 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. Definitions and heating values of the fossil fuels are documented in the appendixes 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. This year, the sectoral distribution of energy consumption used to estimate emissions in this report was adjusted to anticipate a future revision in EIA energy data (see box on page 73).

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 <401°F, petrochemical feedstocks with a boiling temperature ≥401°F, motor gasoline blending components, miscellaneous products, petroleum coke, pentanes plus, still gas, special naphthas, waxes, and unfinished oils.

Emissions Coefficients

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.⁹⁴ Most of the coefficients for major fuels are assumed to be constant over time. However, for motor gasoline, LPG, jet fuel, and crude oil, EIA developed annualized carbon emissions coefficients to reflect changes in chemical composition or product mix over the years. Appendix B contains a more detailed discussion of the methods employed for developing the coefficients. Table B1 in Appendix B presents a full listing of emissions factors for crude oil, natural gas, and the complete slate of petroleum products.

⁹³Although some of EIA's detailed sectoral surveys are conducted only every 3 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).

⁹⁴Combustion 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). Web site www.iea.org/ipcc/invs6.htm.

Corrections to Energy Consumption Information

While, in general, emissions can be estimated simply by multiplying fuel consumption by the appropriate emissions coefficients, several small adjustments to EIA energy statistics are necessary to eliminate double counting or miscounting of emissions. Usually the adjustments amount to less than 0.1 percent of energy-related carbon emissions. They include:

- **Ethanol.** About 70 million barrels of ethanol are included in annual U.S. gasoline consumption after 1992. Because ethanol is a biofuel, the carbon it contains should not be counted as an emission. Hence, carbon from ethanol is deducted from transportation gasoline consumption. Ethanol consumption is reported in EIA's *Renewable Energy Annual* and the *Petroleum Supply Annual*.
- **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 deducts the carbon in synthetic gas (as reported in the *Natural Gas Annual*) from industrial coal emissions.
- **Still gas to pipelines.** Several refineries sell small volumes of "still gas" as supplemental gas to pipelines. EIA deducts the carbon in still gas sales to pipelines (as reported in the *Natural Gas Annual*) from industrial "other petroleum" consumption.
- **Biogas.** The *Natural Gas Annual* reports that small volumes of "supplemental gas" of biological origin (probably landfill gas) are incorporated in U.S. pipeline gas supplies. In keeping with the accounting rule of excluding carbon of biological origin, these supplies are deducted from U.S. natural gas consumption.
- **Carbon dioxide in geothermal steam.** Geothermal steam at The Geysers in Guerneville, California, where most U.S. geothermal electric power is generated, contains appreciable amounts of carbon

Sectoral Split for Distillate and Residual Fuels in This Year's Report

EIA's *Monthly Energy Review (MER)* and the underlying *MER* data upon which this report is based detail energy consumption data by fossil fuel and by sector. The total consumption amounts by fuel are obtained from various EIA surveys that feed the *MER* data series and reflect the most up-to-date information available. During the early months of the year, the division of total fuel consumption among the residential, commercial, industrial, transportation, and electric utility sectors for the prior year, as reported in the *MER*, is in some cases inferred on the basis of the division among sectors during the prior year. As additional information becomes available, the inferred division is replaced with the actual division. When the sectoral split does not vary from one year to the next, the use of the previous year's split does not introduce problems. Between 1997 and 1998, however, several important factors produced a shift in fuel consumption among the end-use sectors. Because 1998 was an unusually warm year, demand for heating fuel was lower than in 1997; thus, the residential and commercial sector shares of distillate and residual fuel oil consumption should also have been lower. At the same time, the economy grew rapidly, theoretically increasing fuel use in the industrial and transportation sectors.

When the 1997 sectoral split is applied to the 1998 total for distillate and residual fuel, residential and commercial consumption is overstated and transportation and industrial consumption is understated. Consequently, for the calculation of 1998 greenhouse gas emissions, the sectoral splits were adjusted to

anticipate future revisions of *MER* energy data, so that the revisions could be included in this report.

The EIA publication *Fuel Oil and Kerosene Sales 1998* contains the sectoral splits needed to adjust the *MER* data to reflect a shift in consumption among sectors for distillate and residual fuels. To provide a better estimate of the sectoral split in 1998, the data from the *Fuel Oil and Kerosene Sales 1998* report were used in conjunction with the *MER* data. There are two data series in the report: actual and adjusted. The adjusted series matches the fuel totals from EIA's *Petroleum Supply Annual (PSA)*. Because the *MER* totals also match the *PSA* totals, the adjusted data series was used, and the totals for fuel consumption and emissions remained the same as reported in the *MER*. The total amounts were then reallocated to the four end-use sectors for 1998 according to the amounts given in the *Fuel Oil and Kerosene Sales 1998* report.

The table below shows the percentage changes in sectoral shares for the four end-use sectors. Residential and commercial consumption from the *MER* was adjusted downward by 13.3 percent and 7.8 percent for distillate and residual fuel, respectively. Industrial emissions were adjusted downward by 2.5 percent, because the weather-related component of energy consumption in the industrial sector (which includes, for example, farms) was enough to cause a decline in the use of distillate and residual fuels. Transportation emissions were adjusted upward by 3 percent, because diesel fuel consumption rose in conjunction with the economic expansion seen in 1998.

Sectoral Adjustments to 1998 Data for Distillate and Residual Fuel Consumption

(Quadrillion Btu)

Data Source	Fuel	Sector			
		Residential	Commercial	Industrial	Transportation
<i>MER</i>	Distillate	0.90	0.45	1.12	4.76
	Residual	0.00	0.11	0.26	0.68
	Total	0.90	0.55	1.39	5.44
<i>Fuel Oil Sales</i>	Distillate	0.78	0.42	1.11	4.91
	Residual	0.00	0.09	0.24	0.70
	Total	0.78	0.51	1.35	5.61
Percent Change		-13.3%	-7.8%	-2.5%	3.0%

Sources: **MER**: Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(99/09) (Washington, DC, September 1999). **Fuel Oil Sales**: Energy Information Administration, *Fuel Oil and Kerosene Sales 1998*, DOE/EIA-0535(98) (Washington, DC, August 1999).

Estimation Methods: Carbon Dioxide

dioxide dissolved in the steam, which is released into the atmosphere when the steam is brought to the Earth's surface for power production. EIA includes emissions from this source, at a rate of less than 0.1 million metric tons of carbon per year.

Carbon Sequestration: Nonfuel Use of Fossil Fuels

Gross emissions can be estimated by multiplying fossil fuel consumption by an emissions factor embodying the estimated carbon content of the fuel. However, portions of the fossil fuels consumed are not actually combusted but are used as chemical feedstocks, construction materials, lubricants, solvents, or reducing agents (Table A1). EIA estimates "nonfuel" use of fossil fuels annually in Table 1.15 of the *Annual Energy Review*.⁹⁵ For this report, EIA has estimated the fate of the carbon in fuels used for nonfuel purposes (see Table 5 in Chapter 2), based on the rates of sequestration shown in Table A2. Some but not all of the carbon is emitted to the atmosphere. The principal nonfuel uses of fossil fuels, the methods of estimating nonfuel consumption, and the fate of the carbon are listed below.

- **Natural Gas.** Nonfuel use of natural gas is based on periodic (1985, 1988, 1991, and 1994) reports in EIA's Manufacturing Energy Consumption Survey

(MECS). Based on MECS, nonfuel use is divided into three categories: nitrogenous fertilizers, other chemical use, and all other nonfuel uses. Feedstock use of natural gas to make nitrogenous fertilizers is a nonsequestering use, because the underlying chemical in nitrogenous fertilizers is ammonia (NH₃), which is manufactured by steam reforming of natural gas and reacting the synthesis gas with atmospheric nitrogen, leaving the carbon in the feedstock literally "up in the air." In many cases, the carbon dioxide is recovered to make urea or for industrial use. However, carbon in urea and industrial carbon dioxide are generally only temporarily delayed on their way to the atmosphere. EIA assumes that other nonfuel uses in the chemical industry result in 100-percent carbon sequestration. Natural gas is used as a feedstock for a range of chemical products other than ammonia, particularly methanol. 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 to count it again in the feedstock would be 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.

Table A1. U.S. Fossil Fuel Consumption for Nonfuel Use, 1990-1998
(Quadrillion Btu)

End Use	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Petroleum									
Asphalt and Road Oil	1.17	1.08	1.10	1.15	1.17	1.18	1.18	1.22	1.26
Liquefied Petroleum Gases	1.20	1.38	1.39	1.35	1.55	1.59	1.65	1.65	1.58
Pentanes Plus	0.08	0.04	0.06	0.28	0.26	0.30	0.32	0.30	0.26
Lubricants	0.36	0.32	0.33	0.34	0.35	0.35	0.34	0.35	0.37
Industrial	0.19	0.17	0.17	0.17	0.18	0.18	0.17	0.18	0.19
Transportation	0.18	0.16	0.16	0.16	0.17	0.17	0.16	0.17	0.18
Petrochemical Feed	1.12	1.15	1.20	1.22	1.26	1.21	1.21	1.40	1.40
Petroleum Coke	0.18	0.16	0.25	0.17	0.18	0.19	0.21	0.22	0.31
Special Naphtha	0.11	0.09	0.10	0.10	0.08	0.07	0.07	0.07	0.11
Other (Waxes and Misc.)	0.23	0.26	0.20	0.20	0.20	0.20	0.19	0.20	0.22
Coal	0.02	0.02	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Natural Gas to Chemical Plants	0.59	0.59	0.61	0.62	0.69	0.69	0.70	0.72	0.75
Total	5.07	5.09	5.29	5.45	5.77	5.81	5.89	6.16	6.29

P = preliminary data.

Notes: Asphalt and lubricants are as reported in EIA's *State Energy Data Report 1996*, DOE/EIA-0214(96) (Washington, DC, February 1999) for 1990-1996, and *Monthly Energy Review*, DOE/EIA-0035(99/09) (Washington, DC, September 1999) for 1997 and 1998. Some slight differences exist between this table and the *Annual Energy Review*. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Source: Energy Information Administration, *Annual Energy Review 1998*, DOE/EIA-0384(98) (Washington, DC, July 1999), Table 1.15, p. 33, and underlying estimates.

⁹⁵Energy Information Administration, *Annual Energy Review 1998*, DOE/EIA-0384(98) (Washington, DC, July 1999), p. 33.

Table A2. Rates of Sequestration for U.S. Fossil Fuel Consumption

Fuel Type	Fraction of Fuel Combusted	Fraction of Nonfuel Use of Energy Sequestered
Petroleum		
Motor Gasoline	0.990	--
LPG	0.995	0.80
Jet Fuel	0.990	--
Distillate Fuel	0.990	0.50
Residual Fuel	0.990	0.50
Asphalt and Road Oil	0.990	1.00
Lubricants	0.990	0.50
Petrochemical Feed	0.990	0.75
Aviation Gas	0.990	--
Kerosene	0.990	--
Petroleum Coke	0.990	0.50
Special Naphtha	0.990	0.00
Other		
Aviation Gas		
Blending Components	0.990	--
Crude Oil	0.990	--
Naphtha <401°F	0.990	0.75
Other Oil ≥401°F	0.990	0.50
Petrochemical Feed		
Still Gas	0.990	0.80
Motor Gasoline		
Blending Components	0.990	--
Miscellaneous	0.990	1.00
Natural Gasoline	0.990	--
Plant Condensate	0.990	--
Pentanes Plus	0.990	0.80
Still Gas	0.995	--
Special Naphthas	0.990	0.00
Unfinished Oils	0.990	--
Unfractionated Stream	0.990	--
Waxes	0.990	1.00
Coal		
Residential and Commercial	0.990	--
Industrial Coking	0.990	0.75
Industrial Other	0.990	--
Electric Utility	0.990	--
Natural Gas		
Flare Gas	1.000	--
Natural Gas	0.995	0.29-0.52
Crude Oil		
	0.990	--

Sources: EIA estimates documented in this chapter; and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.28-1.29, web site www.iea.org/ipcc/invs6.htm.

- Liquefied Petroleum Gases.** Nonfuel use of LPG (ethane, propane, and butane) through 1996 is estimated on the basis of sales of these products to the chemical industry, as reported in the American Petroleum Institute (API) survey, *Sales of Natural Gas Liquids and Liquefied Refinery Gases*, from which EIA deducts chemical industry fuel use of LPG as reported periodically in the MECS. For 1997 and 1998, the sales to the chemical industry are estimated based on the 1996 ratio of the API's data to EIA's *Petroleum Supply Annual* (PSA) value for LPG, which is then multiplied by the PSA data for 1997 and 1998. Most of the ethane, propane, and butane used by the chemical industry is used to manufacture ethylene, propylene, and butadiene, respectively, all of which are intermediate products for plastics. Following the recommendation of the Intergovernmental Panel on Climate Change (IPCC), EIA assumes that 80 percent of nonfuel use is sequestered in plastics, synthetic rubber, and related products.⁹⁶
- Asphalt and Road Oil.** EIA assumes that asphalt and road oil use is nonfuel use by definition, and that all carbon in asphalt and road oil is sequestered.
- Pentanes Plus.** "Pentanes plus" are hydrocarbons heavier than butane extracted from natural gas at gas processing plants. Their principal uses are as contributors to the gasoline pool and as petrochemical feedstocks. Nonfuel use of pentanes plus is estimated on the basis of the API's annual survey of natural gas liquids and refinery gases sold to the chemical industry. Following IPCC practice for LPG, EIA assumes that 80 percent of the carbon in pentanes plus used by the chemical industry is sequestered.
- Petrochemical Feedstocks.** EIA's petroleum surveys recognize two categories of products called "petrochemical feedstocks." These are presumably naphtha and gas oils destined for ethylene crackers, and probably some mix of aromatic hydrocarbons (benzene, toluene, and xylene) and feedstocks used to make aromatic hydrocarbons. All petrochemical feedstock supplies are included in nonfuel use by definition, and, following the practice of the IPCC, EIA assumes that 75 percent of the carbon in synthetic feedstocks and 50 percent of the carbon in gas oil feedstock is sequestered in plastics, synthetic fibers, and related products.

⁹⁶Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.28, web site www.iea.org/ipcc/invs6.htm.

- **Distillate and Residual Fuels.** The MECS reports small volumes (10 million barrels and 1 million barrels, respectively) of distillate and residual oils used for nonfuel purposes in the chemical industry. Following the practice for gas oil petrochemical feedstocks, EIA assumes 50-percent sequestration. Future research may shed more light on the industrial processes that use these fuels.
- **Petroleum Coke.** Petroleum coke is a coal-like solid, about 90 percent carbon by weight, 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. EIA estimates nonfuel use by taking the quantity of petroleum coke supplied and deducting all known fuel uses (refinery use from the *Petroleum Supply Annual*, electric utility use from the *Electric Power Annual*, and industrial use from the MECS). EIA assumes that 50 percent of the carbon in petroleum coke for nonfuel use is sequestered. It should be noted, however, that significant sequestering nonfuel uses of petroleum coke in the United States are difficult to identify. The principal identified nonfuel use is for sacrificial anodes in primary aluminum smelting, a nonsequestering use that EIA counts separately under process emissions (see the next section). 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, nonsequestering uses.
- **Still Gas.** 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. EIA estimates nonfuel use by deducting all known fuel uses (refinery fuel use from the *Petroleum Supply Annual* and pipeline gas supplies from the *Natural Gas Annual*). The remainder is assumed to be dispatched to chemical plants as a feedstock. Following the IPCC practice for LPG, EIA assumes that 80 percent of the carbon in still gas is sequestered.
- **Special Naphtha.** “Special naphtha” is a catch-all 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” after use and swiftly weather into atmospheric carbon dioxide. EIA assumes that all special naphthas are for nonfuel use and that no carbon in special naphtha is sequestered.
- **Lubricants.** The most common petroleum-based lubricant is motor oil, but the category also includes numerous other products, such as industrial greases. Following the IPCC, EIA assumes that 50 percent of the carbon in lubricants is sequestered. 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.
- **Waxes and Polishes.** The principal use of waxes is to make wax paper and food packaging materials, which usually end up in landfills. Following the IPCC, EIA assumes 100-percent nonfuel use and 100-percent carbon sequestration for these materials.
- **Miscellaneous.** EIA assumes 100-percent nonfuel use and 100-percent carbon sequestration for this category.
- **Coal.** The manufacture of coke is the largest nonfuel use of coal. By 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. Coal tar production was obtained, for years prior to 1995, from the International Trade Commission’s *Synthetic Organic Chemicals*. Since 1995, production has been estimated on the basis of the ratio of 1994 coke production to coal tar production. Following the IPCC guidelines, EIA assumes that 75 percent of the carbon in coal tars is sequestered.

Carbon Sequestration: Fraction Combusted

A small amount of carbon sequestration is associated with the combustion of fossil fuels. Using IPCC assumptions, EIA assumes that oxidation of liquid and solid fuels during combustion is 99 percent complete, and that 1 percent of the carbon remains sequestered. Oxidation of gaseous fuels (LPG and natural gas) is

assumed to be 99.5 percent complete.⁹⁷ Conceptually, fuel may be “lost” before combustion due to evaporation, leaks, or spills; it may be subject to incomplete combustion and vented to the atmosphere in the form of volatile organic compounds or particulates; or it may remain at the site of combustion in the form of carbon-containing ash or soot.

Data Sources

Fossil Fuel Consumption: Energy Information Administration, *State Energy Data Report 1996*, DOE/EIA-0214(96) (Washington, DC, February 1999). (1997-1998): Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(99/09) (Washington, DC, September 1999); *Petroleum Supply Annual 1998*, DOE/EIA-0340(98)/1 (Washington, DC, June 1999); *Natural Gas Annual 1997*, DOE/EIA-0131(97) (Washington, DC, October 1998); and *Renewable Energy Annual 1998*, DOE/EIA-0603(98) (Washington, DC, December 1998).

Nonfuel Use of Energy and Biofuels Consumption: Energy Information Administration, *Annual Energy Review 1998*, DOE/EIA-384(98) (Washington, DC, July 1999); Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), and previous years (1985, 1988, and 1991); American Petroleum Institute, *Sales of Natural Gas Liquids and Liquefied Refinery Gas* (various years); U.S. International Trade Commission, *Synthetic Organic Chemicals*, USITC Publication 2933 (various years through 1994); and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.28, web site www.iea.org/ipcc/invs6.htm.

Adjustments to U.S. Energy Consumption

In recent years, there have been several estimates of U.S. carbon emissions, some of which differ by as much as 5 percent. Two significant reasons for the differences in emissions estimates (beyond those associated with differences in coefficients) are the definitions of “energy consumption” and “the United States” employed by researchers. Subtle differences in definition can produce variations of several percentage points in reported energy consumption and, hence, in carbon emissions. Some estimates include U.S. territories while others exclude them. If consumption is estimated as “apparent consumption” based on production plus imports minus exports plus stock change, then statistical discrepancies

will be included in consumption. International bunker fuels are sometimes counted as domestic consumption and sometimes as exports. This section describes how each adjustment is accommodated in the EIA estimates.

U.S. Territories

Emissions Sources

EIA’s energy data for the United States cover only the 50 States and the District of Columbia. In contrast, energy data produced by the International Energy Agency for the United States cover the 50 States plus U.S. territories, including Puerto Rico, the U.S. Virgin Islands, and Guam. Annual energy consumption in the U.S. territories is only about 0.5 quadrillion Btu (Table A3). Because all the U.S. territories are islands, their consumption consists primarily of petroleum products. For the territories as a group, oil consumption ranges between 220,000 and 325,000 barrels per day, and coal consumption averages 315,000 to 425,000 short tons per year, in the U.S. Virgin Islands and Puerto Rico.

Estimation Methods

Energy consumption for U.S. territories is converted to carbon emissions by using the same emissions coefficients applied to U.S. energy data. Carbon emissions for U.S. territories range from 9 to 12 million metric tons per year (see Table 4 in Chapter 2). Because a large portion of reported energy consumption in U.S. territories is from “other petroleum,” there is a degree of uncertainty about the correct emissions factor to be used in this area, as well as the reliability of underlying data.

Data Sources

1980-1997: Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, DC, various years), and the International Energy Database (March 1999). **1998:** EIA estimate.

International Bunker Fuels

Emissions Sources

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.

⁹⁷Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.29, web site www.iea.org/ipcc/invs6.htm.

Table A3. Energy Consumption in U.S. Territories, 1990-1998
(Quadrillion Btu)

Place	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Puerto Rico	0.30	0.37	0.33	0.34	0.36	0.35	0.33	0.34	0.36
Virgin Islands	0.12	0.12	0.11	0.13	0.14	0.17	0.18	0.21	0.26
American Samoa	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Guam	0.03	0.03	0.03	0.05	0.06	0.05	0.04	0.04	0.03
U.S. Pacific Islands	*	*	*	*	*	*	*	*	*
Wake Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	0.47	0.55	0.50	0.55	0.58	0.60	0.58	0.63	0.68

*Less than 5 trillion Btu.

P = preliminary data.

Notes: Energy consumption in Micronesia ranged from 0.002 to 0.004 quadrillion Btu. Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Sources: Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (various years), and unpublished data included in "Other" countries in the Asia/Pacific region. Data are shown in tables of "Apparent Consumption of Petroleum Products." Data for 1998 based on unpublished preliminary information.

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. Table A4 shows U.S. international bunker fuel usage. For 1998, the amount consumed is about 1.49 quadrillion Btu, largely from kerosene-based jet fuel and residual oil. International bunker fuels account for emissions of about 30 million metric tons of carbon annually which are then subtracted from the U.S. inventory total (see Table 4 in Chapter 2).

Estimation Methods

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. It is assumed that 99 percent of the fuel is combusted. 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

reflects 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 are 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.

Data Sources

Distillate and Residual Fuels (1980-1987): Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (Washington, DC, various years). **(1988-1989, 1991-1998):** U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division, "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries" (unpublished, various years); EIA estimate. **Jet Fuels (1980-1987):** Oak Ridge National Laboratory, *Transportation Energy Data Book* (Oak Ridge, TN, various years). **(1988-1998):** U.S. Department of Commerce, Bureau of Economic Analysis, unpublished BE-36 survey data (various years); Air Transportation Association, *Monthly Fuel Cost and Consumption* (various years), web site www.air-transport.org/public/industry/16.asp.

Other Carbon Dioxide Emissions

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 (natural gas flaring) or by chemical reactions with carbon-containing minerals (for example,

Table A4. Carbon Emissions from International Bunker Fuels Supplied in the United States, 1990-1998

Item	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Carbon Emissions (Million Metric Tons)									
Marine Bunkers									
Distillate Fuel	1.6	1.6	1.5	1.7	1.4	1.6	1.2	1.2	1.7
Residual Fuel	16.9	17.1	14.3	11.4	11.2	11.1	11.4	12.2	12.7
Total Marine	18.5	18.7	15.8	13.0	12.6	12.7	12.7	13.4	14.4
Aviation Bunkers									
U.S. Carriers	5.0	5.0	5.3	5.3	5.5	5.7	6.0	6.3	6.6
Foreign Carriers	5.8	6.1	6.3	6.6	6.7	7.2	7.5	8.2	8.8
Total Aviation	10.9	11.1	11.6	11.9	12.3	13.0	13.5	14.5	15.4
Total Carbon Emissions	29.3	29.8	27.4	24.9	24.8	25.7	26.1	27.9	29.8
Fuel Consumption (Quadrillion Btu)									
Marine	0.9	0.9	0.7	0.6	0.6	0.6	0.6	0.6	0.7
Aviation	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.8	0.8
Total	1.4	1.5	1.4	1.2	1.2	1.3	1.3	1.4	1.5

P = preliminary data.

Source: EIA estimates, based on unpublished fuel consumption data from the U.S. Department of Commerce.

calcining sodium carbonate [limestone] to make lime or cement).

Energy Production

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.⁹⁸ 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 Methods

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 emissions, the figures are aggregated, converted into Btu, and then multiplied by an emissions coefficient of 14.92 million metric tons of carbon per quadrillion Btu.

As estimates presented in Chapter 2 indicate, natural gas flaring is a minor source of emissions, accounting for only about 2 to 5 million metric tons of carbon annually. There is some uncertainty associated with this estimate, given that operators in the field are not required to meter gas that is vented or flared.

The carbon dioxide produced in conjunction with natural gas is estimated by multiplying regional natural gas production data by regional carbon dioxide contents from a Gas Research Institute (GRI) study. The estimates of carbon dioxide emitted during transmission and distribution are derived by multiplying pipeline and end-use consumption data by the carbon dioxide content of natural gas delivered to consumers from a second GRI study. Emissions associated with production activities are calculated by subtracting consumption-related emissions from the total carbon dioxide initially produced.

⁹⁸See discussion of carbon dioxide manufacture for the treatment of vented carbon dioxide.

Data Sources

Flaring (1980-1997): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). **(1998):** *Natural Gas Monthly*, DOE/EIA-0130(99/08) (Washington, DC, August 1999). **Carbon Dioxide Produced with Natural Gas: Composition (1980-1998):** Gas Research Institute, *Chemical Composition of Discovered and Undiscovered Natural Gas in the United States: 1993 Update*, GRI-93/0456.1; Gas Research Institute, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*, GRI-92/0123. **Production (1980-1996):** Dwight's Energy Data Lease/Well Production File. **(1997):** Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, 1998). **(1998):** Energy Information Administration, *Natural Gas Monthly*, DOE/EIA-0130(99/06) (Washington, DC, June 1999). **Transmission and End-Use Consumption (1980-1997):** Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). **(1998):** Energy Information Administration, *Natural Gas Monthly*, DOE/EIA-0130(99/06) (Washington, DC, June 1999).

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 (CaCO₃) to create lime (CaO). These two compounds are basic materials in a variety of manufacturing processes, particularly cement, iron and steel, and glass. Other sources of industrial emissions include the production and use of soda ash (Na₂CO₃), the manufacture of carbon dioxide, and aluminum production.

For this source category, emissions estimates are based on the compound used in the industrial process. Table A5 shows activity data for industrial processes. 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. In recent years (1990 through 1998), carbon dioxide emissions from industrial sources have ranged from 16 to 19 million metric tons of carbon annually. Each industrial process, emissions source, and estimation method is discussed below.

Table A5. Production Data for Industrial Sources of Carbon Dioxide, 1990-1998
(Thousand Metric Tons)

Item	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Cement Clinker	63,326	61,608	62,184	65,745	69,787	69,983	70,361	72,686	75,254
Masonry Cement	2,911	2,592	2,806	2,962	3,613	3,603	3,469	3,634	3,700
Lime Produced	15,832	15,667	16,199	16,700	17,400	18,500	19,200	19,700	19,300
Limestone in Iron Smelting	3,955	3,635	3,098	2,561	2,538	2,615	2,538	2,549	2,574
Limestone in Steelmaking	682	738	612	1,087	1,225	1,126	949	750	798
Limestone in Glass	272	269	354	439	680	754	450	203	203
Limestone in FGD	4,369	4,552	4,479	4,274	4,621	5,815	6,125	6,595	6,595
Dolomite	986	732	641	549	526	428	691	691	691
Soda Ash Production	8,147	8,152	8,269	8,056	8,111	9,167	9,056	9,500	9,738
Soda Ash in Glass	3,177	2,997	3,082	3,095	3,150	3,130	3,040	3,130	3,130
Soda Ash in FGD	179	155	156	146	191	211	206	295	295
Sodium Silicate	740	789	827	913	914	1,091	1,002	1,101	1,040
Sodium Tripolyphosphate	451	419	419	419	419	419	419	419	419
Aluminum Manufacture	4,048	4,121	4,042	3,695	3,299	3,375	3,577	3,603	3,700
Copper Primary Smelting	1,577	1,580	1,710	1,790	1,840	1,930	2,010	2,060	2,140

P = preliminary data.

Sources: U.S. Department of the Interior, Geological Survey, *Mineral Commodity Summaries* (Washington, DC, various years). U.S. Department of the Interior, United States Geological Survey, *Cement Annual Report* (Washington, DC, various years). American Iron and Steel Institute, *Annual Statistical Report* (Washington, DC, various years). U.S. Department of the Interior, Geological Survey, *Soda Ash Annual Report* (Washington, DC, various years) (soda ash production calculated from quantity of trona ore production). U.S. Department of the Interior, Geological Survey, *Crushed Stone Annual Report* (Washington, DC, various years). Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1997* (Washington, DC, September 1997). Energy Information Administration unpublished survey data, *Steam Electric Plant Operation and Design Report, Form EIA-767* (Washington, DC, various years). Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), and *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994).

Cement Manufacture

More than half of the carbon dioxide emissions from industrial sources originate from cement manufacturing (see Chapter 2).

Emissions Sources. 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 Methods. One mole of calcined 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. In order to estimate emissions from cement manufacture, a carbon coefficient must be calculated. EIA has adopted the IPCC recommendation that 64.6 percent of cement clinker is lime.⁹⁹ Multiplying this lime content factor by the ratio of carbon produced to lime produced yields the coefficient for cement clinker. A separate coefficient is necessary for estimating emissions from the additional lime used to produce masonry cement. In this case, the amount of lime not accounted for as clinker is assumed to be 3 percent.¹⁰⁰ This factor is then multiplied by the same production ratio of carbon to lime, generating the carbon coefficient for masonry cement.

Lime Manufacture

Lime is an important chemical with a variety of industrial, chemical, and environmental applications.

Emissions Sources. 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 Methods. Based on the ratio of the molecular weight of carbon dioxide to the weight of calcium carbonate, EIA assumes that 785 metric tons of carbon dioxide, or 214 metric tons of carbon, are released for every 1,000 metric tons of lime produced. This factor is applied to annual levels of lime manufacture to estimate potential emissions. 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.

Limestone and Dolomite Consumption

These are basic raw materials used by a wide variety of industries, including the construction, agriculture, chemical, and metallurgical industries.

Emissions Sources. Limestone (including dolomite) can be used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems in utility and industrial plants, or as a raw material in glass manufacturing. Limestone is heated during these processes, generating carbon dioxide as a byproduct.

Estimation Methods. Assuming that limestone has a carbon content of 12 percent and dolomite 13.2 percent, EIA applies the appropriate factor to the annual level of consumption in the iron smelting, steelmaking, and glass manufacture industries, and in flue gas desulfurization systems that use this sorbent. This amounts to 120 metric tons of carbon for every 1,000 metric tons of limestone consumed, or 132 metric tons of carbon for every 1,000 tons of dolomite consumed (when dolomite is distinguished in the data). In the case of limestone (including dolomite) used in flue gas desulfurization units, the estimate of carbon emitted was adjusted based on the application of a capacity utilization rate from the calcination process of sorbents used, typically limestone (including dolomite). According to information obtained in May 1999 from the U.S. Geological Survey 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. In this edition of *Emissions of Greenhouse Gases in the United States*, estimates of carbon dioxide emissions from the use of limestone as a sorbent in flue gas desulfurization units have been revised to reflect this newly acquired information on calcium utilization.

Soda Ash Manufacture and Consumption

Commercial soda ash (sodium carbonate) is used in many familiar consumer products, such as glass, soap and detergents, paper, textiles, and food.

⁹⁹Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.6, web site www.iea.org/ipcc/invs6.htm.

¹⁰⁰U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1993* (Washington, DC, 1994), p. 32.

Emissions Sources. 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 driven off 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 and sodium tripolyphosphate are included as chemicals manufactured from soda ash and components of detergents.

Estimation Methods. For soda ash manufacture, in order to ensure that carbon dioxide from the carbonation of brines is not included in emissions estimates, 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 million metric tons of carbon for every 1,000 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.

Carbon Dioxide Manufacture

Emissions Source. 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, in the United States, there is an 80 percent to 20 percent split between carbon dioxide produced as a byproduct and carbon dioxide produced from wells.¹⁰¹ Emissions of byproduct carbon dioxide are incorporated into the natural gas energy consumption estimates as nonfuel, 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 Methods. The Freedonia Group estimates that non-sequestering industrial use of carbon dioxide resulted in emissions of 1.3 million metric tons of carbon in 1993.¹⁰² If 20 percent of this industrial use is supplied by wells, emissions can be estimated at 0.26 million metric tons of carbon. Based on the Freedonia report, the 1998 estimate is calculated by assuming an annual 4.2-percent increase, implying emissions of 0.32 million metric tons of carbon.

Aluminum Manufacture

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 the electricity used to generate the 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 nonsequestering nonfuel use of a fossil fuel. To avoid double counting, 50 percent of nonfuel use of petroleum coke is carried as "sequestering." Thus, process emissions from aluminum smelting can be considered as a deduction from the sequestering portion of nonfuel use of petroleum coke.

Estimation Methods. In previous years, following the work of Abrahamson, EIA has used the midpoint of a range of emissions factors of 1.5 to 2.2 metric tons of carbon dioxide (0.41 to 0.60 metric tons of carbon) emitted per metric ton of aluminum smelted.¹⁰³ The 1994 MECS indicated that nonfuel use of fuels by aluminum smelters (SIC 3334) totaled 40 trillion Btu in 1994.¹⁰⁴ The composition of nonfuel use by fuel type has been withheld for confidentiality purposes, but it is

¹⁰¹The Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), p. 46.

¹⁰²The Freedonia Group, Inc., *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994), p. 37.

¹⁰³D. Abrahamson, "Aluminum and Global Warming," *Nature*, Vol. 356 (April 1992), p. 484.

¹⁰⁴Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), Table A3, p. 49.

probable that most of the 40 trillion Btu consists of petroleum coke, which would imply an emissions factor of about 0.338 metric tons of carbon per metric ton of aluminum smelted (0.04 quadrillion Btu of coke \times 27.85 million metric tons of carbon per quadrillion Btu / 3.295 million metric tons of aluminum smelted in 1994). EIA now uses an emissions factor of 0.4 metric tons carbon per metric ton of aluminum smelted, which is at the low end of Abrahamson's range and also equals the mass balance for a "typical" aluminum smelter from another source.¹⁰⁵

Data Sources for Industrial Processes

The U.S. Geological Survey reports listed below can be found on the Internet at minerals.er.usgs.gov/pubs/commodity.

Cement and Clinker Production (1980-1997): U.S. Department of the Interior, U.S. Geological Survey, *Cement Annual Report* (Washington, DC, various years). **(1998):** Clinker production is an EIA estimate, based on cement production from the U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries* (Washington, DC, 1999).

Lime Manufacture: (1980-1998): U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries* (Washington, DC, various years).

Limestone Consumption in Iron Smelting, Steel-making, and Glass Manufacture: (1980-1997): U.S. Department of the Interior, U.S. Geological Survey, *Crushed Stone Report* (Washington, DC, various years). **(1998):** EIA estimate. **Limestone Consumption in Flue Gas Desulfurization: (1980-1997):** Energy Information Administration, unpublished survey data, Form EIA-767, "Steam Electric Plant Operation and Design Report" (Washington, DC, various years). **(1998):** EIA estimate.

Soda Ash Manufacture and Soda Ash Consumption in Glass Making (1980-1998): U.S. Department of the Interior, U.S. Geological Survey, *Soda Ash Report* (Washington, DC, various years). **Soda Ash Consumption in Flue Gas Desulfurization (1980-1997):** Energy Information Administration, unpublished survey data, Form EIA-767, "Steam Electric Plant Operation and Design Report" (Washington, DC, various years). **(1998):** EIA estimate. **Sodium Silicate and Sodium Tripolyphosphate: (1980-1997):** Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1998* (Washington, DC, September 1998), pp. 37-38. **(1998):** EIA estimate.

Carbon Dioxide: Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), and *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994).

Aluminum (1980-1998): U.S. Department of the Interior, U.S. Geological Survey, *Aluminum Report* (Washington, DC, various years).

Methane

Energy Sources

Oil and 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.¹⁰⁶ 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

¹⁰⁵Drexel University Project Team, *Energy Analysis of 108 Industrial Processes* (Lilburn, GA: The Fairmont Press, 1996), p. 282.

¹⁰⁶National 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.

periods of high consumption. These storage facilities emit methane in compressor exhaust and from dehydrators.

- **Distribution.** The pressure of gas received from the transmission system is lowered at the gate station and 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.

Methane may also be emitted during *oil refining and transportation*. These emissions occur when methane is separated from crude oil during refining. After oil is transferred to storage tanks methane may be emitted by vapor displacement. Vapor displacement also occurs during loading and unloading of oil barges and tankers.

Estimation Methods

Natural Gas Systems. 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. The activity data are multiplied by emissions factors derived from point-in-time emissions estimates for 1992 developed in a study sponsored jointly by the U.S. Environmental Protection Agency (EPA) and the Gas Research Institute (EPA/GRI).¹⁰⁷ The EPA/GRI study provides activity data and disaggregated emissions factors for 86 separate gas industry process components. In an effort to take advantage of this level of detail, this report estimates the number of each process component for the years 1990-1998. Each process component is scaled to a widely available metric, such as gas withdrawals or pipeline miles most related to the process activity. The derived activity data are then applied to the component emissions factor from the EPA/GRI report.

Oil Wells. The number of operating oil wells in the United States is multiplied by a per-well emissions factor from the EPA's report to Congress, *Anthropogenic Methane Emissions in the United States*.¹⁰⁸

Oil Refining and Transportation. Estimates are calculated by using emissions from a 1992 Radian Corporation report¹⁰⁹ in conjunction with refinery data collected by EIA.

Data Sources

Natural Gas Systems. Emission factors and activity data for 1992 are from the joint EPA/GRI study: 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). 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* (various years); transmission and distribution pipeline mileage are published annually by the American Gas Association in *Gas Facts*.

Oil Wells. The number of operating oil wells is available annually in the February issue of the *World Oil* journal.

Oil Refining and Transportation. Data on the volume of crude oil refined and the volume of crude oil transported on marine vessels can be found in EIA's *Annual Energy Review*, DOE/EIA-0384 (Washington, DC, various years), and *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

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:

- **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

¹⁰⁷National 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.

¹⁰⁸U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, Report to Congress (Washington, DC, April 1993), p. 2-22.

¹⁰⁹Radian Corporation, *Global Emissions of Methane From Petroleum Sources*, Prepared for the American Petroleum Institute (Research Triangle Park, NC, February 1992), Table A-1, p. A-1.

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.

- **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.
- **Surface Mines.** Because coal mined from the surface has formed at lower temperature and pressure 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. Thus, while methane emissions from surface mines are heterogeneous in nature, they are systematically smaller than emissions from underground mines.
- **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, methane remaining in the coal pores after transport will be released prior to combustion.
- **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 permit commercial recovery of the gas as either pipeline gas, power generation fuel, or mine site uses. Because coal mine methane recovered commercially is combusted, the quantities recovered are subtracted from estimates of total coal mine methane emissions.

Estimation Methods

Ventilation Systems in Underground Mines. Emissions from this source are segregated into two classes: emissions from “gassy” mines and emissions from “nongassy” mines.¹¹⁰ Because methane concentrations and airflows in gassy mines are carefully monitored by the MSHA, a fairly reliable set of data can be derived for emissions from ventilation systems in gassy mines. However, MSHA data are voluminous, inconsistent in format, and difficult to compile, and they are available for only a subsample of years (1980, 1985, 1988, 1990, 1993, 1994, 1996, 1997, 1998). Thus, the available data are used in conjunction with coal production data for those years to develop emissions factors per ton of coal mined on a basin-by-basin level (Table A6).¹¹¹ Emissions factors for nonsample years are interpolated or extrapolated. The resulting emissions factors are then multiplied by production data (see Table A7) to estimate emissions from this source.

Emissions from nongassy mines make up less than 2 percent of all emissions from underground mines.¹¹² Basin-level emissions 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 emissions factors are applied to annual production data. For 1998, emissions from nongassy mines are scaled to changes in emissions from gassy mines.

Degasification Systems in Underground Mines. 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 through 1996 are based on data collected by the EPA’s Office of Air and Radiation, Coalbed Methane Outreach Program, and published in *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*.¹¹³ For years prior to 1993 and for 1997, emissions from degasification systems are estimated by multiplying annual production in mines known to have degasification systems in place by a per-ton emissions

¹¹⁰Gassy 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.

¹¹¹For purposes of this analysis, the Northern Appalachia basin includes Pennsylvania, Northern West Virginia, Maryland, and Ohio; the Central Appalachia basin 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.

¹¹²M.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.

¹¹³U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997), p. 5-19.

Table A6. Methane Emissions Factors for Gassy Underground Coal Mines, 1990-1998
(Cubic Feet Per Day Per Short Ton of Coal Produced)

Basin	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Northern Appalachia	1.01	1.09	1.17	1.24	0.79	0.80	0.81	0.75	0.75
Central Appalachia	1.45	1.42	1.39	1.35	1.17	1.17	1.17	0.98	0.98
Warrior	4.62	4.48	4.34	4.20	5.31	4.63	3.94	3.62	3.62
Illinois	0.44	0.46	0.48	0.49	0.47	0.49	0.50	0.45	0.45
Western	1.51	1.33	1.15	0.96	1.11	0.98	0.85	1.39	1.39

P = preliminary data.

Sources: Coal Production numbers from Energy Information Administration Form 7-A, *Coal Production*, DOE/EIA-0118 (Washington, DC, various years), and *Coal Industry Annual*, DOE/EIA-0584, Ventilation data for 1990 and 1993 provided by G. Finfinger, U.S. Department of Interior, Bureau of Mines, Pittsburgh Research Center. Ventilation data for 1994, 1996, and 1997 provided by Roger Fernandez, U.S. Environmental Protection Agency, Coalbed Methane Outreach Program.

Table A7. U.S. Coal Production by Type of Mining and Basin for Mines With Annual Production Exceeding 10,000 Tons, 1990-1998
(Million Metric Tons)

Mine Type and Basin	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Underground									
Northern Appalachia	95.5	93.5	92.5	69.7	90.8	88.6	96.5	101.7	NA
Central Appalachia	178.6	165.3	164.1	149.1	155.0	151.0	155.9	161.2	NA
Warrior	15.9	15.5	14.5	14.1	13.1	16.0	16.5	16.8	NA
Illinois	62.8	63.5	66.4	50.8	62.8	62.6	60.9	58.9	NA
Western	31.3	30.8	31.1	34.1	40.3	40.8	41.6	43.0	NA
Total Underground	384.2	368.6	368.6	317.8	362.0	359.0	371.4	381.5	381.6
Surface	548.3	534.0	535.4	539.1	575.4	577.5	593.2	607.0	632.5
Total, All Mines	933.4	903.4	904.7	857.5	937.4	936.8	965.0	988.5	1,014.0

P = preliminary data. NA = data not available.

Sources: Energy Information Administration, *Coal Industry Annual*, DOE/EIA-0584 (various years).

factor. Because mine-by-mine production data are not yet available for the current year, 1998 emissions from degasification systems were scaled up to match the increase in degasification activity report to EIA's 1605(b) Voluntary Reporting of Greenhouse Gases Program.

Surface Mines. Emissions from U.S. surface mines have not been systematically measured. However, 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.¹¹⁴ This report adopts the central value of that range and multiplies it by U.S. surface coal production.

Post-Mining Emissions. Like emissions from surface mines, post-mining emissions are not measured systematically. Thus, global average emissions 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.¹¹⁵ The central values of these ranges are adopted and multiplied by annual production data for this report.

Methane Recovery for Energy. Methane recovery for energy is restricted to a small sample of mines that

¹¹⁴Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.98-1.112, web site www.iea.org/ipcc/invs6.htm.

¹¹⁵Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.98-1.112, web site www.iea.org/ipcc/invs6.htm.

typically meter their gas sales. Thus, total methane recovery can be estimated from the volume and heat content of sales.

Data Sources

Ventilation Systems in Underground Mines. Coal mine ventilation data for the approximately 200 gassiest U.S. mines were drawn from a database prepared by the Department of Interior's Bureau of Mines for the years 1980, 1985, 1988, 1990, and 1993. Ventilation data for 1994, 1996, 1997, and 1998 were obtained from the EPA, Climate Protection Division, Coalbed Methane Outreach Program. Coal production data are reported to EIA on Form EIA-7A, "Coal Production Report." Basin-level emissions for nongassy mines in 1988 were calculated by the EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-19-3-24.

Degasification Systems in Underground Mines. Data on drainage from degasification systems from 1993 through 1996 are from the EPA's Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997). Emissions factors for this source are derived from estimates of 1988 emissions from degasification systems prepared by the EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-19B-3-24. Annual production figures are reported to EIA on Form EIA-7A, "Coal Production Report."

Surface Mines. Emissions factors for surface mines are found in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm. Coal production data are reported to EIA on Form EIA-7A, "Coal Production Report."

Post-Mining Emissions. Emissions factors for post-mining emissions are found in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm. Coal production data are reported to EIA on Form EIA-7A, "Coal Production Report."

Methane Recovery for Energy. Methane recovery estimates for 1990 from EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993). Volumes of methane recovered during 1993 were

obtained from U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines* (Washington, DC, September 1994), p. 6-6. Recovery volumes for 1996 were obtained from the EPA's Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997). Recovery estimates for intervening years were interpolated. Methane recovery for 1998 was scaled based on reports to EIA's 1605(b) Voluntary Reporting Program.

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 Methods

An emissions factor based on fuel type (for example, coal, wood, natural gas) and combustion technology (for example, utility boiler, industrial boiler, woodstove) is applied to consumption data for each fuel and technology type.

Data Sources

Emissions coefficients for stationary fuel were obtained from the EPA's Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm. Fuel consumption data were drawn from the Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, September 1997) for 1980-1995; and *Monthly Energy Review*, DOE/EIA-0035(99/09) (Washington, DC, September 1999) for 1996-1998. Residential woodfuel consumption data were derived from EIA's *Annual Energy Review 1998*, DOE/EIA-0384(97) (Washington, DC, July 1999). EIA no longer reports separate

consumption data for the commercial and residential sectors. However, commercial wood consumption is not nearly as prone to changes in weather and remains nearly stable year over year. This report assumes any changes in residential and commercial wood consumption are attributable to the residential sector.

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. 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. Other sources include aircraft, ships and locomotives, in addition to methane emissions from farm and construction equipment. There is, however, some evidence that jet airplane engines may consume ambient methane during flight, thereby reducing their net emissions.

Estimation Methods

Methane emissions from highway vehicles are estimated by applying emissions factors (per vehicle mile traveled) to vehicle use data. 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. Due to improvements in technology and increasing stringency of environmental regulations, motor vehicle methane emissions have generally declined over time. For non-highway sources, emissions coefficients are applied directly to annual fuel consumption data.

Data Sources

Emissions factors for all vehicles are provided in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm. EIA collects data on miles traveled in personal transportation vehicles (cars and light-duty trucks) as part of its triennial Residential Transportation

Energy Consumption Survey (RTECS): Energy Information Administration, *Household Vehicles Energy Consumption 1994*, DOE/EIA-0464 (Washington, DC, July 1996, and previous years). This survey contains data for the years 1983, 1985, 1988, 1991, and 1994. Vehicle miles traveled for other years are estimated using weighted averages from survey data in conjunction with statistics on the U.S. fleet of cars and trucks by model year, provided by provided by the American Automobile Manufacturers Association, *AAMA Vehicle Facts and Figures* (Detroit, MI, various years) and by Ward's Communications Inc., *Ward's Automotive Yearbook* (Southfield, MI, 1999). 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, DC, various years), web site www.fhwa.dot.gov/ohim/ohimstat.htm.

Fuel consumption for ships, locomotives, farm and construction equipment is based on data from EIA's *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, 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, DC, 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), web site www.cta.ornl.gov/publications/tedb.html.

Landfill Methane Emissions

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 50 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 concentrations to 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 converted to 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 Methods

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 1992.¹¹⁶ Methane emissions from landfills without gas recovery systems have not been measured, and even the number of landfills is subject to considerable uncertainty. 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.

To estimate methane emissions from all waste not disposed of in a landfill with measured emissions, waste volumes are subjected to a slightly modified version of the EMCON Methane Generation Model.¹¹⁷ 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 decomposing waste will begin producing methane after a 5-year lag and will continue emitting over a 40-year period. Table A8 shows the EMCON methane generation model parameters.

Waste flows were estimated from 1940 through 1997. 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.

Data Sources

Data on waste generated and landfilled for the period 1988 through 1998 (Table A9) were drawn from "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-1998). 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 EPA's Office of Solid Waste and Emergency Response, Franklin Associates have estimated municipal solid waste (MSW) generated and landfilled for the years 1960 through 1996: 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). See U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1996 Update*, EPA-530-S-96-001 (Washington DC, March 1997). In contrast to the *Biocycle* data, 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.

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

¹¹⁶S.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.

¹¹⁷D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environment Change* (December 1992), pp. 311-328.

Table A8. EMCON Methane Generation Model Parameters

Waste Category	Decomposable Portion (Percent by Dry Weight)	Methane Yield (Cubic Feet per Pound)	Lag Time (Years)	Time Constant
High Yield (Default)				
Readily Decomposable	4.0	4.50	0.2	3
Moderately Decomposable	45.0	3.55	1.5	10
Slowly Decomposable	5.2	0.50	5.0	20
Low Yield (Default)				
Readily Decomposable	4.0	2.75	0.3	4
Moderately Decomposable	45.0	1.95	2.0	20
Slowly Decomposable	5.2	0.29	5.0	40
High Yield (Modified)				
Readily Decomposable	4.0	8.82	0.0	3
Moderately Decomposable	45.0	6.96	2.0	10
Slowly Decomposable	5.2	0.98	5.0	20
Low Yield (Modified)				
Readily Decomposable	4.0	5.39	0.0	4
Moderately Decomposable	45.0	3.82	2.0	20
Slowly Decomposable	5.2	0.57	5.0	40

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

Table A9. Estimates of U.S. Waste Generated and Landfilled, 1990-1998
(Million Short Tons)

Source	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Waste Generated	266.4	254.6	264.7	278.4	292.9	296.4	297.1	308.9	339.9
Waste Landfilled	205.2	193.6	190.6	197.7	196.3	186.8	184.2	188.5	207.4
Waste in Place	6,868.7	7,062.3	7,252.9	7,450.6	7,646.9	7,833.7	8,017.9	8,206.4	8,413.7

P = preliminary data.

Note: Totals may not equal sum of components due to independent rounding.

Source: "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-1998).

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 GNP and population was developed. Annual methane recovery data for the U.S. Environmental Protection Agency's Landfill Methane Outreach Program database.¹¹⁸

Domestic and Commercial Wastewater Treatment

Emissions Sources

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 digestion, aerobic, and facultative (combining aerobic and anaerobic processes) stabilization lagoons, septic tanks, and cesspools.¹¹⁹ 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

¹¹⁸See web site www.epa.gov/lmop.

¹¹⁹U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *International Anthropogenic Methane Emissions: Estimates for 1990*, EPA-230-R-93-010 (Washington, DC, January 1994), p. 10-9.

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.

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 (24 percent).¹²⁰ 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.¹²¹

Estimation Methods

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 simply 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 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. Therefore, it is necessary to base the current estimate of methane emissions from wastewater treatment on the highly simplified approach recommended by the IPCC,¹²² which assumes that each person in a developed nation contributes 0.05 kilogram of BOD₅ to domestic wastewater annually, and 15 percent of this wastewater is treated anaerobically, yielding 0.22 kilogram of methane per kilogram of BOD₅ in the wastewater.¹²³ It is assumed that recovery of methane at municipal wastewater treatment facilities is negligible.

Data Source

Estimates of the U.S. resident population on July 1 of each year were obtained from the U.S. Census Bureau.

Agricultural Sources

Enteric Fermentation in Domesticated Animals

Emission Sources

The breakdown of carbohydrates in the digestive track of herbivores (including insects and humans) results in the production of methane.¹²⁴ The volume of methane produced from this process (enteric fermentation) is largest in those animals that possess a rumen, or forestomach, such as cattle, sheep, and goats. 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.

Estimation Method

The level of methane emissions from enteric fermentation in domesticated animals is a function of several variables, including quantity and quality of feed intake, the growth rate of the animal, its productivity (reproduction and/or lactation), and its mobility. To estimate emissions from enteric fermentation, the animals are divided into distinct, relatively homogeneous groups. For a representative animal in each group, feed intake, growth rate, activity levels, and productivity are estimated. An emissions factor per animal is developed based on these variables. The factor is then multiplied by population data for that animal group to calculate an overall emissions estimate. Because emissions from cattle represent about 94 percent of U.S. emissions from enteric fermentation, the estimation method for cattle is more complex and detailed.

¹²⁰U.S. Census, 1980, 1990.

¹²¹William Hahn, Science Applications International Corporation, personal communication, May 23, 1996.

¹²²Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 6.23, web site www.iea.org/ipcc/invs6.htm.

¹²³Biological 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. BOD₅ is a standardized measurement of BOD that measures the oxygen consumed over a 5-day period.

¹²⁴P.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.

Cattle. The U.S. cattle population is separated into dairy and beef cattle. Dairy cattle are then divided into replacement heifers 0-12 months old, replacement heifers 12-24 months old, and mature cows. Dairy cattle are further subdivided into regional populations in an effort to capture variations in diet and feed quality. Beef cattle are divided into six classes: replacements 0-12 months old, replacements 12-24 months old, mature cows, bulls, steers and heifers raised for slaughter under the weanling system, and steers and heifers raised for slaughter under the yearling system. These populations are then multiplied by emissions factors developed for each category of cattle based on their intake requirements.¹²⁵ Because characteristics critical in determining energy intake, and thus emissions rates, for cattle—such as growth rates and milk production—change annually, an effort to scale emission factors to these changes is made. For dairy cattle, emission factors are scaled to average milk production per cow on a regional basis. For beef cattle, emissions rates were pegged to average pre-slaughter live weights for the calves and adult cattle, respectively (Table A10).

Other Animals. For sheep, pigs, goats, and horses, populations are not desegregated below the species level. Emissions factors for each animal group are multiplied by their respective populations. Emission factors are drawn from the work of Crutzen et al.¹²⁶

Data Sources

Population and slaughter weight data for cattle and population data for sheep and swine were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Livestock,

Dairy, and Poultry Branch web site at www.mannlib.cornell.edu. Population data for goats and horses are extrapolated from the USDA's *Census of Agriculture* for the years 1987, 1992 and 1997.¹²⁷

Solid Waste of Domesticated Animals

Emission Sources

When the solid waste of animals is allowed to decompose under anaerobic conditions, methane is produced. 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.¹²⁸ Thus, they result in the greater methane emissions.

Estimation Method

Methane emissions from the solid waste of domesticated animals 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. The volume of waste produced is controlled by the animal's size, diet, and energy requirements. As a proxy for these variables, typical animal mass as estimated in a 1990 inventory of livestock and poultry prepared by the U.S. Environmental Protection Agency¹²⁹ is used to determine emissions per animal. Animal sizes are adopted directly for all animals except cattle, for which masses are adjusted

Table A10. Average Pre-Slaughter Live Weights for U.S. Cattle and Calves, 1990-1998
(Pounds)

Animal Class	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Cattle	1,136	1,163	1,169	1,161	1,189	1,183	1,169	1,173	1,173
Calves	260	281	346	376	388	384	372	341	341

P = preliminary data.

Source: U.S. Department of Agriculture, web site www.mannlib.cornell.edu.

¹²⁵U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 5-3; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. G-2, web site www.epa.gov/globalwarming/inventory/1999-inv.html.

¹²⁶P.J. Crutzen, I. Aselmann, and W.S. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," *Tellus*, Vol. 38B (1986), pp. 274-275.

¹²⁷U.S. Department of Agriculture, National Agricultural Statistics Service, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Series," Part 51 (Washington, DC, 1987, 1992, and 1997).

¹²⁸U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993).

¹²⁹U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993).

annually based on live pre-slaughter weights as reported by the U.S. Department of Agriculture. Volatile solids produced per kilogram of animal weight, maximum methane-producing capacity of each animal's waste and the share of waste handled in each management system are adopted from the work of Safley et al.¹³⁰ For all animals except dairy cattle, the share of waste handled in each management system is also drawn from Safley et al.

Methane conversion factors for dairy cattle are adopted on a State-by-State basis and are calculated from a weighted average of each State's manure management technique. Dairy cattle size and volatile solid production are drawn from the EPA. Resulting emissions factors are applied to State population data acquired from the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch.

Data Sources

Population and slaughter weight data for cattle, and population data sheep, poultry, and swine were provided by the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), Livestock, Dairy, and Poultry Branch and were obtained via the Internet at www.mannlib.cornell.edu. Average broiler chicken populations for each year were estimated by multiplying the estimated number of broiler chickens hatched annually by 0.1425 based on their 7 week life cycle as recommended by the USDA's Economic Research Service.¹³¹ Population data for goats and horses were extrapolated from USDA, NASS, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Studies," Part 51 (Washington, DC, 1987, 1992, 1997).

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 Methods

A range of daily emissions rates has been developed from studies of rice fields in California,¹³² Louisiana,¹³³ and Texas.¹³⁴ The high and low ends of the range, 0.1065 and 0.5639 grams of methane per square meter of land cultivated, are applied to the growing season length and the harvested area for each State that produces rice. In States with a second ("ratoon") crop, the additional area harvested is incorporated into the estimates.

Data Source

The area of rice harvested and the length of growing season data were obtained from the U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (annual reports).

Burning of Crop Residues

Emissions Sources

Between 40 and 50 percent of dry matter in crop residue is carbon.¹³⁵ When crop residues are burned for fodder, land supplementation, or fuel, incomplete combustion produces methane emissions.

Estimation Methods

As reported by the EPA, this report assumes that 3 percent of all crop residues are burned, with the exception of rice grown in California.¹³⁶ The share of rice crop residues in California estimated to be combusted declines in straight-line fashion from 99 percent in 1990 to 50 percent in 1996. The 50 percent estimate is held constant for 1997 and 1998. To derive methane

¹³⁰L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions from Livestock and Poultry Manure* (Washington, DC: U.S. Environmental Protection Agency, February 1992), p. 18.

¹³¹Personal communication (May 1993).

¹³²R. 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.

¹³³R.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.

¹³⁴C.W. Lindau and P.K. Bolich, "Methane Emissions From Louisiana First and Ratoon Rice Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48.

¹³⁵A. 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.

¹³⁶U.S. Environmental Protection Agency, Office of Policy, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. 5-20.

Estimation Methods: Methane

emissions, the dry weight and carbon content of each crop were determined and then multiplied by estimated combustion efficiencies (Table A11).

Data Sources

Crop harvest sizes were obtained from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (Annual Reports).

Industrial Processes

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 Methods

The IPCC has published emissions factors for methane emitted during the manufacture of ethylene, ethylene dichloride, styrene, methanol, and carbon black (Table

A12). Production figures for the chemicals are multiplied by those emissions factors.

Data Source

Chemical production figures were obtained from the Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years).

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 Methods

The IPCC has published emissions factors for methane emitted during the production of coke, sinter, and pig

Table A11. Factors Used To Estimate Methane and Nitrous Oxide Emissions from Burning of Crop Residues

Crop Type	Ratio of Residue to Crop Volume	Dry Matter Content (Percent)	Carbon Content (Percent)	Nitrogen Content (Percent)
Barley	1.2	85.0	45.7	0.43
Beans	2.1	85.4	^c 45.0	^a 2.30
Corn	1.0	78.0	47.1	0.81
Oats	1.3	^b 90.1	^a 42.0	^a 0.84
Peas	1.5	^b 90.2	^c 45.0	^c 2.30
Peanuts	1.0	90.1	^c 42.3	^c 1.10
Potatoes	0.4	^c 86.7	42.3	1.10
Rice	1.4	85.0	41.4	0.67
Rye	1.6	^c 90.0	^c 48.5	^c 0.70
Sorghum	1.4	88.0	^a 34.0	^d 0.85
Soybeans	2.1	86.7	^a 44.0	^d 2.30
Sugar Beets	0.2	^c 90.0	40.7	2.28
Sugar Cane	1.2	37.2	47.0	0.19
Wheat	1.3	85.0	48.5	0.28

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), except where indicated by: (a) C. Li, S. Frolking, and R. Harriss, “Modeling Carbon Biogeochemistry in Agricultural Soils,” *Global Biogeochemical Cycles*, Vol. 8 (September 1994); (b) E. Darley, *Emission Factors from Burning Agricultural Wastes Collected in California*, Final Report, CAL/ARB Project 4-011 (Riverside, CA: University of California, 1977); (c) U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1993*, EPA 230-R-94-014 (Washington, DC, September 1994); (d) G. Barnard, “Use of Agricultural Residues as Fuel,” in J. Pasztor and L. Kristoferson (eds.), *Bioenergy and the Environment* (Boulder, CO: Westview Press, 1990).

Table A12. Methane Emissions Factors for Industrial Processes
(Grams of Methane Emitted per Kilogram of Product Produced)

Industrial Product	Methane Emissions Factor
Coke	0.5
Sinter	0.5
Pig Iron	0.9
Carbon Black	11.0
Ethylene	1.0
Dichloroethylene	0.4
Styrene	4.0
Methanol	2.0

Source: Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.6, web site www.iea.org/ipcc/invs6.htm.

iron.¹³⁷ Production figures for iron and steel inputs are multiplied by those emissions factors.

Data Source

Coke, sinter, and pig iron production data are published annually by the American Iron and Steel Institute in its *Annual Statistical Report* (Washington, DC, various years).

Nitrous Oxide

Most anthropogenic nitrous oxide emissions in the United States can be attributed to agricultural and energy sources. In particular, more than 52 percent of estimated emissions of nitrous oxide were attributable to nitrogen fertilization of agricultural soils. Motor vehicle fuel combustion accounts for another 18 percent of 1998 emissions. It should be noted that the range of uncertainty associated with emissions from mobile combustion and fertilizer use is quite large. Emissions estimates in this report include: mobile source combustion from passenger cars, buses, motorcycles, trucks, and other mobile sources; stationary source combustion from the commercial, residential, industrial, and electrical utility sectors; fertilizer application; burning of crop residues; livestock manure management; human sewage; waste combustion; and industrial production of adipic acid and nitric acid.

¹³⁷Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.23, web site www.iea.org/ipcc/invs6.htm.

Energy Use

Mobile Combustion

Emissions Sources

Nitrous oxide emissions are produced as a byproduct of fuel combustion. During combustion, nitrous oxide (N₂O) is produced as a result of chemical interactions between nitrogen oxides (NO, NO₂ and NO₃) and other combustion products. Since nitrous oxide decomposes at high temperatures, most stationary combustion systems (such as electric power generation) emit little nitrous oxide. However, under some conditions, the catalytic converters fitted as pollution control devices on most U.S. vehicles will convert nitrogen oxides into nitrous oxide. The relevant conditions appear to be when the catalytic converter is just warming up, but before it reaches normal operating temperature, if the catalytic converter is not working properly, or if the catalyst is affected by excessive levels of sulfur in the gasoline.

Estimation Methods

In general, EIA estimates nitrous oxide emissions from highway vehicles by multiplying emissions factors (grams of nitrous oxide per mile driven) by national-level vehicle miles traveled. 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 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, an emissions factor in grams of nitrous oxide per unit of fuel consumed is applied to fuel consumption data. Since off-road vehicles rarely have catalytic converters (and vintage data is scarce) no attempt is made to track vehicle vintages for the non-highway sources.

Data Sources

Emissions factors for motor vehicle nitrous oxide have been the subject of considerable discussion and new research over the past year. Last summer, the IPCC released its *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas*

Inventories (Paris, France, 1997). This document included revised nitrous oxide emissions factors for motor vehicles that were four times higher those used in the previous reference manual and in the previous edition of this report. However, the EPA's Office of Mobile Sources, stimulated by the IPCC report, undertook an automotive testing program in the summer of 1998. The Office of Mobile Sources results were published in U.S. Environmental Protection Agency, *Emissions of Nitrous Oxide from Highway Mobile Sources*, EPA-420-R-98-009 (Washington, DC, August 1998), and have been used in this report. These emissions factors are considerably lower than the emissions factors in the IPCC report but somewhat higher than emissions factors used in EIA's *Emissions of Greenhouse Gases in the United States* reports for 1996 and before, and higher than the emissions factors suggested by the IPCC for use with European vehicles.

EIA collects data on miles traveled in personal transportation vehicles (cars and light-duty trucks) as part of its triennial Residential Transportation Energy Consumption Survey (RTECS): Energy Information Administration, *Household Vehicles Energy Consumption 1994*, DOE/EIA-0464(94) (Washington, DC, July 1996, and previous years). This survey contains data for the years 1983, 1985, 1988, 1991, and 1994. Vehicle miles traveled for other years are estimated using weighted averages from survey data in conjunction with statistics on the U.S. fleet of cars and trucks by model year, provided by the American Automobile Manufacturers Association, *AAMA Vehicle Facts and Figures* (Detroit, MI, various years) and by Ward's Communications Inc., *Ward's Automotive Yearbook* (Southfield, MI, 1999). 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, DC, various years), web site www.fhwa.dot.gov/ohim/ohimstat.htm.

Fuel consumption for ships, locomotives, farm and construction equipment is based on data from the Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, 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, DC, 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), web site www-cta.ornl.gov/publications/tedb.html.

Stationary Combustion

Emissions Sources

As with mobile sources, nitrous oxide emissions are produced as 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 72 percent of annual emissions. As a sector, electric utilities consistently account for more than one-half of total emissions. Other important sources are commercial facilities, industrial facilities, and residences.

Estimation Methods

Nitrous oxide emissions from stationary combustion are estimated by multiplying fuel consumption figures for each fuel type and stationary source by emissions factors for each type of fuel. It should be noted that for the first time, estimates of nitrous oxide emissions from stationary combustion include emissions from the consumption of wood in the residential, industrial, and electric utility sectors. In addition, the emissions factors used in this report differ from those used in previous years; therefore, emissions estimates will be different from those presented in last year's report. Emissions are estimated by applying emissions 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.

Data Sources

Fuel consumption data are from EIA's *State Energy Data Report* (EIA-0214) database. The emissions factors used in this report are those recommended by the IPCC as derived from studies of numerous conventional systems: G.G. De Soete, "Nitrous Oxide From Combustion and Industry: Chemistry, Emissions and Control," in A.R. van Amstel (ed.), *International IPCC Workshop Proceedings: Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control* (Bilthoven, Netherlands: RIVM, 1993), pp. 287-337.

Agriculture

Nitrogen Fertilization of Agricultural Soils

Emissions Sources

Nitrous oxide is a waste product of certain classes of bacteria normally present in soil. When nitrogen (in the form of natural or artificial fertilizers) is added to

natural or agricultural soils, the action of these bacteria is stimulated. However, the extent to which adding nitrogen stimulates nitrous oxide emissions is highly uncertain. The bacteria that emit nitrous oxide have natural competitors, which may be more or less successful in particular settings. In addition, conditions may be more or less propitious for bacterial action: the soil may be too moist or too dry, too compacted, too acid or alkaline, too warm or too cold. The form in which nitrogen is applied may be subject to faster or slower release to the waiting bacteria. Further, excess nitrogen will escape from the location of application through runoff and will be subject to decomposition in diverse natural environments. Thus, measured emissions from even large numbers of specific sites are exceptionally difficult to generalize into an estimate of national emissions.

The most recent estimation methods of the IPCC have been revised to take a more comprehensive view of nitrous oxide emissions from this source. It broadens consideration of the sources of nitrogen applied to soils and considers nitrous oxide emissions downstream from the site of emissions.

Estimation Methods

Following the most recent IPCC *Reference Manual*, this report estimates nitrogen applications to soils from the following sources:

- Use of nitrogen fertilizers (computed directly from fertilizer data)
- Nitrogen in animal manure applied to agricultural soils (estimated from animal populations)
- Nitrogen in crop residues applied to agricultural soils (estimated from crop production statistics)
- Biological fixation of nitrogen in agricultural soils (estimated from crop production statistics)

For estimating nitrous oxide emissions from the first three sources, following the IPCC guidelines as revised in 1996, EIA assumes that 1.25 percent of the nitrogen applied is emitted to the atmosphere as nitrous oxide and 30 percent escapes into the environment. Some 2.5 percent 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 be ultimately converted into nitrous oxide.¹³⁸

To estimate nitrous oxide emissions from the biological fixation of nitrogen in crops, annual production statistics for nitrogen-fixing crops (alfalfa, beans, lentils, peanuts, and soybeans) were obtained from the U.S. Department of Agriculture's *Crop Production* annual reports. Crop product values for these crops were then converted to total crop (crop product plus crop residue) dry biomass in mass units of dry matter, by applying residue-to-crop ratios and dry matter fractions. The total crop values in dry biomass units were then used to calculate the crop nitrogen content that is released in the form of nitrous oxide. Finally, nitrous oxide emissions factors were then applied to calculate nitrous oxide emissions from the biological fixation of nitrogen in crops.¹³⁹

Data Sources

Estimates of total U.S. fertilizer consumption were obtained from reports by the Tennessee Valley Authority Fertilizer Research Center for various years through 1994: J.T. Berry et al., *Commercial Fertilizers* (Muscle Shoals, AL: Tennessee Valley Authority, Fertilizer Research Center, Reports for 1986-1991 and 1993-1994)C and The Fertilizer Institute for 1995 through 1998. Estimates of Nitrous oxide from the biological fixation of nitrogen in crops, were based on crop production statistics obtained from the U.S. Department of Agriculture's *Crop Production* annual reports. For nitrogen in animal manure, see the section on "Solid Waste of Domesticated Animals." For nitrogen in crop residues, see the section on "Crop Residue Burning" under methane or nitrous oxide.

Crop Residue Burning

Emissions Sources

Crop residues are commonly disposed of by incorporation into the soil, spreading over the soil surface to prevent erosion, as animal bedding, or through burning. Burning crop residues releases nitrous oxide into the atmosphere. The burning of crop residues occurs throughout the United States, although it is illegal in certain areas. There are no accurate estimates of the amount of crop residue burned in the United States.

¹³⁸Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.53, web site www.iea.org/ipcc/invs6.htm.

¹³⁹Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.85-4.94, web site www.iea.org/ipcc/invs6.htm.

Estimation Methods

As reported by the EPA, this report assumes that 3 percent of all crop residues are burned, with the exception of rice grown in California.¹⁴⁰ The share of rice crop residues in California estimated to be combusted declines in straight-line fashion from 99 percent in 1990 to 50 percent in 1996. The 50 percent estimate is held constant for 1997. These estimates of crop residues burned are in contrast to earlier estimates of 10 percent for all crops, adopted from default values provided by the IPCC. 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.

Data Sources

Crop harvest sizes were obtained from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (annual reports); and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html.

Solid Waste of Domesticated Animals

Emissions Sources

Nitrous oxide is emitted as part of the denitrification of animal manure. The volume of nitrous oxide emissions is a function of the amount of manure produced, the nitrogen content of the manure, and the method for handling the animal waste. 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.

Estimation Methods

Nitrous oxide emissions from the solid waste of domesticated animals are estimated by linking emissions to the volume of solid waste produced by a given animal, the volatile solids in that waste, the nitrogen content of the waste, and the manner in which the waste is managed. Animal populations are divided into distinct, relatively homogeneous groups. The U.S. cattle population is separated into dairy and beef cattle. Emissions of nitrous oxide from poultry, sheep, pigs, goats, and horses are also estimated. For each group of animals, a

per-head volatile solids production and an associated nitrogen content within the volatile solids are assigned. These values are multiplied by animal populations to derive total nitrogen excreted. For each animal group, excretions are distributed among the manure management systems used. The ratio of nitrous oxide production to nitrogen content for each management technique is applied to provide an emissions estimate for each animal group, broken down by manure management system. The emissions are then summed to calculate an overall emissions estimate.

Data Sources

Population and slaughter weight data for cattle and population data for sheep, poultry, and swine were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch, web site www.mannlib.cornell.edu. Average broiler chicken populations for each year were estimated by multiplying the estimated number of broiler chickens slaughtered annually by 0.1425, based on their 7-week life cycle as recommended by the USDA's Economic Research Service.¹⁴¹ Population data for goats and horses were extrapolated from U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Series," Part 51 (Washington, DC, 1982, 1987, and 1992). Volatile solids content, nitrogen content of wastes by species, manure management systems, and nitrogen to nitrous oxide conversion rates were taken from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.88-4.93, web site www.iea.org/ipcc/invs6.htm.

Waste Management

Waste Combustion

Emissions Sources

Like other stationary and mobile combustion processes, the burning of garbage and nonhazardous solid waste produces nitrous oxide emissions. 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

¹⁴⁰U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. 93.

¹⁴¹Personal communication, May 1993.

combustion temperatures.¹⁴² Very high temperatures reduce nitrous oxide emissions.

Estimation Methods

The total annual volume of municipal solid waste generated in the United States was multiplied by the share of waste incinerated. Total waste incinerated was then multiplied by a factor of 30 grams of nitrous oxide per metric ton of waste incinerated to calculate total nitrous oxide emissions from this source.

Data Sources

Waste generation data and share incinerated were drawn from *Biocycle* magazine, "The State of Garbage in America" (April 1997). The emissions factor was taken from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html.

Human Sewage in Wastewater

Emissions Sources

When human sewage is treated in wastewater systems, the nitrogen-based organic matter in the waste generates nitrous oxide through nitrification and denitrification. Under aerobic conditions, ammonia is converted to nitrate. As oxygen dissipates and an anaerobic environment governs, nitrate is converted to nitrous oxide.

Estimation Methods

Nitrous oxide emissions are estimated as a function of national population, per capita protein consumption, and the fraction of nitrogen in protein. The fraction of nitrogen in protein is assumed to be 16 percent, and 1 kilogram of nitrous oxide is assumed to be emitted per 100 kilograms of nitrogen in wastewater.

Data Sources

U.S. population data are from the Bureau of Census. Per-capita protein intake is from the Food and Agriculture Organization, *FAOSTAT Statistical Database*. Nitrogen content and nitrous oxide conversion factor

are from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-R-99-236-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html.

Industrial Processes

Adipic Acid Production

Emissions Sources

Manufacture of adipic acid is one of the two principal sources of nitrous oxide from industrial processes. Adipic acid is used primarily in the manufacture of nylon fibers and plastics in carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizers for polyvinyl chloride and polyurethane resins, lubricants, insecticides, and dyes. In the United States, three companies, which operate a total of four plants, manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid. Creation of nitrous oxide is an intrinsic byproduct of this chemical reaction.

Estimation Methods

Emissions of nitrous oxide from production of adipic acid are calculated by multiplying adipic acid production figures by nitrous oxide emissions coefficients. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.¹⁴³ Currently, three plants control emissions by thermally decomposing the nitrous oxide, and 98 percent of the potential emissions from the production of adipic acid, subject to abatement controls, are eliminated by this technique.¹⁴⁴ In 1998, 97.4 percent of total estimated U.S. production of adipic acid was subject to abatement control measures.

Data Sources

Adipic acid production figures were obtained *Chemical and Engineering News*, annual report on the "Top 50 Industrial Chemicals" (April issue, various years). For 1996 through 1998, U.S. total adipic acid production was obtained from the Chemical Manufacturers Association. The adipic acid emissions coefficient was taken from M. Thiemens and W. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 22, 1991), p. 932.

¹⁴²U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. 111.

¹⁴³M.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.

¹⁴⁴Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

Nitric Acid Production

Emissions Sources

Nitric acid is a primary ingredient in fertilizers. The process for manufacturing this acid involves oxidizing ammonia (NH₃) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation.

Estimation Methods

The IPCC guidelines indicate emissions factors of 2 to 9 grams of nitrous oxide per kilogram of nitric acid manufactured.¹⁴⁵ The emissions estimates presented in this report are calculated by multiplying the annual quantity of nitric acid produced by the midpoint (5.5 grams nitrous oxide per kilogram of product) of the emissions range. There is, however, a considerable degree of uncertainty associated with this estimate.

Data Sources

Nitric acid production figures were based on data published by the U.S. Department of Commerce, Bureau of the Census, in its annual and quarterly *Current Industrial Reports* on fertilizer materials. See also web site www.census.gov/industry/mq28b984.txt. The nitric acid emissions coefficient was taken from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.iea.org/ipcc/invs6.htm.

Halocarbons and Other Gases

Emissions Sources

Halocarbons and other gases 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
- As blowing agents for making insulating foams
- As fugitive emissions from various industrial processes, including the manufacture of halocarbons.

The emissions profile differs for each emissions source. Refrigerants are used in a closed cycle inside cooling

equipment, and they tend to leak out when the equipment is scrapped or serviced. Some portion of the refrigerants is captured and recycled or destroyed, rather than emitted, when equipment is serviced. Halocarbons in solvent applications are often recycled, but net consumption (after recycling) is probably a good indicator of emissions. Halocarbons used as blowing agents can be characterized by the type of foam manufactured: halocarbons used to make “open cell” foam are released to the atmosphere immediately, while halocarbons 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 Methods

For the years 1990 through 1997, EIA has relied primarily on estimates of halocarbon emissions presented in the EPA’s *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999). The preliminary 1998 emissions estimates for HFC-23, PFCs, and sulfur hexafluoride are advance estimates developed by EPA and provided to EIA, courtesy of Ms. Deborah Ottinger of the EPA’s Office of Air and Radiation. The preliminary 1998 emissions estimates for the remaining HFCs were derived primarily by extrapolating the trends shown in the EPA estimates.

Data Sources

EPA estimates of emissions of halocarbons and other gases are from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory/1999-inv.html.

Information on halocarbon production, consumption, and sales is spotty. Information on production and sales of some compounds, up to 1994, is provided in U.S. International Trade Commission, *Synthetic Organic Chemicals: United States Production and Sales, 1994*, USITC Publication 2933 (Washington, DC, November 1995). The Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) provides information on “world” and “northern hemisphere” production, sales, and emissions of certain halocarbons, as well as a breakdown of sales by anticipated end use: *Alternative Fluorocarbons Environmental Acceptability Study, Production, Sales and Atmospheric Release of Fluorocarbons Through 1995* (Washington, DC, January 1997). The

¹⁴⁵Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.18, web site www.iea.org/ipcc/invs6.htm.

end-use share data can be used to (crudely) estimate U.S. consumption for particular types of end uses. Large industrial emitters of certain halocarbons are required to report emissions, destruction, and recycling

of these compounds. This information is published in U.S. Environmental Protection Agency, *1997 Toxics Release Inventory* (Washington, DC, April 1999), web site www.epa.gov/opptintr/tri/pdr99/drhome.htm.

Appendix B

Carbon Coefficients Used in This Report

Overview

The first edition of *Emissions of Greenhouse Gases in the United States*, published in September 1993, applied emissions coefficients for petroleum and natural gas developed by Marland and Pippin¹⁴⁶ and adopted by the Intergovernmental Panel on Climate Change.¹⁴⁷ Those coefficients, developed for broad international use, covered only the six petroleum product categories in the International Energy Agency's taxonomy. The Energy Information Administration (EIA) collects data on more than 20 petroleum products, and U.S. petroleum products often differ in composition from those consumed abroad. In the first edition of this report, EIA estimated emissions coefficients for the remaining petroleum products based on their underlying chemical composition. EIA also used emissions coefficients for coal by rank (anthracite, bituminous, subbituminous, and lignite) and State of production, developed using 5,426 coal samples from the EIA coal analysis file.

In 1994, EIA developed specific and updated emissions coefficients for all petroleum products in their data collection system, based on their density, heat content, and carbon share. These variables were estimated on the basis of the underlying chemical composition of the fuels and, where available, ultimate analyses of product samples.¹⁴⁸ An emissions coefficient for natural gas was also generated, based on 6,743 gas samples in a Gas Research Institute database. The magnitude of potential variation in emissions coefficients for fossil fuels is constrained by the limits imposed by the chemical properties of the hydrocarbon compounds that define the fuels.¹⁴⁹ In all but a few cases, the revised emissions coefficients differed from those developed by Marland and Pippin by less than 5 percent.

The composition of marketed petroleum products varies over time because of changes in exploration, recovery,

and refining technology, economic changes (e.g., changes in the price of oil), and regulatory changes (e.g., requirements for reformulated gasoline in the Clean Air Act Amendments of 1990). The composition of two petroleum products which make significant contributions to U.S. greenhouse gas emissions, motor gasoline and jet fuel, has changed significantly over the last decade. Thus, EIA provides annual updates of the emission coefficients for these fuels (Table B1). In addition, EIA publishes annual updates of emissions coefficients for crude oil and liquefied petroleum gases.

Crude oil consumption in the United States is a very small portion of carbon emissions, because nearly all crude is refined into finished petroleum products. However, crude oil refinery input can be used to develop a national mass balance estimate of carbon emissions that may be used as a benchmark for the more disaggregated estimation approach used by EIA. EIA has developed a regression equation reflecting the relationship between the density, sulfur content, and carbon content of crude oil. From these data a crude oil emissions coefficient can be calculated. This regression equation is applicable for any nation that collects these basic petroleum statistics and supports a mass balance approach to estimating emissions where detailed product data are not collected. The density of crude oil entering U.S. refineries has risen gradually over the last decade. Through 1996, this resulted in a greater carbon content in each barrel of crude oil. However, because sulfur content in crude oil rose in 1997 and 1998, some carbon was crowded out and the emission coefficients declined slightly.

In 1997, EIA began publishing separate emissions coefficients for LPG fuel use and LPG nonfuel use. LPG may be used as fuel or as a petrochemical feedstock. About three quarters of the carbon in petrochemical feedstocks will be sequestered. Further, if the mix of paraffinic hydrocarbons used for petrochemical

¹⁴⁶G. 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.

¹⁴⁷Intergovernmental Panel on Climate Change, *Estimation of Greenhouse Gas Emissions and Sinks* (Paris, France, 1991), p. 2-18.

¹⁴⁸An ultimate analysis provides an exact breakdown of the elements present in a compound or mixture.

¹⁴⁹For a more detailed discussion of fossil fuel chemistry and emissions coefficients, see Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), Appendix A, pp. 73-92, web site www.eia.doe.gov/oiaf/1605/87-92rpt/appa.html.

Carbon Coefficients

Table B1. Carbon Emissions Coefficients at Full Combustion, 1990-1998

(Million Metric Tons of Carbon per Quadrillion Btu)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Petroleum									
Motor Gasoline	19.41	19.41	19.42	19.43	19.45	19.38	19.36	19.35	19.33
LPG	16.99	16.98	16.99	16.97	17.01	17.00	16.99	16.99	16.99
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33	19.33
Distillate Fuel	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Residual Fuel (All Other)	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Residual Fuel (Utility)	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29
Asphalt and Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Petrochemical Feed	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Aviation Gas	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Special Naphtha	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86
Waxes and Miscellaneous	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81
Industrial Sector "Other" ^a	17.46	17.83	17.39	16.12	16.36	15.69	16.25	16.32	15.64
Coal									
Residential/Commercial	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00
Industrial Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56
Other Industrial	25.58	25.60	25.62	25.61	25.63	25.63	25.61	25.63	25.63
Electric Utility	25.68	25.69	25.69	25.71	25.72	25.74	25.74	25.76	25.76
Flare Gas	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92
Natural Gas	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Crude Oil	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24	20.24

P = preliminary data.

^aComposite coefficient based on final calculations, accounting for fraction not combusted and deductions for nonfuel use, using unpublished disaggregated energy data.

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998), pp. 105-110, and estimates presented in this report.

feedstock differs substantially from those used for fuel, using a single emissions coefficient for LPG will bias estimates of emissions. Thus, EIA now adjusts the emissions coefficient for LPG based on the mix of compounds used as fuel and feedstock.

Motor gasoline consumption accounts for about 20 percent of all U.S. greenhouse gas emissions. Thus, changes in composition can have important effects on national emission levels. In 1995, a requirement for reformulated gasoline in nonattainment areas implemented under the Clean Air Act Amendments changed the composition of gasoline consumed in the United States. During 1995, 25 percent of all gasoline consumed in the United States was reformulated, rising to 32 percent in 1997. Because the additives contained in reformulated gasoline have much lower carbon shares than typical gasoline, the national average emissions coefficient for motor gasoline has declined by about 0.25 percent over the past 3 years (Table B1). At the same time, the heat content of gasoline additives is lower than that of standard gasoline. Thus, an average

gallon of gasoline sold today has a lower energy content than an average gallon sold 4 years ago. Holding car weight, horsepower, and miles traveled constant will require increased consumption of gasoline.

Jet fuel consumption is responsible for more than 4 percent of U.S. carbon dioxide emissions. Like motor gasoline, jet fuel consumed in the United States has undergone a dramatic change in composition over the past decade. Until 1993, two types of jet fuel were widely used in the United States. Kerosene-based jet fuel was generally used in the commercial airline industry and naphtha-based jet fuels were used primarily by the U.S. Department of Defense. The emissions coefficient for naphtha-based jet fuels was about 3 percent higher than that for kerosene-based jet fuel. In 1989, 13 percent of all jet fuel consumed was naphtha-based. By 1996, that figure had fallen to 0.3 percent, and in 1997 total naphtha-based jet fuel consumption was negligible. Thus, the emissions coefficient for jet fuel, weighted by consumption of each fuel type, fell

steadily between 1988 and 1996 and has now stabilized at the level of kerosene-based jet fuel.¹⁵⁰ Notably, the emissions coefficient for jet fuel is now the same as the coefficient for motor gasoline.

Motor Gasoline

As with all petroleum products, the emissions coefficient for motor gasoline is a function of its density and carbon content. This relationship is particularly clear in the case of motor gasoline because the share of impurities found in the fuel must be kept very low to maintain the operating condition of modern automobile engines and limit the environmental effects of vehicle use. Motor gasoline density varies between summer and winter grades and from low octane to high octane. This variation takes into account the differing performance requirements of gasoline associated with temperature changes. Partly as a result of the leaded gasoline phaseout, the density of gasoline increased slowly and steadily across all octane grades and in all seasons from 1987 through 1994.¹⁵¹ In order to maintain the "anti-knock" quality and octane ratings of motor gasoline in the absence of lead, the portion of aromatic hydrocarbons used in gasoline was increased. Aromatic hydrocarbons take the form of C_nH_{2n-2} , a

lower ratio of hydrogen to carbon than other hydrocarbons typically found in gasoline. Because carbon is much heavier than hydrogen, this lower ratio results in increased fuel density and higher shares of carbon. As a result, the emissions coefficient for motor gasoline rose slowly from 19.39 million metric tons carbon per quadrillion Btu in 1988 to 19.45 million metric tons carbon per quadrillion Btu in 1994. Table B2 shows the increasing densities and emissions coefficients between 1990 and 1994.

Reformulated gasoline was consumed in large volumes (about 25 percent of overall gasoline consumption) for the first time during 1995. The density of reformulated gasoline is about one percent less than standard gasoline and the much lower carbon contents of the principal additives to reformulated gasoline (Table B3) reduce the overall share of carbon in reformulated fuel. Taking into account the 25 percent of fuel consumed with a lower emissions profile, the emissions coefficient for motor gasoline dropped from 19.45 million metric tons per quadrillion Btu in 1994 to 19.38 million metric tons per quadrillion Btu in 1995. In 1996, the share of motor gasoline that was reformulated rose to 30.8 percent. By the summer of 1996, most reformulated gasoline no longer contained any tertiary amyl methyl ether (TAME) or any ethyl tertiary butyl ether (ETBE). Nearly

Table B2. Changes in Motor Gasoline Density, 1990-1998
(Degrees API)

Fuel Grade	1990	1991	1992	1993	1994	1995	1996	1997	1998
Winter Grade									
Low Octane	62.0	61.8	61.4	61.0	60.1	59.8	60.6	61.5	P61.9
Mid Octane	60.8	60.4	60.2	59.9	59.4	59.1	59.9	60.7	P61.1
High Octane	59.0	59.3	59.0	58.7	58.5	58.0	58.5	59.3	P59.6
Summer Grade									
Low Octane	58.2	58.0	57.4	56.1	55.7	56.1	56.9	57.1	57.6
Mid Octane	57.4	57.1	56.4	55.5	54.8	55.6	56.2	56.6	56.7
High Octane	55.5	55.7	55.6	54.4	53.8	55.1	55.3	56.4	55.7
Average Emissions Coefficient									
(Million Metric Tons Carbon									
per Quadrillion Btu)									
	19.41	19.41	19.42	19.43	19.45	^a 19.38	^a 19.36	^a 19.35	^a P19.33

^aEmissions coefficient weighted for reformulated gasoline, which has a lower density than standard gasoline.

P = preliminary data.

Sources: National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer and Motor Gasoline, Winter* (1990-1998); and M. DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, ANL/ESD/TM-22, Vol. 2, Appendices A-S (Chicago, IL: Argonne National Laboratory, November 1993), p. c-6. Properties of reformulated fuels from California Air Resources Board.

¹⁵⁰For a more detailed discussion of jet fuel coefficients, see Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), Appendix A, pp. 73-92; and Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998), Appendix B, pp. 105-110.

¹⁵¹National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer, and Motor Gasoline, Winter* (1984-1994).

Table B3. Characteristics of Major Reformulated Fuel Additives

Additive	Density (Degrees API)	Carbon Share (Percent)	Emissions Factor (Million Metric Tons per Quadrillion Btu)
MTBE	59.1	68.2	16.92
ETBE	59.1	70.5	17.07
TAME	52.8	70.5	17.00

Sources: California Air Resources Board, and estimates developed for this report.

all additive used in reformulated gasoline was MTBE, the additive with the lowest emissions coefficient (Table B3). The increase use of reformulated gasoline continued through 1997 and 1998, driving the overall emissions coefficient to 19.33 million metric tons per quadrillion Btu. The downward trend in emission coefficients associated with market penetration by reformulated fuels is accompanied by a decrease in the energy content of fuels on a volumetric basis.

To derive an overall emissions coefficient for gasoline, individual coefficients for standard motor gasoline consumed in the winter and summer months, respectively, were developed. These coefficients were based on the densities of product samples collected by the National Institute on Petroleum and Energy Research used in conjunction with a carbon share of 86.6 percent as estimated by Mark DeLuchi.¹⁵² Emissions coefficients for reformulated fuels consumed during the summer and winter were calculated using the following procedure. First, the carbon share of each additive used in reformulated gasoline was calculated from its chemical formula and combined with the additive's density and energy content as provided by the California Air Resources Board to produce individual coefficients for each fuel additive. Next, the reformulated fuel was separated into its standard fuel components and its additive portions based on fuel samples examined by NIPER.¹⁵³ The additive portions were defined as the net increase in MTBE, ETBE, or TAME as compared with the additives in standard fuel, since small amounts of these compounds are present in standard gasoline. The emissions coefficients for standard gasoline and for each of the additives were then weighted by their proportion in reformulated fuel to arrive at a coefficient for reformulated fuel in each season.

After independent coefficients were developed for both standard and reformulated fuel, each season's coefficients were combined by weighting according to the ratio of standard vs. reformulated consumption. The combined summer and winter coefficients were then weighted based on seasonal consumption, with just over half occurring in summer, to derive an overall emissions coefficient for motor gasoline.

Crude Oil

While crude oil composition is highly heterogeneous, the share of carbon in a fixed amount of crude oil (e.g., a gallon or barrel) varies somewhat systematically with such commonly available identifying characteristics as density and sulfur content. Because the economic value of a barrel of crude oil is largely a product of the oil's density and sulfur content these values are regularly recorded. Further, EIA maintains detailed data on the average density and sulfur content of crude oil entering U.S. refineries.¹⁵⁴ Thus, the annual emissions coefficient for crude oil is pegged to these two variables.

Ultimate analyses of 182 crude oil samples were used to derive a relationship between crude oil density, sulfur content, and the percentage of carbon in crude oil. The sulfur content and density of these samples was regressed against their carbon content. This regression analysis produced the following equation, which is used to estimate the carbon content of crude oil:

$$\text{Percent Carbon} = 76.99 + (10.19 * \text{Specific Gravity}) + (-0.76 * \text{Sulfur Content}) .$$

Annualized emissions coefficients are developed by inserting the average density and sulfur content for crude oil entering U.S. refineries for each year from

¹⁵²National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer*, and *Motor Gasoline, Winter* (1980-1998); and M. DeLuchi, *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity*, ANL/ESD/TM-22, Vol. 2, Appendixes A-S (Chicago, IL: Argonne National Laboratory, November 1993), p. c-6.

¹⁵³National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* (1995-1998), and *Motor Gasoline, Winter* (1994-1995 to 1998-1999).

¹⁵⁴Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

1987 through 1998. This provides the share of carbon in an average barrel of oil during each year. After the share of carbon is derived, it is used in conjunction with fuel density to estimate the total mass of carbon in a barrel of crude oil. An emissions coefficient per unit of energy is then calculated using EIA's standard energy content for crude oil of 5.8 million Btu per barrel.

The 1998 emissions coefficient for crude oil is 20.23 million metric tons carbon per quadrillion Btu, a slight decrease from the 1997 value. Despite an increase in density for crude oil entering U.S. refineries, carbon content has declined due to crowding out caused by growing sulfur contents (Table B4).

Liquefied Petroleum Gases

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and *n*-butane. Because each of these hydrocarbons is a pure paraffinic compound, 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 ethane, C₂H₆, which has an atomic weight of 30, is 80 percent. The densities of these compounds are also well known, allowing emissions coefficients to be calculated easily. EIA collects data on consumption of each compound and then reports them as LPG in the *Petroleum Supply Annual*.¹⁵⁵ By weighting each compound's individual emissions coefficient by its share of energy consumed, an overall emissions coefficient for LPG is derived.

More than 95 percent of all ethane and just under 85 percent of butane consumed goes to nonfuel uses. In contrast, nearly all LPG used as fuel is propane. Thus, the emissions coefficient for LPG used as fuel is 17.20 million metric tons carbon per quadrillion Btu, which is the emissions coefficient for propane (Table B5). On the other hand, the carbon emissions coefficient for LPG for nonfuel use is pulled down to 16.86 million metric tons carbon per quadrillion Btu by the large presence of the lighter ethane and its emissions factor of 16.25 million metric tons per quadrillion Btu. These coefficients have remained unchanged since 1996.

Table B4. U.S. Crude Oil Characteristics, 1990-1998

Characteristic	1990	1991	1992	1993	1994	1995	1996	1997	1998
Density (API Gravity)	31.86	31.64	31.32	31.30	31.39	31.30	31.13	31.07	30.98
Density (Specific Gravity)	0.8662	0.8674	0.8691	0.8692	0.8686	0.8692	0.8701	0.8704	0.8708
Sulfur Content (Percent)	1.10	1.13	1.16	1.15	1.14	1.13	1.15	1.25	1.31
Carbon Share (Percent)	84.98	84.97	84.96	84.97	84.97	84.99	84.99	84.91	84.86
Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24	20.24

Note: Emissions coefficients assume 100 percent combustion.

Sources: Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years); and Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), p. 91.

¹⁵⁵Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years), Table 2.

Carbon Coefficients

Table B5. Emissions Coefficients for Liquefied Petroleum Gases, 1990-1998
(Percent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Carbon Content of LPG Consumption for Fuel Use (Million Metric Tons)									
Ethane	0.47	0.30	0.45	0.28	0.39	0.40	0.47	0.46	0.44
Propane	13.67	13.53	14.48	14.78	14.79	14.82	16.34	16.79	16.07
Butane	1.33	0.87	1.29	1.08	1.27	0.83	0.82	0.81	0.77
Total	15.46	14.70	16.22	16.14	16.45	16.06	17.63	18.06	17.28
LPG Consumption for Fuel Use (Quadrillion Btu)									
Ethane	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.03
Propane	0.79	0.79	0.84	0.86	0.86	0.86	0.95	0.98	0.93
Butane	0.08	0.05	0.07	0.06	0.07	0.05	0.05	0.05	0.04
Total	0.90	0.85	0.94	0.94	0.96	0.93	1.03	1.05	1.00
Weighted Average Fuel Use Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	17.21	17.21	17.21	17.22	17.22	17.20	17.20	17.20	17.20
Carbon Content of LPG Consumption for Nonfuel Use (Million Metric Tons)									
Ethane	8.86	10.11	10.07	10.57	10.54	11.00	12.07	11.90	11.44
Propane	9.08	10.11	10.45	9.45	11.21	11.56	11.09	11.39	10.90
Butane	2.27	2.98	2.90	2.68	4.35	4.22	4.60	4.55	4.33
Total	20.22	23.20	23.42	22.70	26.10	26.78	27.76	27.84	26.67
LPG Consumption for Nonfuel Use (Quadrillion Btu)									
Ethane	0.55	0.62	0.62	0.65	0.65	0.68	0.74	0.73	0.70
Propane	0.53	0.59	0.61	0.55	0.65	0.67	0.64	0.66	0.63
Butane	0.13	0.17	0.16	0.15	0.25	0.24	0.26	0.26	0.24
Total	1.20	1.38	1.39	1.35	1.55	1.59	1.65	1.65	1.58
Weighted Average Nonfuel Use Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	16.83	16.84	16.84	16.80	16.88	16.87	16.85	16.86	16.86

Note: Emissions coefficients assume 100 percent combustion.

Sources: **Consumption:** Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).
Nonfuel Use: American Petroleum Institute, *Sales of Natural Gas Liquids and Liquefied Refinery Gases* (Washington, DC, various years).

Appendix C

Uncertainty in Emissions Estimates

Overview

The Energy Information Administration (EIA) has prepared subjective estimates of the reliability of the different methods used to estimate emissions in this report. The estimates fall into several categories:

- Uncertainty associated with underlying activity data and uncertainty associated with emissions factors
- Random errors and bias errors
- Potential for upward and downward bias errors
- Reliability of emissions estimates by source.

The distribution of uncertainty estimates is summarized in Table C1, which excludes estimates for emissions and sequestration from land use changes and forestry. Summarizing all the uncertainties, it is possible that U.S. national greenhouse gas emissions, taken as a group, may differ by as much as 12 percent from the estimates in this report. Much of the uncertainty in national emissions comes from nitrous oxide emissions, for which estimates are accurate only to within 100 percent and which accounts for about half the uncertainty in the national estimate. Excluding this source, the uncertainty of the total estimate is less than 10 percent.

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. This is because estimates of energy-related carbon dioxide are probably accurate to well 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.

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 excluded from the definition of “U.S. emissions.” Definitional changes tend to raise or lower emissions estimates systematically.
- **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. But 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 have different time-series properties.
- **Errors in Emissions Factors.** Errors in emissions 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.

Uncertainty in Emissions Estimates

Table C1. Reliability of Emissions Estimates in This Report

Greenhouse Gas and Source of Emissions	Share of Source in U.S. Emissions Total (Percent)	Estimated Errors in Activity Data (Percent of Total for Source)			Estimated Errors in Emissions Factors (Percent of Total for Source)			Weighted Uncertainty (Percent of Total Emissions)	
		Bias		Random	Bias		Random	Low	High
		Low	High		Low	High			
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 and 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 and 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
Other Gases									
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	0.0	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 emissions 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 presented in this Appendix.

- **Computational Errors.** Computational errors can exist in the estimation of emissions 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.¹⁵⁶

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

¹⁵⁶Every 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. EIA 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.

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.

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 hard 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 exceeds 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, suggesting an

emissions range from 1.3 billion to 1.5 billion metric tons.

Estimates of methane emissions are much more uncertain. The level of precision is probably on the order of 30 to 40 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.

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 the principal source of nitrous oxide emissions appears to be on the order of 100 percent, and there may be significant missing sources.

Carbon Dioxide

Sources of Uncertainty

Most carbon dioxide emissions estimated in this report result from the combustion of fossil fuels. The uncertainties in estimates of emissions from fossil fuel combustion can be divided into four types:

- **Uncertainties in the Volumes of Fuel Consumed.** In general, volumetric fuel data are believed to be fairly reliable, plus or minus about 3 to 5 percent; estimates of total consumption by fuel are more reliable than estimates by sector or by particular product.
- **Uncertainties in the Characteristics of Fuel Consumed.** Fuel data are collected on a volume or weight basis, but the density and energy content of fuels must often be estimated. The energy content of natural gas is reliable to 0.5 percent, but the reliability of energy content estimates for coal and petroleum products is lower.
- **Uncertainties in the Emissions Coefficients.** Emissions coefficients can be computed with a high degree of precision for a particular fuel sample on the basis of a laboratory analysis. If the characteristics of a fuel are difficult to measure accurately, however, the emissions coefficient for the sample fuel may not match the actual characteristics of the fuel consumed. The pipeline-quality natural gas coefficient is probably accurate to within 1 percent,

but the reliability of the coal and petroleum product coefficients is lower, because they are more heterogeneous fuels.

- **Uncertainties of Coverage.** These uncertainties may arise from excluded or unknown sources of emissions.

Fuel Consumption

In general, energy statistics produced by EIA are most accurate for energy industries that are highly concentrated and/or heavily regulated and least accurate for activities that are decentralized, with large numbers of producers or consumers, and for fuels that have many heterogeneous states. It is impossible to be certain about the absolute magnitude and distribution of errors in the energy data, but it is likely that most are bias errors rather than random sampling errors. EIA collects the same data from nearly the same respondents every year (although survey frames are systematically updated), using nearly the same methods. Product flows that escape the coverage of the statistical system are likely to stay outside the statistical system from one year to the next. Similarly, if respondents make undetected definitional or computational errors (for example, misclassifying a petroleum product), they are likely to repeat their mistakes for prolonged periods.

There is indirect evidence in favor of the relative unimportance of random error in energy statistics, in the form of the relative lack of variability of the statistics compared with other economic time series. That most EIA surveys are censuses, with what is intended to be 100-percent coverage of eligible respondents, rather than small sample surveys, reduces the scope for random errors.

If, as is suspected, random error is relatively unimportant, then most of the error is bias error, made in essentially the same way every year. Therefore, while the level of U.S. emissions of carbon dioxide could be systematically lower or higher than reported here, the reported trends over time are more likely to be reliable than the uncertainties in the energy data would suggest. Since energy production and consumption are covered by multiple surveys, it is possible to use this information to gain insight into the possible uncertainties in the energy data.

Coal. Coal production and consumption data are based on weight—short tons of coal. Coal consumption by

regulated electric utilities, including both tonnage and energy content, is universally reported to EIA and the Federal Energy Regulatory Commission (FERC). In 1998, utility coal consumption accounted for about 87 percent of U.S. coal consumption.¹⁵⁷ There are likely to be only minor errors (around 1 percent) in reported utility coal consumption. Industrial, residential, and commercial coal consumption estimates are subject to potentially larger errors, especially in the counting of residential and commercial sector consumption; however, residential and commercial coal consumption is very small, and even large errors would have a negligible impact on emissions estimates. The statistical discrepancy for coal production (the difference between reported consumption and reported production less exports, plus imports, plus stock changes) averaged less than 10 million metric tons, or less than 1 percent of consumption, in the period 1993-1998.¹⁵⁸

Natural Gas. Most natural gas is sold or transported by State-regulated local distribution companies. Excluding imports, the statistical discrepancy for natural gas has an average value of between 2 and 3 percent of consumption, with reported consumption usually smaller than reported production. This may imply some systematic source of under-reporting of consumption. Inaccuracies in natural gas volumetric data come from inherent limitations in the accuracy of natural gas metering, as well as from the usual problems of misreporting and timing differences. For example, natural gas consumption by electric utilities, as reported by the utilities, averaged about a 13-percent difference from natural gas consumption as reported by natural gas sellers in 1997.¹⁵⁹

Petroleum. U.S. petroleum consumption is estimated on the basis of “petroleum products supplied,” which means the volume of petroleum products shipped from primary storage facilities. Since there are only about 200 oil refineries in the United States, coverage of crude oil inputs and refinery outputs is generally complete. EIA requires a detailed breakdown and accounting of petroleum products produced by refineries, including refinery fuel. There are several reporting anomalies in EIA petroleum data:

- Each year more crude oil is supplied to refineries than can be accounted for by oil production, imports, and stock changes. This “unaccounted for crude oil” averaged 115,000 barrels per day, or less than 1.0 percent of refinery supply, in

¹⁵⁷Energy Information Administration, *Quarterly Coal Report*, DOE/EIA-0121(99/1Q) (Washington, DC, August 1999), Table 37, p. 42.

¹⁵⁸Energy Information Administration, *Quarterly Coal Report*, DOE/EIA-0121(99/1Q) (Washington, DC, August 1999), Table 1, p. 1.

¹⁵⁹Energy Information Administration, *Natural Gas Annual 1997*, DOE/EIA-0131(97) (Washington, DC, October 1998), Table A1, p. 228.

1998.¹⁶⁰ Unaccounted for crude oil is likely due to imprecisions in recorded crude oil production, import, and stock change data. In EIA's *State Energy Data Report*, which presents consumption estimates, unaccounted for crude oil is included in consumption.

- Every year, several thousand more barrels per day of "unfinished oils" reach refineries than can be accounted for by sales and imports of unfinished oils.¹⁶¹ In 1998, there were on the average 147,660 barrels per day of unaccounted for unfinished oils. The unfinished oil discrepancy is probably the result of asymmetric treatment of inter-refiner sales of unfinished oils. To the buyer, who knows the intended use of the product, it is motor gasoline or distillate fuel. To the seller, it is an unfinished oil. In the *State Energy Data Report*, the *Monthly Energy Review*, and this report, the unfinished oil discrepancy is accounted for through an adjustment to "other oils." The implication is that total oil consumption figures are more reliable than the exact distribution of consumption across specific petroleum products. Overall, it is likely that petroleum consumption estimates are accurate to within 5 percent.

Nonfuel Use. Data for nonfuel use of petroleum products are more uncertain than those for total use of petroleum products. There are two main methods of estimating nonfuel use:

- Specialized petroleum products, such as petrochemical feedstocks, waxes and polishes, asphalt, and lubricants, are assumed to be dedicated to nonfuel use.
- Nonfuel use of conventional fuels is estimated on the basis of survey results from EIA's Manufacturing Energy Consumption Survey (MECS), with additional detail from trade association data and from known specific nonfuel uses (such as fertilizer feedstocks for natural gas).¹⁶² MECS is a sample survey conducted only at 4-year intervals, with the sample optimized to detect the use of fuels for heat and power. Using MECS to measure nonfuel use requires interpolating between sample years and correcting for sampling problems associated with reported nonfuel use.

The main uncertainty in estimating carbon sequestered from nonfuel use is not the amount of product used but the fate of its carbon. The sequestration percentages used in this report are estimates, originally based on the typical fate of a particular class of products. The actual distribution of nonfuel uses of products is not always known with precision and could vary considerably from the "typical" usage; however, because sequestration through nonfuel use corresponds to only about 5 percent of total emissions, even large variations in the amount sequestered would have a small effect on estimated total emissions.

Conversion Factors

EIA oil and gas data are collected in volumetric units—barrels of oil and billion cubic feet of gas. Carbon emissions factors for fossil fuels usually take the form of tons of carbon per unit of energy content. Emissions factors are computed by dividing the carbon content (by weight) of a particular fuel by its energy content. Thus, in order to match an emissions factor to a fuel accurately, it is necessary to know its energy content with precision; and in the case of fuel quantity based on volumetric data, it is also necessary to know the density of the fuel. Each step that transforms the data from native units into more useful units inevitably reduces the precision of the resulting data, because the conversion factors are themselves statistical estimates or extrapolations, which may not precisely match the actual composition of the fuel.

Coal. Coal data are collected by State, coal rank, and weight (short tons). Electric utilities are asked to report both the rank and the energy content of the coal they burn. Since, in principle, utilities need to know the energy content of the fuels they purchase with precision, the energy content data should be fairly accurate. On the other hand, there is considerably more uncertainty in the rank or energy content of coal distributed outside the utility sector, which in 1998 accounted for about 13 percent of U.S. coal consumption.

The quality of coal can vary considerably within States and within a particular rank. Lignite, for example, is defined as containing 6,300 to 8,300 British thermal units (Btu) per pound, a range of about 15 percent. Subbituminous coal, by definition, has a range of 8,300

¹⁶⁰Energy Information Administration, *Petroleum Supply Annual 1998*, DOE/EIA-0340(98)/1 (Washington, DC, June 1999), Table S2, pp. 6, 7.

¹⁶¹Energy Information Administration, *Petroleum Supply Annual 1998*, DOE/EIA-0340(98)/1 (Washington, DC, June 1999), Table 2, p. 34.

¹⁶²Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), Table A3.

to 11,500 Btu per pound.¹⁶³ Thus, there may be errors of up to 15 percent in the industrial and residential/commercial coal conversion factors. On the other hand, residential/commercial and industrial coal consumption accounts for only about 5 percent of total U.S. energy-related carbon emissions, and even large errors would have only a small impact on the ultimate estimates.

Natural Gas. The composition of natural gas also varies considerably. In a 1992 survey of several thousand gas samples taken from local distribution companies around the United States, the Btu content ranged from 970 to 1,208 Btu per thousand cubic feet.¹⁶⁴ However, 80 percent of the samples fell within a much narrower range of 1,006 to 1,048 Btu per thousand cubic feet. Further, the average and median values of the samples fell within 0.3 percent of the national-level figure reported in EIA's *Natural Gas Annual*. This comparison suggests that EIA data on the energy content of natural gas are accurate to within 0.5 percent. This is not surprising, because local distribution companies monitor the energy content of natural gas to ensure adherence to contractual specifications, and they report the average energy content to EIA.

Petroleum. The energy content of petroleum products varies more by volume than by weight. The density and the energy content of petroleum products are rarely measured by producers or consumers, and frequently they are not known with precision. Electric utilities measure the energy content of the residual oil they burn and report it to EIA. Liquid petroleum gases (propane, butane, and ethane) are pure compounds, and their energy content can be computed directly.

Liquid transportation fuels (jet kerosene, gasoline, and diesel fuel) are complex mixtures of many compounds, whose physical properties can vary considerably. Neither their density nor their energy content is measured by consumers or directly defined by product specifications. EIA estimates the energy content of these fuels on the basis of standard or "typical" values for each product. The standard energy contents for motor gasoline and kerosene-based jet fuel are drawn from a 1968 report produced by the Texas Eastern Transmission Corporation.¹⁶⁵ The energy content of distillate fuel oil is drawn from a Bureau of Mines

Standard adopted in January 1950.¹⁶⁶ Jet fuel and diesel samples obtained for this report showed an average energy content that differs from EIA estimates by about 2 percent. Samples of motor gasoline analyzed by the National Institute of Petroleum and Energy Research displayed an average energy content that differs from EIA estimates by less than 0.5 percent. Reformulated gasoline, with the additives MTBE, ETBE, and TAME typically representing about 10 percent of its volume, can be expected to have an energy content about 1 percent lower than the energy content of standard gasoline. However, when collecting and disseminating motor gasoline data in units of energy, EIA does not use a distinct conversion factor for reformulated gasoline.

Carbon Emissions Coefficients

Carbon emissions coefficients are calculated by dividing the carbon content of a particular fuel (for example, 0.85 metric tons of carbon per metric ton of fuel) by the energy content of that fuel (for example, 43 million Btu per metric ton) to produce an emissions coefficient (in this example, 19.8 million metric tons of carbon per quadrillion Btu). Both the energy content and the carbon content of the fuel are subject to a degree of uncertainty. The carbon content of fuels has only an indirect and general bearing on their economic value and, consequently, is not necessarily collected by fuel producers or consumers. Although coefficients for coal and natural gas rely on analyses of a large set of fuel samples, coefficients for several petroleum products are based on "typical" or "representative" values, which may or may not perfectly reflect the underlying composition of the fuel. Variation in carbon content is limited to plus or minus 5 percent by the standard ratios of carbon to hydrogen in the hydrocarbon compounds that compose petroleum.¹⁶⁷

Coal. There are large variations in the carbon and energy content of coals in different parts of the United States. Lignite may have as little as 12.6 million Btu per ton and contain 36 percent carbon, and anthracite may have as much as 98 percent carbon and an energy content as high as 27 million Btu per ton.¹⁶⁸ The carbon and heating values of coal are, in general, controlled by two factors:

¹⁶³Energy Information Administration, *Coal Industry Annual 1996*, DOE/EIA-0584(96) (Washington, DC, November 1997), pp. 252, 255.

¹⁶⁴W.E. Liss et al., *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States* (Chicago, IL: Gas Research Institute, March 1992), p. 14.

¹⁶⁵Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, December 1997), p. 497.

¹⁶⁶Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, December 1997), p. 496.

¹⁶⁷Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), pp. 78-80.

¹⁶⁸Energy Information Administration, *Coal Industry Annual 1996*, DOE/EIA-0584(96) (Washington, DC, November 1997), pp. 247-248, 252, 255.

- The ratio of flammable materials (carbon, hydrogen, and sulfur) to nonflammable impurities (moisture, ash, etc.)
- The ratio of carbon to hydrogen and sulfur within the flammable portion of the coal.

Most of the gross variation in both energy and carbon content (for example, between lignite and anthracite) is due to variations in nonflammable impurities. Consequently, if the Btu content of coal is estimated accurately, most of the variation in the carbon content is removed.

There is, however, residual uncertainty about the ratio of carbon to hydrogen and sulfur in particular coals. The carbon content of any particular coal sample can be determined by chemical analysis, but characterizing the average carbon content of national coal production creates some uncertainty. For this report, EIA relied on chemical analyses of several thousand coal samples, sorted by State of origin and coal rank, to compute national weighted average emissions coefficients (in million metric tons of carbon per quadrillion Btu) for each coal rank.

Natural Gas. Natural gas also varies in composition, but the range of variation is much smaller than that for coal. The emissions coefficient used in this report was based on an analysis of some 6,743 recent samples of U.S. natural gas. While there is some residual uncertainty about the exact carbon content of average U.S. natural gas, this uncertainty is on the order of 1 percent or less.

Petroleum Products. Crude oil is refined into a wide range of petroleum products, each presenting a different set of uncertainties. In general, the carbon content of petroleum products increases with increasing density. Uncertainties in emissions coefficients arise primarily from estimating the wrong density for a fuel or from mismatching the carbon and energy content of a particular fuel. The emissions factors for liquefied petroleum gas (LPG) and motor gasoline are probably accurate to within 1 to 2 percent. Coefficients for jet fuel and diesel fuel are probably accurate to within 2 to 4 percent, with much of the uncertainty centered in the standard heat contents used. The estimate for residual fuel is more uncertain but is probably accurate within 3 to 5 percent, as there are remaining uncertainties about the exact density and carbon content of the fuel.

The uncertainty for some minor petroleum products remains large, in some cases because it has proven

difficult to identify exactly how reporters define particular product categories. Products with large remaining uncertainties include petrochemical feedstocks (density and portion of aromatics), lubricants, and waxes and polishes. The uncertainty of the emissions coefficients for these products is probably on the order of 10 percent. Because these products share a large nonfuel use component, their impact on the total carbon emissions figure is muted. Still gas is a highly variable byproduct of the refining process, which is then described as a petroleum product. Thus, the estimated emissions coefficient for still gas may vary by as much as 25 percent.

Adjustments to Energy

U.S. Territories. Energy data for U.S. territories present certain problems. Published petroleum data for Puerto Rico and the Virgin Islands are considerably less detailed than those for the mainland United States. In particular, there is no estimate of nonfuel use for these territories, and much of the petroleum consumption that could potentially be considered nonfuel use is lumped together into "other petroleum." Hence, the reliability of the emissions estimates is lower than that of petroleum emissions estimates generally.

Flare Gas. Estimates of emissions from flare gas are subject to uncertainty from two sources: estimates of the volume of gas flared, and the application of an appropriate emissions coefficient. Estimates of gas flared are based on State-reported volumes of gas "vented or flared" and a State-by-State estimate of the portion flared. The 1997 estimate of all vented and flared gas was 264 billion cubic feet.¹⁶⁹ States may define "vented" or "flared" gas differently. This suggests that estimates may be upwardly biased by the inclusion of nonhydrocarbon gases, such as hydrogen sulfide or carbon dioxide, in the statistics. Anecdotal reports from Wyoming, the State that represents approximately half of the estimated gas flared, indicate that most flaring is of nonhydrocarbon gases and that carbon dioxide emissions may be lower than estimated.

The emissions coefficient applied to flare gas represents the average coefficient for natural gas samples with heat contents between 1,100 and 1,127 Btu per standard cubic foot. EIA estimates the heat content of marketed gas at 1,107 Btu per standard cubic foot.¹⁷⁰ Anecdotal evidence suggests that most flared gas is flared at gas processing facilities, where the wet gas energy content would be representative. However, if flared gas

¹⁶⁹Energy Information Administration, *Natural Gas Annual 1997*, DOE/EIA-0131(97) (Washington, DC, October 1998), Table 3, p. 12.

¹⁷⁰Energy Information Administration, *Annual Energy Review 1998*, DOE/EIA-0384(98) (Washington, DC, July 1999), Table A4, p. 320.

is mostly “rich” associated gas with a heat content between 1,300 and 1,400 Btu per standard cubic foot, the current coefficient biases the estimates downward. Alternatively, it is possible that flare gas from treatment plants is “off spec” gas with a large content of hydrogen sulfide or inert gas and, hence, has an emissions coefficient lower than the one actually used.

Other Sources of Carbon Emissions

The principal source of uncertainty in cement manufacture is the lime content of cement, which is estimated to within about 3 percent. There may also be limitations on the inherent accuracy of the Interior Department data used to calculate the estimate.

A second source of uncertainty, common to all the industrial estimates, is the use of stoichiometric computations to estimate emissions. This method calculates an emissions factor on the basis of a chemical reaction known to have taken place. It assumes, in effect, that the product (cement, lime, soda ash) is 100 percent pure, and that no raw materials are wasted in its production. In practice, impurities in the output would tend to reduce emissions below the stoichiometric estimate, whereas “wastage” of raw materials would tend to raise emissions above the estimate.

Excluded Sources

Appendix D lists several sources of emissions that are excluded because of uncertainty. Taking what is known about all excluded sources, additional emissions would probably be less than 10 million metric tons, or less than 1 percent of estimated emissions. Nonetheless, their exclusion does slightly bias the estimate downward. There are almost certainly other sources of carbon emissions unknown to the authors of this report. There is no way to estimate the impact of such unknown additional sources.

Methane

Estimates of methane emissions are, in general, substantially more uncertain than those for carbon dioxide. Methane emissions are rarely systematically measured. Where systematic measurements have been made, data are restricted to a small portion of the emission sites and a few years. In order to use these data to estimate emissions for the full population of emitters and to

develop time-series emissions estimates, scaling mechanisms and sampling techniques must be applied, introducing additional error.

Where no systematic measurements have been made, estimation methods rely on a limited set of data applied to a large and diverse group of emitters. However, as additional data comes available each year, uncertainty in emissions estimates declines or, at a minimum, is more clearly delineated.

Coal Mining

Emissions from coal mines are currently the fourth-largest source of methane emissions in the United States—behind landfills, oil- and gas-related emissions, and domestic livestock—and they account for approximately 11 percent of national methane emissions. Methane emissions from coal mining have five sources: ventilation systems in underground mines, degasification systems in underground mines, surface mines, post-mining activities, and abandoned or closed mines. Only the first four are included in emissions estimates, because data on emissions from abandoned mines are lacking. The uncertainty associated with estimates of emissions from each of the sources included varies considerably and according to the year of the estimate. The exclusion of emissions from abandoned mines results in a downward bias in the estimates of methane emissions from coal mines. The bias probably is in the range of 0 to 20 percent of total coal mine methane emissions.¹⁷¹ The overall uncertainty of the EIA estimates for emissions from coal mines is probably about 35 percent.¹⁷²

Emissions from ventilation systems in the Nation's gassiest mines are measured on a quarterly basis by the Mine Safety and Health Administration (MSHA). A database, developed from these reports for all mines emitting more than 100,000 cubic feet of gas per day was compiled by the Bureau of Mines for the years 1980, 1985, 1990, and 1993. The Climate Protection Division of the U.S. Environmental Protection Agency (EPA) has since compiled a similar database for 1994, 1996, 1997, and 1998. Although the measurements themselves should be reasonably accurate, each measurement represents a point in time. Variations in methane emissions across time (e.g., resulting from changes in operating practices) suggest an uncertainty in the range of 10 to 40 percent.

¹⁷¹U.S. Environmental Protection Agency, Climate Protection Division, Coalbed Methane Outreach Program, *Draft Analysis of Abandoned Coal Mine Methane Emissions Estimation Methodology* (Washington, DC, December 18, 1998).

¹⁷²S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, “Developing Improved Methane Emission Estimates for Coal Mining Operations,” Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

Estimates of emissions from the ventilation systems of nongassy mines are scaled to emissions estimates for 1988 developed by the EPA.¹⁷³ The EPA estimates emissions from nongassy mines at 2 percent of total emissions from the ventilation systems of underground coal mines. Thus, an error as high as 100 percent for this source would alter the total estimate by only 1 percent.

Emissions from degasification systems have been the single largest source of uncertainty in estimates of emissions from coal mines. This report uses mine-by-mine degasification data collected by the Environmental Protection Agency for the years 1993-1996.¹⁷⁴ For those years between 1988 and 1993, emission factors are interpolated and multiplied by production in mines with degasification systems. For 1997, the 1996 emission factor is applied. For 1998 the 1997 estimate is scaled to changes in degasification reported by two participants in the 1605(b) Voluntary Reporting of Greenhouse Gases Program. The level of uncertainty associated with the 1993-1996 estimates of degasification emissions and the data reported via the Voluntary Program is low.

Reliable measurements of emissions from surface mines are available for only five sites. Thus, estimates for this report were based on an emissions range supplied by the Intergovernmental Panel on Climate Change (IPCC).¹⁷⁵ The range of emissions suggested by the IPCC implies an uncertainty range of plus or minus 75 percent. However, estimates of emissions extrapolated from the five measured sites suggest an uncertainty level of less than 10 percent.¹⁷⁶ Assuming the larger uncertainty level would add only about 10 percent to the overall uncertainty of estimates of emissions from coal mines, because the volume of emissions from surface mines is relatively insignificant.

Emissions from post-mining activities are also estimated on the basis of an emissions range supplied by the IPCC, which implies an uncertainty in the area of plus or minus 60 percent. However, the magnitude of emissions from this source is similar to that of emissions from surface mines, thus also contributing about 10 percent to the overall uncertainty of coal mine emissions estimates.

Oil and Gas Operations

Emissions estimates from oil and gas operations are calculated on the basis of activity data and emissions for 86 separate gas industry process components. A recent study funded jointly by the EPA and the Gas Research Institute (GRI) provided point-in-time activity and emission factor estimates for each component during 1992.¹⁷⁷ To extrapolate estimates for other years from 1990 through 1998, activity data for each process component were associated with and scaled to a widely available data series, such as gross gas withdrawals or pipeline miles. The derived activity data were then applied to the 1992 emissions factor reported by EPA/GRI.

Despite capitalizing on an extended field sampling program and a statistical framework to meet pre-determined accuracy goals, the EPA/GRI study still was forced to rely on a nonrandom sampling method that may not have been fully representative of the sample universe. Thus, there is uncertainty associated with both the activity factors and the emissions factors used in the original estimate. The uncertainty is further magnified by any additional error introduced by the scaling methods used for the activity data.

The uncertainty associated with activity data for 1992 varies dramatically across individual components, from as little as 2 percent to as much 1,114 percent. The uncertainty for emissions factors ranges from 5 percent to nearly 4,000 percent. These uncertainties are not necessarily correlated, and when they are combined to generate an emissions estimate from each component, the uncertainties are between 17 percent and 4,000 percent. On the other hand, because the largest emissions sources are associated with lower levels of emissions, the overall uncertainty of the national estimate is plus or minus 33 percent, probably increasing to on the order of plus or minus 40 percent after scaling activity data to more common industry metrics.

This report excludes methane emissions from the venting of gas. EIA collects data on gas vented or flared as reported by State agencies. The data reported by State agencies capture venting at many stages of the

¹⁷³U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993).

¹⁷⁴U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997).

¹⁷⁵Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.108, web site www.iea.org/ipcc/invs6.htm.

¹⁷⁶S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal Mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

¹⁷⁷M.R. Harrison and R.M. Cowgill, *Methane Emissions From the Natural Gas Industry*, Prepared for the Gas Research Institute and the U.S. Environmental Protection Agency (June 1996).

natural gas system. Thus, much of the reported venting is already captured under the existing EPA/GRI estimation method. Further, anecdotal information from Wyoming indicates that much of the gas reported to be vented is actually nonhydrocarbon gases that do not contribute to methane emissions. It is certain, however, that some methane is vented. The exclusion of such venting biases emissions estimate downward, perhaps by as much as 5 percent.

Additional uncertainty is associated with estimates of methane vented at "stripper wells." Associated natural gas production at oil wells producing less than 10 barrels per day may be at pressures and volumes too low to be of commercial value. The gas may be vented, or it may evaporate from storage tanks. Such emissions are not captured in any data series, and their magnitude is difficult to estimate. Stripper wells contribute 14 percent of U.S. oil production.

Combustion-Related Emissions

Most methane emissions from stationary combustion are the result of wood burning in residential woodstoves. Because estimates of wood consumption and of the condition and efficiency of residential woodstoves are highly uncertain, estimates of emissions from this source may vary by more than an order of magnitude.

Methane emissions from mobile combustion may be larger than the estimate in this report, but it is unlikely that they are significantly smaller. Emissions factors for mobile transportation assume a well-maintained fleet. A fleet of inadequately maintained vehicles may have as much as 10 times the level of emissions of a fleet of well-maintained or new vehicles. Although much of the U.S. fleet is well-maintained, a portion is old and/or poorly maintained.

Landfills

Estimates of methane emissions from landfills were broken into two sources: emissions from waste contained in 105 mostly large landfills with gas recovery systems and emissions from waste contained in all other landfills. Uncertainties associated with estimates of emissions for these two sources differ substantially.

Emissions for many of the 105 mostly large landfills were estimated for 1992 on the basis of volumes of gas

recovered and the efficiency of gas recovery.¹⁷⁸ Gas recovery efficiency was estimated with an associated uncertainty of plus or minus 25 percent. For years other than 1992, emissions from this source were estimated by using a model of landfill waste emissions that is benchmarked to the 1992 data. The model parameters include a low yield and high yield scenario that imply an uncertainty of 35 percent.

Emissions from all other landfills were also estimated from an emissions model, with parameters that could vary by 30 percent from the mean. A crucial input into the model is the amount of waste in place, which was calculated from estimates of waste landfilled annually between 1960 and 1998 and a regression equation to "backcast" waste flows from 1940 to 1960. The range of published estimates for years in which multiple sources were available suggests an uncertainty in the neighborhood of plus or minus 33 percent, and the error associated with the regression equation probably adds another 2 to 10 percent uncertainty.¹⁷⁹

The ratio of waste in place in the 105 landfills to that in all other landfills was assumed to remain constant over time. This may be misleading, because the total number of landfills has been declining, with greater shares of waste believed to be directed toward larger landfills. Because those landfills with measured emissions for 1992 are likely to have higher-than-average emissions per ton of waste, the estimates for earlier years may be biased upward.

Domestic and Commercial Wastewater Treatment

Methane emissions from domestic and commercial wastewater treatment were estimated by IPCC's simplified approach,¹⁸⁰ which is based on the following assumptions: (1) each person contributes 0.5 kilogram per day of BOD₅ to municipal wastewater; (2) 15 percent of wastewater is treated anaerobically; and (3) anaerobic treatment yields 0.22 kilogram of methane per kilogram of BOD₅ treated. These assumptions were derived for developed countries in general, and there is considerable uncertainty about their specific applicability to the United States.

Per capita organic loadings of municipal wastewater in developed nations ranges from 0.024 to 0.091 kilogram BOD₅ per day. Organic loadings depend on such

¹⁷⁸S.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).

¹⁷⁹Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States: 1994 Update* (prepared for U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response); and "The State of Garbage in America," *Biocycle* (various years).

¹⁸⁰Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 6.15-6.23, web site www.iea.org/ipcc/invs6.htm.

factors as the amount of kitchen wastes discharged into sewers and the degree to which industrial wastewater is discharged into municipal wastewater treatment systems. Wastewater treatment methods that are potential sources of methane include anaerobic digesters, facultative and anaerobic lagoons, and septic tanks. However, reliable information on the quantity of wastewater treated by each of these methods is not available. The IPCC emissions factor of 0.22 kilogram of methane per kilogram of BOD₅ is based on an estimate for lagoons in Thailand.¹⁸¹ The applicability of this factor to treatment methods and climatic conditions in the United States is uncertain.

A further source of uncertainty is the ultimate fate of methane generated from wastewater in the United States. As in the case of landfill methane, wastewater methane generated in sewage treatment plants is often combusted to control odors or emissions of volatile organic compounds. Conceptually, the amount of methane combusted should be deducted from estimated emissions, but EIA is not aware of any information on the amount or extent of combustion of off-gases from sewage treatment plants.

Enteric Fermentation in Domesticated Animals

Estimates of methane emissions from enteric fermentation are a function of an emissions factor for each animal group, based on their diet and energy usage multiplied by their population. The magnitude of typical revisions to animal population data by the U.S. Department of Agriculture suggests that population estimates are likely to be accurate within 5 percent. The energy requirements and diets of cattle—by far the largest source of emissions from enteric fermentation—have been carefully studied. For dairy cattle, energy requirements are largely a function of milk production. This report uses State-level data and regional emissions factors for dairy cattle, scaled to milk productivity provided by the EPA.¹⁸² The reduction in uncertainty caused by regional variation should lower overall uncertainty associated with this source by 1 to 2 percent.

There is also some uncertainty associated with the average size of cattle, which could affect the animals' energy requirements. Cattle sizes have changed rapidly

over the past decade in response to market forces. This report uses slaughter weights as a proxy for average animal size and scales emissions factors for beef cattle to animal size, a method that may be imperfect. The slaughter sizes vary over time by approximately 33 percent. There is some uncertainty associated with estimates of the energy requirements of animals other than cattle, but even if this uncertainty were as high as 50 percent, the impact on the overall estimate would be no more than 3 percent.

Solid Waste of Domesticated Animals

Uncertainty in estimates of animal populations is on the order of 5 percent or less. Emissions are largely a function the amount of waste an animal produces. The amount of waste produced is a function of size, productivity, and diet. Thus, changes in animal sizes, which are difficult to monitor, create uncertainty. As discussed above, slaughter weights have been used as an imperfect measure of changes in the size of beef cattle. This proxy measure varies by about 33 percent over time.

The maximum amount of methane that a given amount of an animal's waste can produce under optimal anaerobic conditions can be measured fairly accurately in the laboratory. The share of that production realized under various waste management regimens is much more uncertain. Waste management systems and the portion of potential methane emissions realized vary across States. The use of State-level population data and methane conversion factors for the waste of dairy cattle provided by the EPA¹⁸³ should marginally lower overall uncertainty associated with estimates from this source.

Emissions also vary with ambient air temperatures and, depending on the waste management system, may change by anywhere from 1 to 60 percent. For this report, all animal waste was assumed to be managed at air temperatures between 59 and 77°F. Overestimating the average temperature at which waste is managed would bias emissions estimates upward.

Wetland Rice Cultivation

There are large uncertainties associated with the estimate of methane emissions from wetland rice cultivation. Emissions estimates are based on several studies of rice paddies in the United States, which

¹⁸¹U.S. Environmental Protection Agency, *International Anthropogenic Methane Emissions: Estimates for 1990*, EPA 230-R-93-010 (Washington, DC, January 1994), p. 10-15.

¹⁸²U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, (Washington, DC, April 1999), web site www.epa.gov/globalwarming/inventory.

¹⁸³U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, (Washington, DC, April, 1999), web site www.epa.gov/globalwarming/inventory.

provide daily emissions rate ranges. Studies have shown large seasonal and time-of-day variations in methane flux. Many variables affect methane production in rice fields, including soil temperature, redox potential, and acidity; substrate and nutrient availability; addition of chemical and/or organic fertilizers; rate of methane oxidation; and rice plant variety. The wide range of emissions provided by different researchers suggests an uncertainty of several hundred percent.¹⁸⁴

Crop Residue Burning

Estimates of emissions from the burning of crop residues are calculated on the basis of a carbon content of about 45 percent of dry matter, as recommended by the IPCC,¹⁸⁵ and a 3-percent burn rate for all crop residue except rice in California, as recommended by the EPA.¹⁸⁶ The carbon content probably is accurate to plus or minus 10 percent. The 3-percent burn rate used for all States but California is likely to have a small uncertainty but the burn rate of 50 percent for California may only be accurate to plus or minus 50 percent.

Chemical Production

Estimates of methane emissions from chemical production are highly uncertain because of the wide variety of production processes and inputs. Organic chemical production requires the cracking and reforming of hydrocarbon bonds. How the bonds crack and reform depends on several variables, including the composition of the feedstock, the temperature of the reaction, the catalyst used, and the reaction vessel. As a result, the quantities of products and byproducts, including methane, vary. Methane may be released through leaks in seals and valves. Therefore, methane emissions are dependent on the operation and maintenance practices of the producer.

Iron and Steel Production

There is substantial uncertainty associated with estimates of methane emissions from iron and steel

production, with the plausible range of estimates ranging from 80 percent below the point estimate presented in this report to 100 percent above the point estimate. Several factors may constrain methane emissions from iron and steel production. The pollution controls used on coke ovens to prevent emissions of volatile organic compounds usually eliminate methane as well. Exhaust gases from blast furnaces that are typically captured and used for fuel contain methane. Because the emissions factors used in this report are global emissions factors provided by the IPCC,¹⁸⁷ they may not accurately portray the level of emission controls found in U.S. plants. Further, the efficacy of pollution control systems is likely to vary with operation and maintenance techniques.

Excluded Sources

Appendix D lists several sources excluded because of excessive uncertainty or insufficient data. Known sources excluded from methane emissions estimates are industrial wastewater, associated gas at oil wells, abandoned coal mines, industrial landfills, and open dumps. There are other sources of methane that have yet to be identified and thus are absent from emissions estimates. Excluded sources would invariably add to total emissions, but the magnitude of the additions is impossible to estimate.

Nitrous Oxide

Many sources of nitrous oxide emissions are difficult to quantify, and estimates are highly uncertain. Nitrous oxide has been viewed as a minor contributor to overall U.S. greenhouse gas emissions, and until recently few resources have been devoted to improving measurement and estimation methods. However, the inclusion of nitrous oxide in the Kyoto Protocol and revised emissions factors that doubled its share of U.S. emissions have increased the attention given to nitrous oxide. Estimates of emissions from the largest source of nitrous oxide, nitrogen fertilization of agricultural soils, have doubled as a result of a more expansive definition

¹⁸⁴R.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. Landau and P.K. Bolich, "Methane Emissions from Louisiana First and Ratoon Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48; R.L. Sass, F.M. 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.L. Sass, F.M. Fisher, and Y.B. Wang, "Methane Emissions from Rice Fields: The Effect of Floodwater Management," *Global Biogeochemical Cycles*, Vol. 6 (1992), pp. 249-262.

¹⁸⁵Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.67-4.86, web site www.iea.org/ipcc/invs6.htm.

¹⁸⁶U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, (Washington, DC, April, 1999), web site www.epa.gov/globalwarming/inventory.

¹⁸⁷Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.22, web site www.iea.org/ipcc/invs6.htm.

of this source. Uncertainties are likely to be reduced as additional research focuses on nitrous oxide emissions.

Mobile Sources

Nitrous oxide emissions from mobile sources are, after nitrogen fertilization of soils (see below), one of the largest sources of uncertainty in the total estimate. Nitrous oxide is emitted from motor vehicles equipped with catalytic converters, but the conditions under which the emissions are produced are not well defined. Research evidence indicates that catalytic converters can convert nitrogen oxides (NO₂) into nitrous oxide (N₂O) when they are operating at relatively low temperatures, but that full conversion to ordinary nitrogen (N₂) occurs when the catalytic converter is operating at its normal operating temperature.

Estimating national-level nitrous oxide emissions from this source thus presents a daunting challenge, because emissions depend on:

- Whether or not vehicles are equipped with catalytic converters, and the type of catalytic converter
- The portion of the vehicle fleet with properly functioning catalytic converters
- National average “driving cycles,” indicating the portion of the time the national vehicle fleet that is driven with warm (but neither hot nor cold) catalytic converters.

In 1997, the IPCC published new emissions factors that were some four times higher than the emissions factors used in earlier editions of *Emissions of Greenhouse Gases in the United States*. The origin of the new emissions factors lies in a confluence of two events: scientific research indicated significant missing sources of nitrous oxide; and an emissions report published by the Canadian government, based on recent research,¹⁸⁸ indicated much higher Canadian emissions of nitrous oxide from mobile sources than had been anticipated. The research subsequently found its way into the revised IPCC guidelines and into work undertaken by the former EPA Office of Policy, Planning, and Evaluation.¹⁸⁹ The EPA Office of Mobile Sources reacted by mounting a program of testing U.S. motor vehicles for nitrous oxide emissions in June and July 1998. Preliminary results, published in August 1998, recommend emissions factors for U.S. use that are about 25 percent

higher than those used by EIA in 1997 and about one-third the magnitude of those recommended by the IPCC.¹⁹⁰

The work done by EPA’s Office of Mobile Sources indicated that the linkage between the Canadian research and the emissions factors actually used in the Canadian inventory was weak, and that the emissions factors used in the Canadian inventory were at least 50 percent higher than would be indicated by the underlying research. Further, the Canadian tests were undertaken using test gasoline with sulfur levels at least twice the U.S. average, and the U.S. testing indicated that, by affecting the catalytic converter, the higher sulfur content may have greatly increased nitrous oxide emissions. However, all the tests of motor vehicles for nitrous oxide emissions reported in the literature involve fewer than 50 vehicles combined, and the sampling of the vehicles is neither random nor representative. Vehicles have also been tested under a limited range of conditions. Test results to date have been, as noted, highly variable, and we do not yet have a complete understanding of the causes of motor vehicle nitrous oxide emissions.

The largest single influence on nitrous oxide emissions is how the vehicle is driven or, at the national level, the characteristics of the national average trip. In the Canadian tests, automobiles driven in the “highway mileage test” (used to calculate the figures shown on the “highway mpg” sticker on new cars) had emissions per kilometer about one-fourth the level of *the same vehicles* driven over the “Federal test program” (used to show compliance with Federal emissions standards). The highway mpg test uses a warm start, an average distance of 20 miles, and an average speed of 40 mph. The Federal test program simulates a 9.5-mile, stop-and-go, 19 mph average from a cold start. It would be reasonable to conclude that a high level of emissions occurs at the cold start, which is then allocated over some number of miles. The longer the trip, the lower the emissions per mile.

The IPCC emissions factors are calculated in grams of nitrous oxide per kilometer driven, but the actual relevant emissions would seem to be grams of nitrous oxide per cold start. If the length and character of the “national average trip” approximates the trip used to calculate the emissions factor, then the emissions factor gives the correct result. The EPA designed the Federal

¹⁸⁸A. Jaques, F. Neitzert, and P. Boileau, *Trends in Canada’s Greenhouse Gas Emissions (1990-1995)* (Ottawa: Environment Canada, October 1997), pp. 23-24. The cited research was: V. Ballantyne, P. Howes, and L. Stephanson, *Nitrous Oxide Emissions From Light Duty Vehicles*, SAE Technical Paper 940304 (March 1994).

¹⁸⁹Now the EPA Office of Policy and Reinvention.

¹⁹⁰U.S. Environmental Protection Agency, *Emissions of Nitrous Oxide From Highway Mobile Sources*, EPA-420-R-98-009 (Washington, DC, August 1998), web site www.epa.gov/oms/climate.htm. The author of this report is Harvey Michaels.

test program to resemble the “national average trip,” as determined by the U.S. Department of Transportation’s National Personal Transportation Survey. This implies that the EPA’s emissions factors may be reasonable as a first approximation. There are, however, several potential sources of uncertainty:

- **Potential for the Wrong Model of Emissions.** It may turn out that a “per unit fuel consumption” or a “per trip” model of emissions produces more accurate results than the current “per kilometer” method. This is particularly the case in that national gasoline consumption is easier to measure than national vehicle miles traveled.
- **Uncertainties About the Correct Emissions Factors.** At present, there is a tremendous (fourfold) variation in observed emissions factors (measured in grams per kilometers) across different catalytic-converter-equipped vehicles and across the same vehicle subject to multiple tests or different tests. Under the circumstances, there can be little assurance at present that the emissions factors that are being used are closely representative of on-road emissions factors.
- **Uncertainties About Activity Data.** At present, the EIA emissions estimates are based on estimates of national vehicle miles traveled, drawn from the Federal Highway Administration (FHWA) and partitioned by vehicle type and vintage. Total national vehicle miles traveled are drawn from a variety of State surveys of varying quality, undertaken for varying purposes. In recent years, the States have experienced great difficulty in accurately partitioning data between cars and light trucks, given recent increases in sales of light trucks as automobile substitutes. The partitioning is important for nitrous oxide emissions, because light-duty vehicle emissions factors are about 50 percent higher than automobile emissions factors. The FHWA recently revised the “split” between cars and light trucks for data back to 1993 but has not revised 1992 and earlier data.
- **Variations by Model Year.** The new emissions factors vary considerably by model year, with very low factors for pre-1983 model cars, higher factors for 1983-1995 model cars, and lower factors for post-1996 model cars. Thus, the partitioning of vehicle miles traveled between cars and light trucks, and by model year, is a source of added uncertainty.

In summary, the largest uncertainty is associated with the emission factors themselves. The range of reported emissions factors might vary by as much as a factor of 4. Choosing the incorrect model of emissions could also produce large (but probably less than 100 percent) errors. The problems associated with the activity data are of smaller magnitude, but still substantial. An imprecise partitioning of vehicle miles traveled between cars and trucks could push emissions up or down by perhaps 10 to 20 percent. The estimate of total vehicle miles traveled is more reliable than its components, particularly in view of the number of independent checks (such as gasoline consumption) that prevent the aggregate data from wandering too far from the (unobservable) actual values.

Stationary Source Combustion

As the result of improved studies, emissions factors recommended by the IPCC are now limited to one value for each fuel type, regardless of application. Although the emissions factor for coal is 1.4 kilograms of nitrous oxide per terajoule of energy input, emissions may range from 0 to 10 kilograms. For oil, the recommended emissions factor is 0.6 kilogram, with a possible range of 0 to 2.8 kilograms. The range is smallest for natural gas (0 to 1.1 kilograms), with 0.1 kilogram as the suggested factor.¹⁹¹ The emissions factors were derived from studies of “conventional” combustion facilities (those equipped with burners and grate combustion, with flame temperatures well above 1,000°C).

The underlying “problem” with estimating nitrous oxide emissions from combustion is that high-temperature combustion, by itself, apparently does not create much nitrous oxide, and it may destroy nitrous oxide. Under some circumstances, however, nitrogen oxides (NO, NO₂, and NO₃), which are combustion by-products, may react to form nitrous oxide in exhaust stacks, sample bottles used for testing emissions, or perhaps in the atmosphere after being emitted. The existence of this circumstance has made it difficult to measure emissions accurately and raises the possibility that stationary combustion, through the medium of NO_x emissions, may ultimately prove to be a larger source of nitrous oxide than currently estimated.

Solid Waste of Domesticated Animals

Similar to methane emissions from the solid waste of domesticated animals, nitrous oxide emissions are a

¹⁹¹Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.36, web site www.iea.org/ipcc/invs6.htm.

function of animal populations, volatile solids production, the nitrogen content of the volatile solids, and how efficiently the manure management system used converts nitrogen to nitrous oxide. Uncertainty in estimates of animal populations is on the order of 5 percent or less. Volatile solids content, the nitrogen content of the waste of each species, manure management systems, and nitrogen to nitrous oxide conversion rates are from the IPCC.¹⁹² The IPCC emissions factors were derived from limited data and are global averages, which may differ from U.S. averages. Also, the IPCC factors show an identical nitrogen to nitrous oxide conversion rate for both anaerobic lagoons and liquid/slurry management systems. These systems are likely to have different nitrous oxide yields.

Nitrogen Fertilization of Agricultural Soils

This year's report includes higher levels of emissions from nitrogen fertilization of agricultural soils due to a broader accounting of the sources of nitrogen placed on agricultural soils. In addition to estimates of emissions from chemical fertilizers, the stubble from the previous year's crops, animal waste on fields and secondary emissions from nitrogen runoff into bodies of water, this year's report includes estimated emissions from biological fixation of nitrogen.

The activity data supporting these estimates also vary in reliability. Estimates of the nitrogen content of chemical fertilizer consumption, based on U.S. Department of Agriculture and trade association statistics, are probably reasonably reliable. However, nitrogen fertilizer accounts for only about one-quarter of the nitrogen applied to agricultural soils. The balance is accounted for by animal manure, and the plowing under of crop residues. The accounting of the volume and disposition of animal manure can be accurate only in a general way, because it is itself a calculated figure (number of animals times manure per animal times share spread on soils times nitrogen content of manure), in which all the variables (except animal populations) have only a moderate (25 percent or so) degree of certainty. The accounting worsens for agricultural residues, because this calculated figure (crop times residue ratio times nitrogen content times share not combusted) systematically undercounts failed crops, and the residue ratio and nitrogen contents can have only a moderate degree of certainty. Nonetheless, the actual nitrogen application to agricultural soils from all three sources, taken together, is probably within 50 percent of the actual (unobservable) figure.

The consequences of applying nitrogen to agricultural soils are far more problematic. Nitrous oxide emissions occur when a particular class of nitrous-oxide-emitting bacteria expand their ecological niche in agricultural soils. The bacteria compete with other, with non-emitting bacteria, and with plants to consume soil nitrogen. Thus, actual emissions from any particular plot of land will be determined by whether conditions are propitious, and they may range from nil to at least twice the national average emissions factor.

Conditions can be "propitious" for bacterial action generally, or specifically for nitrous-oxide-emitting microbes. Propitious conditions include high soil temperatures, adequate moisture, and soil that is neither too acid nor too alkaline, not too compacted, etc. Nitrogen fertilizers can also be deployed in ways that are more or less prone to stimulate bacterial action. Both scientific understanding of the conditions that promote nitrous-oxide-emitting bacteria and suitably detailed knowledge about the conditions on American farmlands for the calculation of more detailed and accurate emissions factors are absent at present. Thus, whatever the state of the activity data, the emissions factors applied can only be considered accurate to plus or minus 100 percent.

Crop Residue Burning

The accuracy of emissions estimates for crop residue burning is limited, because the practice of burning crop residues in the United States has not been systematically quantified. As described above in the discussion of methane emissions from crop residue burning, a default figure of 3 percent was used in the calculation, with the exception of California, for which a default figure declining from 99 percent to 50 percent.

Waste Combustion

Nitrous oxide emissions from waste combustion are estimated by multiplying the volume of waste combusted annually by an emissions factor for each ton combusted. Data on waste combustion probably are accurate to within plus or minus 33 percent, but the emission factor may vary by an order of magnitude.

Human Sewage in Wastewater

Emissions from human sewage in wastewater are a function of U.S. population, per capita protein intake, and the conversion rate of nitrogen to nitrous oxide during wastewater treatment. Population and per capita

¹⁹²Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual*, IPCC Guidelines for National Greenhouse Gas Inventory, Vol. 3 (Paris, France, 1994), pp. 4.94-4.110.

protein intake have a very small error band, but the rate at which nitrogen is converted to nitrous oxide is highly uncertain. The conversion rate is altered by the presence or absence of oxygen, wastewater temperatures, and acidity. In the absence of other data, a global average emissions factor provided by the IPCC was applied.

Adipic Acid Production

For adipic acid production, emissions estimates are based on three data inputs: production activity, an emissions factor, and emissions abatement activity. The primary sources of uncertainty are the amount of production at plants with emissions abatement and the effectiveness of the abatement techniques in eliminating nitrous oxide. In addition, the emissions factor for adipic acid production was determined by stoichiometry. Because plant-specific production figures must be estimated by disaggregating total adipic acid production on the basis of existing plant capacities, any national estimate will be an imprecise figure if the conversion of nitric acid to adipic acid is less than 100 percent efficient.

Nitric Acid Production

The emissions factor for nitric acid production is also uncertain. It is drawn from measurements at a single DuPont plant, which indicate a range of emissions from 2 to 9 grams of nitrous oxide per kilogram of acid

production. Because the midpoint of the range was used in the calculation, estimates may err by as much as 65 percent. Applying the emissions factor range to total production also adds uncertainty, because the emissions reported at the DuPont plant may not be representative of emissions at all nitric acid production plants.

Halocarbons and Other Gases

Emissions of hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are drawn from the work of the EPA. In general, most of these compounds are manufactured chemicals, and the amounts produced and sold can be determined, despite the fact that actual production and sales are not reported to the U.S. Government. On the other hand, the flow from sales of manufactured chemicals to emissions from their use is based on model output, particularly for HFC-134a and other refrigerants.

There are also significant fugitive emissions of these compounds, including the formation of perfluoroethane and perfluoromethane from aluminum smelting, fugitive emissions of sulfur hexafluoride from magnesium smelting, and emissions of HFC-23 from the manufacture of HCFC-22. Estimates of emissions from these sources are based on activity data multiplied by emissions factors, and the uncertainty of the estimates is probably on the order of 30 to 50 percent.

Appendix D Emissions Sources Excluded

Certain sources of greenhouse gas emissions 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 estimation methods, or classification as “natural” sources.

Biofuel Combustion

The carbon found in biofuels is the result of atmospheric uptake. During the combustion of biofuels, there is an immediate release of the carbon in the form of carbon dioxide. Thus, as part of the natural carbon cycle, carbon is reabsorbed over time. Because they produce no net change in the overall carbon budget, such emissions are not included in this report. If the initial flux had been counted, 1998 carbon dioxide emissions estimates would have been approximately 72 million metric tons of carbon higher than reported in Chapter 2 (Table D1).

Emissions are estimated by multiplying Energy Information Administration (EIA) energy consumption data for biofuels by the applicable emissions factors. Carbon dioxide emissions factors for combustion of wood fuels and municipal solid waste are taken from the EIA

report, *Electric Power Annual 1997*.¹⁹³ The emissions coefficient for alcohol fuels, 17.99 million metric tons of carbon per quadrillion Btu, was derived specifically for use in this report.

Enhanced Oil Recovery

Carbon dioxide is injected into petroleum reservoirs for the purpose of retrieving additional oil. Over time, the carbon dioxide seeps into the producing well, creating a mixture of oil, natural gas, and carbon dioxide. If the energy content is sufficiently high, the gaseous portion of this mix will probably be sent to a gas plant. If the energy content is low, the gas is likely to be 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 recycled, so that annual emissions are a fraction of the carbon dioxide recovered, which in turn is probably less than the volume of carbon dioxide injected. The annual amount of carbon dioxide used for enhanced oil recovery is probably on the order of 12 million metric tons,¹⁹⁴ and emissions would be some fraction of that figure. Emissions from this source may be included in future reports.

Table D1. Estimated U.S. Carbon Dioxide Emissions from Biofuels, 1990-1998
(Million Metric Tons of Carbon)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Municipal Solid Waste	9.24	8.14	9.31	8.90	9.36	9.47	9.50	8.89	8.15
Alcohol Fuel	1.63	1.29	1.57	1.75	1.92	2.06	1.47	1.92	2.08
Wood and Wood Waste	57.48	57.62	60.32	58.58	60.84	63.70	64.89	61.31	62.50
Total	68.34	67.05	71.20	69.23	72.13	75.24	75.85	72.12	72.73

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998).

Sources: Underlying energy data from Energy Information Administration, *Annual Energy Review 1998*, DOE/EIA-0384(98) (Washington, DC, July 1999), pp. 251-252. Emissions coefficients for municipal solid waste combustion and wood and wood waste from Energy Information Administration, *Electric Power Annual 1997*, Vol. 2, DOE/EIA-0348(97/2) (Washington, DC, October, 1998), Table A3, p. 120.

¹⁹³Energy Information Administration, *Electric Power Annual 1997*, Vol. 2, DOE/EIA-0348(97/2) (Washington, DC, October, 1998), Table A3, p. 120.

¹⁹⁴The U.S. Department of Commerce reports total sales of industrial carbon dioxide at approximately 17 million metric tons annually, while Freedonia Group, Inc., reports that approximately 5 million metric tons are used for purposes other than enhanced oil recovery.

“Off Spec” Gases

Combustion of “off spec” gases and fuels is not covered as a separate line item in this report, but much of the emissions from this source may be included in the “flaring” category, which is covered in this report, or as industrial consumption of “still gas” by refineries.

Overseas U.S. Military Oil Consumption

Domestic military energy consumption is incorporated into U.S. energy statistics; however, energy consumption for overseas operations is a more complex issue. The data can either be reported in the national energy statistics of the host country or included in U.S. export statistics if domestic oil is transported to ships and other facilities. In some circumstances, the oil consumption may go unreported.

Estimating, even roughly, the quantity of oil consumed for overseas military operations is an uncertain procedure. The Defense Energy Support Center reports that petroleum “sales” (i.e., transfers to military sources and operating units) for fiscal year 1998 totaled approximately 102 million barrels.¹⁹⁵ Of that, approximately 79 percent was acquired domestically and is assumed to be included in U.S. statistics. A reasonable estimate of military oil consumption not reported elsewhere would, therefore, be 21 percent of total military consumption of jet fuel, middle distillates, and residual oil.¹⁹⁶ By this method, excluded emissions for 1997 were estimated at 2.3 million metric tons of carbon (Table D2).

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.

Unaccounted for Gas

The editions of *Emissions of Greenhouse Gases in the United States* published by EIA before 1997 included an emissions a category called “unmetered natural gas.” 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 transmission systems. Evidence from the electric utility sector—where transmission companies report gas sales and electric utilities report gas purchases—suggests that there may be undercounting of natural gas consumption.

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. Since 1995, however, the sign of the balancing item has changed, and reported consumption now usually exceeds reported production. This development reduces the credibility of the undercounting theory, and consequently this report no longer carries “unmetered natural gas” consumption as a source of emissions. It is possible, however, that there had been an element of undercounting of natural gas consumption before 1996, which may be on the order of 1 percent (3 million metric tons) of natural gas emissions.

Table D2. Estimated Carbon Emissions from U.S. Military Operations Abroad, 1990-1998
(Million Metric Tons of Carbon)

Item	1990	1991	1992	1993	1994	1995	1996	1997	P1998
Energy Consumption (Quadrillion Btu) . . .	0.24	0.29	0.11	0.19	0.17	0.14	0.18	0.10	0.12
Carbon Emissions	4.62	5.57	2.15	3.63	3.34	2.66	3.43	1.89	2.27

P = preliminary data.

Sources: Energy consumption from Defense Energy Supply Center, *Fact Book* (various years). Data converted from fiscal years in source publication into calendar years by weighted average. Carbon emissions from EIA estimates presented in this appendix.

¹⁹⁵Defense Energy Support Center, *Fact Book 1998*, web site www.dfsc.dla.mil/main/publicati.htm (April 1999).

¹⁹⁶Gasoline is presumably acquired for motor vehicles and, typically, is accounted for in both domestic and foreign energy statistics.

Fermentation

During the fermentation process, 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.

Lead Smelting

Smelting of lead includes a stage in which limestone undergoes calcination. As described in Chapter 2, 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.

Industrial Wastewater Treatment

Methane emissions from industrial wastewater treatment are believed to be a function of the volume of wastewater generated, the organic content of the wastewater, and the method used to treat the wastewater. Methane emissions will be much more greater if the wastewater is treated anaerobically (in the absence of oxygen) than if it is treated aerobically. Because data on volumes of wastewater generated by industry and the methods for treating that wastewater are limited, EIA does not present estimates of methane emissions from industrial wastewater. There is anecdotal evidence that very little industrial wastewater is treated anaerobically. Further, when industrial wastewater is treated anaerobically, the methane generated may be flared or recovered for energy use. Thus, 500,000 metric tons is likely to be at the high end of the emissions estimate range.

Abandoned Coal Mines

The Mine Safety and Health Administration estimate that some 7,500 underground coal mines have been abandoned in the United States since 1970.¹⁹⁷ Measurements taken from 20 abandoned mines showed

¹⁹⁷U.S. Environmental Protection Agency, Coalbed Methane Outreach Program, *Draft Analysis of Abandoned Coal Mine Methane Emissions Estimation Methodology* (December 18, 1998)

¹⁹⁸S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

¹⁹⁹U.S. Environmental Protection Agency, 1997, *Introductory Analysis of Opportunities to Reduce Methane Emissions from Abandoned Coal Mines*, unpublished internal report.

a total of 25,000 metric tons of emissions.¹⁹⁸ Data gathered from these mines suggest a range in emissions from abandoned mines of 25,000 to 700,000 metric tons.¹⁹⁹ U.S. EPA is currently developing a comprehensive database of abandoned mines in the U.S. This database will include date of abandonment, specific emissions, seam thickness, mine depth, mining method, and ventilation emissions. Upon completion, this data should provide the ability to develop improved estimation methods. Until then, existing estimates are too uncertain to appear in this report.

Methane Emissions from Industrial Wastewater

Industrial operations in the United States use immense quantities of fresh water. Many industries, particularly food processing industries, discharge wastewater containing large volumes of organic material. Some portion of the organic material may decompose anaerobically, particularly if the industrial facility deliberately uses anaerobic decomposition as a treatment strategy. However, estimating emissions from this source presents certain significant challenges, because there is no clear mechanism for determining accurately the following:

- Volume of wastewater discharged
- Volume of organic matter included in the wastewater
- Extent and type of industrial wastewater treatment
- Fate of untreated organic matter discharged into the environment.

Anecdotal evidence suggests that beer manufacturers produce large volumes of organic matter and cause it to decompose anaerobically so that they can recover methane for energy purposes. It is possible that methane emissions from industrial wastewater are, in fact, a large emissions source, but there is insufficient evidence currently available to make a plausible estimate.

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 from industrial wastewater. 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 more uncertain.

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.

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.²⁰⁰ 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 1991.²⁰¹ 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 minimal—typically between 5 and 10 million metric tons of methane per year for worldwide temperate-zone wetlands (which include U.S. wetlands)—when compared with estimated global wetlands emissions of 110 million metric tons.²⁰² 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 lost might be on the order of $0.57 \times 0.005 \times 5$ to 10 million metric tons of methane, or from 10,000 to 20,000 metric tons of methane annually over the decade.

Land Use Changes Affecting Methane and Nitrous Oxide

The scientific literature suggests that both grasslands and forest lands are weak natural sinks for methane and weak natural sources for nitrous oxide. 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. Experiments indicate that cultivation reduces methane uptake by soils and increases 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. 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.

²⁰⁰T. Dahl, U.S. Department of the Interior, Fish and Wildlife Service, *Wetlands Losses in the United States: 1780's to 1980's* (Washington, DC, 1990).

²⁰¹U.S. Department of Agriculture, Soil Conservation Service, *1991 Update of National Resources Inventory Wetlands Data for Non-Federal Rural Lands* (Washington, DC, not dated), p. 4.

²⁰²See 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.

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.²⁰³ 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.²⁰⁴ 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 should be captured by reduced application of nitrogen fertilizers; thus, reporting emissions reductions using this method would result in significant double counting of units already included in the agriculture statistics in Chapter 4.

If such estimates are to be applied to emissions inventories, a problem of crediting the uptakes applies. 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. The method that should be used to credit such permanent reductions to a particular year is not obvious.

²⁰³See 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).

²⁰⁴A. Mosier and D. Schimel, "Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide," *Chemistry & Industry*, Vol. 2 (December 1991), p. 875.

Appendix E

Emissions of Energy-Related Carbon Dioxide in the United States, 1949-1998

This appendix presents estimates of U.S. carbon dioxide emissions for the period 1949-1998. The data were developed originally at the request of the President's Council of Economic Advisors, for inclusion in a graphic that appeared in the 1997 *Economic Report of the President*.²⁰⁵ U.S. energy data have undergone a number of shifts over the years, and the estimates can be divided into three periods:

- **1980-1998.** The emissions estimates for this period were developed using the methods and sources described in this report. For 1980 through 1996, the energy data on which the emissions estimates are based come from the Energy Information Administration (EIA) data series published in the *State Energy Data Report*.²⁰⁶ Estimates for 1997 and 1998 are based on energy data from EIA's *Monthly Energy Review*.
- **1960-1979.** Before 1980, EIA did not maintain a detailed accounting of carbon sequestration due to nonfuel use of fossil fuels. Hence, the data for industrial sector petroleum use, particularly in the category "other petroleum," are not as reliable as those for subsequent years. EIA has also not attempted to develop annual emissions coefficients for fuels in use before 1980, and the estimates do

not reflect any changes in fuel quality. The energy data for this period are also drawn from the database of the *State Energy Data Report*.

- **1949-1959.** EIA has made no attempt to distinguish between residential and commercial energy consumption for historical data earlier than 1960. To provide consistent estimates for this appendix, the combined data for residential and commercial energy consumption have been prorated by fuel according to the ratio of consumption in 1960. Composite sectoral petroleum emissions factors are used for this period, based on 1960-weighted petroleum products emissions. The energy data for this period are drawn from the *Annual Energy Review*.²⁰⁷

In future years, EIA hopes to be able to create annual emissions factors for electric utility coal for the period 1949-1979, to extend the estimates to cover U.S. territories and non-energy carbon dioxide, to estimate sequestration from nonfuel use in somewhat more detail for the period 1974-1979, and to use historical data on consumption of petroleum products by product and sector for the 1949-1959 period, rather than the 1960-based sectoral averages.

²⁰⁵Council of Economic Advisors, *Economic Report of the President* (Washington DC, February 1998), p. 167.

²⁰⁶Energy Information Administration, *State Energy Data Report 1996*, DOE/EIA-0214(96) (Washington, DC, February 1999), pp. 21-26, web site www.eia.doe.gov/emeu/sep/states.html.

²⁰⁷Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0384(97) (Washington, DC, July 1998), pp. 37, web site www.eia.doe.gov/emeu/aer/contents.html.

Carbon Dioxide Emissions, 1949-1998

Table E1. Energy-Related Carbon Dioxide Emissions from the Residential and Commercial Sectors, 1949-1998
(Million Metric Tons of Carbon)

Year	Residential					Commercial				
	Natural Gas	Petroleum	Coal	Electricity	Total	Natural Gas	Petroleum	Coal	Electricity	Total
1949	15.1	23.2	30.2	19.0	87.4	5.0	13.2	42.2	15.0	75.3
1950	17.8	27.6	29.9	20.2	95.4	5.9	15.7	41.7	15.9	79.2
1951	21.8	30.1	26.4	22.5	100.8	7.2	17.1	36.8	17.8	78.8
1952	23.9	30.8	24.0	24.0	102.8	7.9	17.5	33.5	19.0	77.9
1953	24.8	31.3	20.6	26.2	103.0	8.2	17.8	28.8	20.7	75.4
1954	27.8	33.5	17.9	27.5	106.7	9.2	19.0	25.0	21.7	74.9
1955	30.9	36.0	17.8	30.0	114.7	10.2	20.4	24.9	23.7	79.2
1956	34.1	37.6	16.6	32.4	120.7	11.2	21.3	23.1	25.6	81.3
1957	36.7	36.5	12.7	34.7	120.7	12.1	20.7	17.7	27.4	78.0
1958	40.2	39.1	12.4	35.3	127.0	13.2	22.2	17.3	27.9	80.6
1959	43.5	39.9	10.6	39.1	133.1	14.3	22.6	14.8	30.9	82.6
1960	46.2	43.8	10.6	42.3	142.9	15.2	24.9	14.5	33.4	88.0
1961	48.4	45.1	9.6	44.4	147.5	16.0	25.3	13.2	34.6	89.2
1962	51.8	47.1	9.2	47.4	155.5	18.0	25.9	13.0	37.0	93.9
1963	53.2	47.4	8.0	51.9	160.5	18.7	25.5	11.1	41.7	97.0
1964	56.1	45.7	7.1	55.9	164.9	20.3	25.2	9.5	44.5	99.6
1965	57.9	47.8	6.6	60.2	172.5	21.4	28.1	9.0	47.9	106.4
1966	61.3	47.5	6.3	66.6	181.7	24.0	29.1	9.1	52.9	115.1
1967	63.9	49.2	5.4	69.8	188.4	29.0	30.1	7.8	55.7	122.6
1968	65.9	51.6	4.9	79.0	201.5	30.7	30.6	7.0	61.7	130.0
1969	70.0	52.5	4.6	87.1	214.2	33.3	30.7	6.6	66.4	137.0
1970	71.3	52.8	4.0	95.9	224.0	35.3	31.4	5.5	72.5	144.7
1971	73.3	53.3	3.7	100.8	231.1	37.0	30.5	5.2	76.3	149.0
1972	75.7	55.5	2.9	109.0	243.1	38.5	30.9	4.0	83.6	156.9
1973	72.0	54.2	2.7	117.5	246.4	38.3	31.6	3.8	90.3	164.0
1974	70.5	49.4	2.7	114.6	237.1	37.6	28.7	3.8	87.2	157.4
1975	72.3	47.9	2.2	113.1	235.5	36.8	26.3	3.1	90.1	156.3
1976	74.1	52.3	2.1	119.4	247.9	39.1	29.4	3.0	96.8	168.4
1977	70.8	51.8	2.2	129.0	253.7	36.7	30.4	3.1	102.8	173.0
1978	71.8	50.4	2.2	130.8	255.2	38.0	29.1	3.3	103.2	173.6
1979	72.7	40.8	1.9	134.1	249.5	40.8	26.9	2.9	106.7	177.3
1980	69.9	33.6	1.6	143.2	248.2	38.4	26.1	2.3	111.5	178.2
1981	67.0	29.6	1.8	141.3	239.7	37.1	22.0	2.5	116.6	178.2
1982	68.4	27.6	1.9	139.5	237.5	38.5	20.3	2.9	116.4	178.1
1983	65.0	25.9	1.9	143.2	236.1	36.1	22.5	3.0	118.4	179.9
1984	67.5	25.6	2.1	146.0	241.1	37.3	23.8	3.2	124.3	188.7
1985	65.7	28.4	1.8	149.9	245.8	36.0	20.6	2.7	130.2	189.6
1986	63.8	27.9	1.8	150.5	244.0	34.3	21.9	2.7	131.4	190.4
1987	63.9	28.8	1.7	156.6	251.0	36.0	21.5	2.6	137.2	197.2
1988	68.5	29.9	1.7	164.7	264.8	39.5	20.7	2.6	144.8	207.6
1989	70.9	29.7	1.5	165.3	267.5	40.3	19.2	2.3	148.2	209.9
1990	65.1	24.0	1.6	162.4	253.1	38.8	18.0	2.4	147.4	206.7
1991	67.5	24.5	1.4	163.7	257.1	40.4	17.1	2.2	146.7	206.4
1992	69.4	24.9	1.5	160.1	255.9	41.5	16.1	2.2	145.6	205.4
1993	73.4	26.3	1.5	170.5	271.7	42.4	14.9	2.2	151.8	211.3
1994	71.7	25.4	1.4	169.8	268.3	42.9	14.9	2.1	153.9	213.8
1995	71.8	25.8	1.4	171.3	270.3	44.9	14.1	2.1	156.8	217.9
1996	77.6	27.6	1.4	179.3	285.9	46.8	14.6	2.1	162.4	226.0
1997	73.7	27.1	1.5	182.6	284.8	47.6	13.9	2.2	174.3	238.0
1998	66.3	24.8	1.5	191.9	284.5	44.9	12.9	2.2	178.4	238.4

Sources: **1997-1998**—Estimates documented in this report, based on energy data in the *Monthly Energy Review*. **1980-1996**—Estimates documented in this report, based on energy data in the *State Energy Data Report*. **1960-1979**—Calculated from energy data in the *State Energy Data Report*. **1949-1959**—Calculated from energy data in the *Annual Energy Review*.

Table E2. Energy-Related Carbon Dioxide Emissions from the Industrial and Transportation Sectors, 1949-1998
(Million Metric Tons of Carbon)

Year	Industrial					Transportation				
	Natural Gas	Petroleum	Coal	Electricity	Total	Natural Gas	Petroleum	Coal	Electricity	Total
1949	45.9	57.7	131.6	33.1	268.4	1.9	119.1	42.9	0.5	164.5
1950	51.1	66.0	140.2	38.4	295.7	2.8	129.7	38.9	0.6	172.0
1951	58.3	70.5	149.9	42.6	321.2	3.1	142.7	34.2	0.6	180.6
1952	60.2	71.6	133.5	43.7	309.0	3.4	149.1	24.5	0.6	177.6
1953	61.9	73.5	143.6	49.1	328.1	3.4	156.1	18.2	0.6	178.4
1954	62.2	75.1	114.5	48.5	300.3	3.7	157.8	11.5	0.6	173.6
1955	67.7	82.9	136.0	60.5	347.0	4.5	169.9	10.5	0.7	185.5
1956	70.1	85.1	137.1	65.3	357.7	4.5	176.4	8.5	0.7	190.0
1957	73.6	84.0	133.8	65.4	356.8	4.6	179.8	6.0	0.7	191.2
1958	75.0	85.8	109.7	61.3	331.8	5.2	183.3	2.9	0.7	192.1
1959	81.3	90.3	106.8	67.4	346.0	5.2	190.6	2.2	0.8	198.7
1960	86.0	89.5	110.2	68.1	353.8	5.2	195.5	1.9	0.7	203.2
1961	86.9	89.1	105.3	69.7	350.9	5.6	199.3	0.5	0.7	206.1
1962	90.8	92.0	106.4	73.2	362.4	5.7	207.9	0.4	0.7	214.7
1963	95.2	93.5	111.3	78.1	378.2	6.3	215.5	0.4	0.6	222.8
1964	100.3	98.6	119.1	83.4	401.4	6.5	221.9	0.4	0.6	229.4
1965	103.5	102.1	124.0	88.8	418.3	7.5	228.9	0.4	0.6	237.3
1966	110.0	105.6	125.9	97.4	438.8	8.0	241.1	0.4	0.6	250.0
1967	113.6	105.5	119.4	99.6	438.0	8.5	253.1	0.3	0.6	262.5
1968	121.4	107.2	117.5	107.9	454.0	8.8	274.2	0.3	0.5	283.7
1969	129.8	111.3	113.4	114.1	468.6	9.3	285.7	0.2	0.5	295.8
1970	133.7	111.1	111.5	117.4	473.6	10.7	295.2	0.2	0.5	306.6
1971	138.7	111.3	94.8	119.0	463.8	11.0	307.0	0.1	0.5	318.6
1972	139.1	121.4	96.0	129.8	486.3	11.3	325.5	0.1	0.5	337.4
1973	147.2	128.4	97.7	139.2	512.5	10.7	343.8	0.1	0.5	355.1
1974	141.1	121.2	94.7	135.7	492.7	9.8	335.5	0.0	0.5	345.9
1975	120.7	114.6	88.9	132.3	456.4	8.6	339.6	0.0	0.6	348.8
1976	124.0	127.0	88.2	148.5	487.6	8.0	356.9	0.0	0.6	365.6
1977	122.3	137.8	83.7	157.2	501.0	7.8	371.3	0.0	0.6	379.7
1978	121.2	135.9	83.1	157.0	497.1	7.8	386.8	0.0	0.5	395.1
1979	120.9	143.6	88.3	165.4	518.1	8.8	383.2	0.0	0.6	392.7
1980	118.4	128.2	75.4	162.6	484.6	9.4	368.1	0.0	0.6	378.1
1981	116.3	110.0	75.8	161.6	463.7	9.5	364.0	0.0	0.6	374.1
1982	100.1	104.0	61.2	142.5	407.8	8.8	356.1	0.0	0.6	365.6
1983	95.2	96.0	60.2	148.0	399.3	7.3	359.0	0.0	0.6	366.9
1984	104.1	105.8	69.3	156.8	436.0	7.8	370.5	0.0	0.7	379.0
1985	98.9	99.9	67.8	158.0	424.5	7.5	376.1	0.0	0.7	384.3
1986	93.1	101.8	64.7	152.6	412.2	7.2	391.1	0.0	0.7	399.0
1987	101.8	101.4	66.1	158.0	427.3	7.7	402.6	0.0	0.7	411.0
1988	106.9	104.8	71.1	165.4	448.2	9.1	417.5	0.0	0.7	427.3
1989	112.8	98.9	69.4	169.0	450.1	9.4	422.5	0.0	0.7	432.6
1990	118.3	100.7	68.4	166.2	453.7	9.8	421.2	0.0	0.7	431.8
1991	120.2	95.0	64.8	162.2	442.2	9.0	414.6	0.0	0.7	424.3
1992	125.9	103.9	62.7	166.4	458.8	8.8	421.6	0.0	0.7	431.1
1993	131.3	97.7	62.4	167.5	458.9	9.3	426.4	0.0	0.7	436.4
1994	132.7	101.2	63.4	169.7	467.1	10.2	438.2	0.0	0.7	449.1
1995	140.2	96.0	63.4	166.4	466.0	10.4	446.5	0.0	0.6	457.6
1996	145.0	103.8	60.5	170.6	480.0	10.6	457.4	0.0	0.7	468.7
1997	142.9	105.6	60.0	175.2	483.7	11.2	461.5	0.0	0.7	473.4
1998	140.0	100.9	58.0	178.8	477.7	10.8	473.4	0.0	0.7	484.9

Sources: **1997-1998**—Estimates documented in this report, based on energy data in the *Monthly Energy Review*. **1980-1996**—Estimates documented in this report, based on energy data in the *State Energy Data Report*. **1960-1979**—Calculated from energy data in the *State Energy Data Report*. **1949-1959**—Calculated from energy data in the *Annual Energy Review*.

Carbon Dioxide Emissions, 1949-1998

Table E3. Energy-Related Carbon Dioxide Emissions from the Electricity Generation Sector, and Total Energy-Related Carbon Dioxide Emissions by End-Use Sector, 1949-1998
(Million Metric Tons of Carbon)

Year	Electricity Generation Sector				End-Use Sectors				
	Natural Gas	Petroleum	Coal	Total	Residential	Commercial	Industrial	Transportation	Total
1949	8.2	8.7	50.7	67.6	87.4	75.3	268.4	164.5	595.6
1950	9.4	10.0	55.7	75.1	95.4	79.2	295.7	172.0	642.2
1951	11.4	8.5	63.6	83.5	100.8	78.8	321.2	180.6	681.5
1952	13.5	8.9	64.9	87.3	102.8	77.9	309.0	177.6	667.3
1953	15.4	10.8	70.4	96.7	103.0	75.4	328.1	178.4	684.9
1954	17.4	8.9	72.0	98.3	106.7	74.9	300.3	173.6	655.6
1955	17.1	10.0	87.7	114.8	114.7	79.2	347.0	185.5	726.3
1956	18.4	9.5	96.0	124.0	120.7	81.3	357.7	190.0	749.7
1957	19.9	10.6	97.8	128.3	120.7	78.0	356.8	191.2	746.6
1958	20.4	10.4	94.3	125.1	127.0	80.6	331.8	192.1	731.4
1959	24.3	11.7	102.1	138.1	133.1	82.6	346.0	198.7	760.3
1960	25.7	11.7	107.1	144.5	142.9	88.0	353.8	203.2	787.9
1961	27.2	11.8	110.3	149.4	147.5	89.2	350.9	206.1	793.7
1962	29.3	11.9	117.1	158.3	155.5	93.9	362.4	214.7	826.6
1963	32.0	12.4	127.9	172.3	160.5	97.0	378.2	222.8	858.6
1964	34.7	13.4	136.3	184.4	164.9	99.6	401.4	229.4	895.2
1965	34.7	15.3	147.5	197.4	172.5	106.4	418.3	237.3	934.5
1966	39.1	18.7	159.6	217.4	181.7	115.1	438.8	250.0	985.7
1967	41.1	21.4	163.2	225.7	188.4	122.6	438.0	262.5	1,011.5
1968	47.0	25.0	177.1	249.2	201.5	130.0	454.0	283.7	1,069.2
1969	52.0	33.3	182.8	268.1	214.2	137.0	468.6	295.8	1,115.6
1970	58.3	45.0	183.0	286.3	224.0	144.7	473.6	306.6	1,149.0
1971	58.9	52.9	184.8	296.6	231.1	149.0	463.8	318.6	1,162.5
1972	58.8	65.5	198.6	322.9	243.1	156.9	486.3	337.4	1,223.7
1973	53.8	74.4	219.3	347.5	246.4	164.0	512.5	355.1	1,277.9
1974	50.6	71.2	216.2	338.0	237.1	157.4	492.7	345.9	1,233.1
1975	46.5	67.0	222.6	336.1	235.5	156.3	456.4	348.8	1,197.0
1976	45.4	73.6	246.4	365.4	247.9	168.4	487.6	365.6	1,269.5
1977	47.3	82.6	259.8	389.6	253.7	173.0	501.0	379.7	1,307.4
1978	47.4	84.5	259.6	391.5	255.2	173.6	497.1	395.1	1,320.9
1979	51.9	69.6	285.3	406.9	249.5	177.3	518.1	392.7	1,337.7
1980	54.8	55.3	307.8	417.9	248.2	178.2	484.6	378.1	1,289.0
1981	54.1	46.3	319.7	420.1	239.7	178.2	463.7	374.1	1,255.7
1982	48.0	33.0	318.0	399.0	237.5	178.1	407.8	365.6	1,188.9
1983	43.1	32.5	334.6	410.2	236.1	179.9	399.3	366.9	1,182.2
1984	46.3	27.0	354.3	427.7	241.1	188.7	436.0	379.0	1,244.8
1985	45.5	22.9	370.3	438.8	245.8	189.6	424.5	384.3	1,244.2
1986	38.7	30.6	365.9	435.2	244.0	190.4	412.2	399.0	1,245.6
1987	42.2	26.4	383.7	452.5	251.0	197.2	427.3	411.0	1,286.5
1988	39.0	32.9	403.7	475.7	264.8	207.6	448.2	427.3	1,347.9
1989	41.2	35.4	406.5	483.2	267.5	209.9	450.1	432.6	1,360.0
1990	41.2	26.4	409.0	476.7	253.1	206.7	453.7	431.8	1,345.2
1991	41.1	24.9	407.3	473.3	257.1	206.4	442.2	424.3	1,330.0
1992	40.7	20.2	411.9	472.8	255.9	205.4	458.8	431.1	1,351.3
1993	39.5	22.3	428.6	490.5	271.7	211.3	458.9	436.4	1,378.2
1994	44.0	20.5	429.4	494.0	268.3	213.8	467.1	449.1	1,398.3
1995	46.8	13.9	434.4	495.2	270.3	217.9	466.0	457.6	1,411.7
1996	39.9	15.3	457.7	513.0	285.9	226.0	480.0	468.7	1,460.5
1997	43.6	17.5	471.7	532.8	284.8	238.0	483.7	473.4	1,480.0
1998	47.8	24.8	477.3	549.8	284.5	238.4	477.7	484.9	1,485.4

Note: Emissions from electricity generation are prorated across the end-use sectors.

Sources: **1997-1998**—Estimates documented in this report, based on energy data in the *Monthly Energy Review*. **1980-1996**—Estimates documented in this report, based on energy data in the *State Energy Data Report*. **1960-1979**—Calculated from energy data in the *State Energy Data Report*. **1949-1959**—Calculated from energy data in the *Annual Energy Review*.

Appendix F

Common Conversion Factors

Permutations of SI Units

- 1 gC = 1 gram carbon (C)
- 1 GgC = gigagram carbon (C) = 1,000 metric tons carbon (C)
- 1 TgC = 1 teragram carbon (C) = 1 million metric tons carbon (C)
- 1 PgC = 1 petagram carbon (C) = 1 billion metric tons carbon (C)
- 1 ppmv = 1 part per million by volume in the atmosphere
- 1 ppbv = 1 part per billion by volume in the atmosphere
- 1 pptv = 1 part per trillion by volume in the atmosphere

Density

- 1 thousand cubic feet of methane = 42.28 pounds
- 1 thousand cubic feet carbon dioxide = 115.97 pounds
- 1 metric ton natural gas liquids = 11.6 barrels
- 1 metric ton unfinished oils = 7.46 barrels
- 1 metric ton alcohol = 7.94 barrels
- 1 metric ton liquefied petroleum gas = 11.6 barrels
- 1 metric ton aviation gasoline = 8.9 barrels
- 1 metric ton naphtha jet fuel = 8.27 barrels
- 1 metric ton kerosene jet fuel = 7.93 barrels
- 1 metric ton motor gasoline = 8.53 barrels
- 1 metric ton kerosene = 7.73 barrels
- 1 metric ton naphtha = 8.22 barrels
- 1 metric ton distillate = 7.46 barrels
- 1 metric ton residual oil = 6.66 barrels
- 1 metric ton lubricants = 7.06 barrels
- 1 metric ton bitumen = 6.06 barrels
- 1 metric ton waxes = 7.87 barrels
- 1 metric ton petroleum coke = 5.51 barrels
- 1 metric ton petrochemical feedstocks = 7.46 barrels
- 1 metric ton special naphtha = 8.53 barrels
- 1 metric ton miscellaneous products = 8.00 barrels

Alternative Measures of Greenhouse Gases

- 1 pound methane, measured in carbon units (CH₄-C) = 1.333 pounds methane, measured at full molecular weight (CH₄)
- 1 pound carbon dioxide, measured in carbon units (CO₂-C) = 3.6667 pounds carbon dioxide, measured at full molecular weight (CO₂)
- 1 pound carbon monoxide, measured in carbon units (CO-C) = 2.333 pounds carbon monoxide, measured at full molecular weight (CO)
- 1 pound nitrous oxide, measured in nitrogen units (N₂O-N) = 1.571 pounds nitrous oxide, measured at full molecular weight (N₂O)

Weight

- 1 kilogram = 2.205 pounds
- 1 short ton = 0.9072 metric tons
- 1 metric ton = 1.1023 short tons = 2,204.6 pounds
- 1 cubic meter = 35.3147 cubic feet
- 1 cubic centimeter = 3.531×10^{-5} cubic feet

Area

- 1 acre = 0.40468724 hectare (ha) = 4,047 m²
- 1 hectare (ha) = 10,000 m² = 2.47 acres
- 1 kilometer = 0.6214 miles

Energy

- 1 joule = 947.9×10^{-21} quadrillion Btu
- 1 exajoule = 10^{18} joules = 0.9479 quadrillion Btu
- 1 quadrillion Btu = 1.0551 exajoule

References

- Abrahamson, D. "Aluminum and Global Warming." *Nature* 356. April 1992.
- Air Transportation Association. *Monthly Fuel Cost and Consumption*. Various years. Web site www.air-transport.org/public/industry/16.asp.
- Alternative Fluorocarbons Environmental Acceptability Study. *Historic Production, Sales and Atmospheric Release of HCFC-142b*. Washington, DC, February 1994.
- Alternative Fluorocarbons Environmental Acceptability Study. *Production, Sales and Atmospheric Release of Fluorocarbons Through 1995*. Washington, DC, January 1997.
- Alternative Fluorocarbons Environmental Acceptability Study. *Production, Sales and Atmospheric Release of Fluorocarbons Through 1997*. Web site www.afeas.org/prodsales_download.html.
- American Automobile Manufacturers Association. *AAMA Vehicle Facts and Figures*. Detroit, MI, various years.
- American Gas Association. *Gas Engineers Handbook*. New York, NY: Industrial Press, 1974.
- American Gas Association. *Gas Engineers Handbook: Fuel Gas Engineering Practices*. New York, NY: Industrial Press, 1974.
- American Gas Association. *Gas Facts*. Annual Statistical Report. Washington, DC, various years.
- American Iron and Steel Institute. *Iron and Steel Annual Statistical Report*. Washington, DC, various years.
- American Petroleum Institute. *Basic Petroleum Data Book*. Washington, DC, various years.
- American Petroleum Institute. *Sales of Natural Gas Liquids and Liquefied Refinery Gases*. Washington, DC, various years.
- American Society for Testing and Materials. *ASTM and Other Specifications for Petroleum Products and Lubricants*. Philadelphia, PA, 1985.
- American Society of Agricultural Engineers. *Manure Production and Characteristics Standards*. St. Joseph, MI, 1988.
- "Analysis of Adipic Acid Market." *Chemical Market Reporter*. June 15, 1998.
- "Annual Report on Top 50 Industrial Chemicals." *Chemical and Engineering News*. April or June issue, various years. Web site <http://pubs.acs.org/notartcl/cenear/970623/prod.html>.
- "Annual Survey of State Agencies." *World Oil*. February issue, various years.
- Augenstein, D. "The Greenhouse Effect and U.S. Landfill Methane." *Global Environmental Change*. December 1992.
- Baldwin, R.L., Thornley, J.H.M., and Beever, D.E. "Metabolism of the Lactating Cow: Digestive Elements of a Mechanistic Model." *Journal of Dairy Research* 54. 1987.
- Barnard, G. "Use of Agricultural Residues as Fuel." *Bioenergy and the Environment*. Ed. J. Pasztor and L. Kristoferson. Boulder, CO: Westview Press, 1990.
- Bartlett, K., and Harriss, R.C. "Review and Assessment of Methane Emissions from Wetlands." *Chemosphere* 26, Nos. 1-4. 1993.
- Berdowski, J.J.M., Beck, L., Piccot, S., Olivier, G.J., and Veldt, C. "Working Group Report: Methane Emissions from Fuel Combustion and Industrial Processes." *Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*. Ed. A.R. van Amstel. RIVM Report no. 481507003. Bilthoven, The Netherlands, 1993.
- Bingemer, H.G., and Crutzen, P.J. "The Production of Methane From Solid Wastes." *Journal of Geophysical Research* 92, D2. February 20, 1987.
- Birdsey, R.A. *Carbon Storage and Accumulation in United States Forest Ecosystems*. U.S. Forest Service General Technical Report WO-59. Washington, DC, 1992.
- Birdsey, R.A. "Changes in Forest Carbon Storage from Increasing Forest Area and Timber Growth." *Forests and Global Change, Vol 1: Opportunities for Increasing Forest Cover*. Ed. R.N. Sampson and D. Hair. Washington, DC: American Forests, 1992.
- Birdsey, R.A., and L.S. Heath, "Carbon Changes in U.S. Forests." *Productivity of America's Forests and Climate Change*. Ed. L.A. Joyce. Fort Collins, CO: USDA Forest Service. General Technical Report RM-GTR-271, 1995.

References

- Blaxter, K.L., and Clapperton, J.L. "Prediction of the Amount of Methane Produced by Ruminants." *British Journal of Nutrition* 19. 1965.
- Bodanzky, D. "Prologue to the Climate Convention." *Negotiating Climate Change: The Inside Story of the Rio Convention*. Ed. I. Minter and J.A. Leonard. Cambridge, UK: Cambridge University Press, 1994.
- Boden, T.A., Kaiser, D., Stepanski, R.J., and Stoss, F.W. *Trends '93: A Compendium of Data on Global Change*. ORNL/CDIAC-65. Oak Ridge, TN: Oak Ridge National Laboratory, September 1994.
- Boden, T.A., Stepanski, R.J., and Stoss, F.W. *Trends '91: A Compendium of Data on Global Change*. ORNL/CDIAC-46. Oak Ridge, TN: Oak Ridge National Laboratory, December 1991.
- Bogner, J.E. "Anaerobic Burial of Refuse in Landfills: Increased Atmospheric Methane and Implications for Increased Carbon Storage." *Ecological Bulletins* 42. 1992.
- Bouwman, A.F. "Exchange of Greenhouse Gases Between Terrestrial Ecosystems and Atmosphere." *Soils and the Greenhouse Effect*. Ed. A.F. Bouwman. New York, NY: John Wiley and Sons, 1990.
- Bremner, J.M., and Blackmer, A.M. "Nitrous Oxide: Emissions From Soil During Nitrification of Fertilizer Nitrogen." *Science* 199. 1978.
- Brown, H., et al. *Energy Analysis of 108 Industrial Processes*. Lilburn, GA: Fairmont Press, 1995.
- Burdick, D.L., and Leffler, W.L. *Petrochemicals in Non-technical Language*. Oklahoma City, OK: Pennwell Publishing Company, 1990.
- Chemical Manufacturers Association, Inc. *U.S. Chemical Industry Statistical Handbook*. Washington, DC, various years.
- Cicerone, R.J., and Shetter, J.D. "Sources of Atmospheric Methane: Measurements in Rice Paddies and Discussion." *Journal of Geophysical Research* 86, C8. August 1981.
- Cicerone, R.J., Shetter, J.D., and Delwiche, C.C. "Seasonal Variation of Methane Flux from a California Rice Paddy." *Journal of Geophysical Research* 88. December 1983.
- Clean Air Act Amendments of 1990*. P.L. 101-549, Nov. 15, 1990. Title VI, "Stratospheric Ozone Protection," 10489AT2849-2872.
- Clinton, W.J., and Gore, A. *The President's Climate Change Action Plan*. Washington, DC, October 1994. Available through the U.S. Department of Energy Office of Public Information and on the internet at <http://gcrio.gcrio.org/USCCAP/toc.html>.
- Cost, N.D., Howard, J., Mead, B., McWilliams, W.H., Smith, W.B., Van Hooser, D.D., and Wharton, E.H. *The Biomass Resource of the United States*. USDA Forest Service General Technical Report WO-57. Washington, DC, 1990.
- Crutzen, P.J., Aselmann, I., and Seiler, W. "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans." *Tellus* 38B. 1986.
- Cubbage, F.C. "Federal Land Conversion Programs." *Forests and Global Change* 1. 1992.
- Dahl, T. *Wetlands Losses in the United States: 1780's to 1980's*. Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service, 1990.
- Dale, C., et al. "First Oxygenated Gasoline Season Shakes Out Differently Than Expected." *Oil and Gas Journal*. October 25, 1993.
- Darley, E. *Emission Factors from Burning Agricultural Wastes Collected in California*. Final Report, CAL/ARB Project 4-011. Riverside, CA: University of California, 1977.
- Daugherty, A. *Major Uses of Land in the United States: 1987*. Agricultural Economic Report No. 643. Washington, DC: U.S. Department of Agriculture, Economic Research Service, 1991.
- Daugherty, A. *Major Uses of Land in the United States: 1992*. Agricultural Economic Report No. 723. Washington, DC: U.S. Department of Agriculture, Economic Research Service, September 1995.
- De Soete, G.G. "Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control." *International IPCC Workshop Proceedings: Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control*. Ed. A.R. van Amstel. Bilthoven, Netherlands: RIVM, 1993.
- Defense Logistics Agency, Defense Fuel Supply Center, Office of the Comptroller. *Fact Book Annual Report*. Alexandria, VA, various years. Web site www.dfsc.dla.mil/main/factbk96.
- DeLuchi, M. *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity*. Vol. 2. ANL/ESD/TM-22. Chicago, IL: Argonne National Laboratory, November 1993.
- Douglas, H. *Handbook of Mineral Economics*. San Francisco, CA: Hugh Douglas and Company, 1983.
- Drexel University Project Team. *Energy Analysis of 108 Industrial Processes*. Lilburn, GA: The Fairmont Press, 1996.
- "DuPont Acts To Cut Perfluoroethane." *Chemical Week*. August 23, 1995.

- “DuPont Chemist Sees HFC-152a As Most Viable Ozone-Safe Aerosol Propellant Candidate.” *Spray Technology & Marketing*. December 1994.
- “DuPont Scientist Says HFC-152a Offers Ozone-Safe, VOC-Free Option for Aerosol Industry.” *Spray Technology & Marketing*. April 1995.
- “DuPont Set To Expand Markets for Ozone-Safe HFC-152a Product.” *Ozone Depletion Online Today*. June 9, 1995.
- Duxbury, J.M., and McConnaughey, P.K. “Effect of Fertilizer Source on Denitrification and Nitrous Oxide Emission in a Maize Field.” *Soil Sci. Soc. Am. J.* 50. 1986.
- E.H. Pechan and Associates, Inc. *The Emission Reduction and Cost Analysis Model for NO_x ERCAM-NO_x*. Report prepared for the U.S. Environmental Protection Agency, Ozone/CO Programs Branch. Research Triangle Park, NC, May 1994.
- Eberle, A.C. “An Engineering Estimate of the Incremental Change in Methane Emissions with Increasing Throughput in a Natural Gas System.” Presented at the 1994 International Workshop on Environmental and Economic Impacts of Natural Gas Losses, March 22 and 23, Prague, The Czech Republic.
- Energy Information Administration. *Annual Energy Outlook 1998*. DOE/EIA-0383(98). Washington, DC, December 1997. Web site www.eia.doe.gov/oiaf/aeo98/homepage.html.
- Energy Information Administration. *Annual Energy Review*. DOE/EIA-0384. Washington, DC, various years. Web site www.eia.doe.gov/emeu/aer/contents.html.
- Energy Information Administration. *Btu Tax on Finished Petroleum Products*. Unpublished draft report. Washington, DC, April 1993.
- Energy Information Administration. *Coal Industry Annual*. DOE/EIA-0584. Washington, DC, various years. Web site www.eia.doe.gov/fueloverview.html.
- Energy Information Administration. *Coal Production*. DOE/EIA-0118. Washington, DC, various years.
- Energy Information Administration. *Cost and Quality of Fuels for Electric Utility Plants*. DOE/EIA-0191. Washington, DC, various years.
- Energy Information Administration. *Electric Power Annual*. DOE/EIA-0348. Washington, DC, various years. Web site www.eia.doe.gov/fueloverview.html.
- Energy Information Administration. *Emissions of Greenhouse Gases in the United States 1985-1990*. DOE/EIA-0573. Washington, DC, September 1993.
- Energy Information Administration. *Emissions of Greenhouse Gases in the United States 1987-1992*. DOE/EIA-0573. Washington, DC, November 1994. Web site www.eia.doe.gov/oiaf/1605/contents.html.
- Energy Information Administration. *Emissions of Greenhouse Gases in the United States 1987-1994*. DOE/EIA-0573(87-94). Washington, DC, October 1995. Web site www.eia.doe.gov/oiaf/1605/95report/contents.html.
- Energy Information Administration. *Emissions of Greenhouse Gases in the United States 1996*. DOE/EIA-0573(96). Washington, DC, October 1997. Web site www.eia.doe.gov/oiaf/1605/gg97rpt/front.htm.
- Energy Information Administration. Form EIA-767, “Steam Electric Plant Operation and Design Report.” Unpublished survey data. Washington, DC, various years.
- Energy Information Administration. *Fuel Oil and Kerosene Sales*. DOE/EIA-0535. Washington, DC, various years. Web site www.eia.doe.gov/fuelpetroleum.html.
- Energy Information Administration. *Household Vehicles Energy Consumption*. DOE/EIA-0464. Washington, DC, various years. Web site www.eia.doe.gov/emeu/rtecs/contents.html.
- Energy Information Administration. *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity*. SR/OIAF/98-03. Washington, DC, October 1998. Web site www.eia.doe.gov/oiaf/kyoto/kyotorpt.html.
- Energy Information Administration. *International Energy Annual*. DOE/EIA-0121. Washington, DC, various years. Web site www.eia.doe.gov/emeu/iea/contents.html.
- Energy Information Administration. *International Energy Outlook 1998*. DOE/EIA-0484(98). Washington, DC, April 1998. Web site www.eia.doe.gov/oiaf/ieo98/home.html.
- Energy Information Administration. *Manufacturing Energy Consumption Survey*. DOE/EIA-0512. Washington, DC, various years. Web site www.eia.doe.gov/emeu/mecs/contents.html.
- Energy Information Administration. *Monthly Energy Review*. DOE/EIA-0035. Washington, DC, various issues. Web site www.eia.doe.gov/emeu/mer/contents.html.
- Energy Information Administration. *Natural Gas Annual*. DOE/EIA-0131. Washington, DC, various years. Web site www.eia.doe.gov/fuelnatgas.html.
- Energy Information Administration. *Natural Gas Monthly*. DOE/EIA-0130. Washington, DC, various issues. Web site www.eia.doe.gov/fuelnatgas.html.

References

- Energy Information Administration. *Petroleum Supply Annual*. DOE/EIA-0340. Washington, DC, various years.
- Energy Information Administration. *Quarterly Coal Report*. DOE/EIA-0121(97/4Q). Washington, DC, May 1998.
- Energy Information Administration. *Renewable Energy Annual 1996*. DOE/EIA-0603(96). Washington, DC, April 1997. Web site www.eia.doe.gov/cneaf/solar.renewables/renewable.energy.annual/contents.html.
- Energy Information Administration. *Short-Term Energy Outlook*. DOE/EIA-0202. Washington, DC, various issues.
- Energy Information Administration. *State Energy Data Report: Consumption Estimates*. DOE/EIA-0214. Washington, DC, various years. Web site www.eia.doe.gov/emeu/sedr/sedr.html.
- Energy Information Administration. *U.S. Electric Utility Demand Side Management 1994*. DOE/EIA-0589(94). Washington, DC, December 1995.
- "Environmental Protection Drives Emissions Reduction Effort." *Electronic Design*. December 1, 1997.
- "EPA Launches PFC Reduction Program." *Chemical Week*. July 31, 1996.
- Fertilizer Institute, *Annual Report on Commercial Fertilizers*. Reports for 1995, 1996, 1997, and 1998. Washington, DC, 1996-1999.
- "Fluorocarbon Outlook Turns Bullish." *Chemical Market Reporter*. May 25, 1998.
- Franklin Associates, Ltd. *Characterization of Municipal Solid Waste in the United States: Annual Updates*. Prepared for U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, various years.
- Freedonia Group, Inc. *Carbon Dioxide*. Business Research Report B286. Cleveland, OH, November 1991.
- Freedonia Group Inc. *Carbon Dioxide*. Industry Study 564. Cleveland, OH, February 1994.
- Gas Research Institute. *Chemical Composition of Discovered and Undiscovered Natural Gas in the United States—1993 Update*. GRI-93/0456. December 1993.
- Gas Research Institute. *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*. GRI-92/0123. March 1992.
- Goodger, E.M. *Hydrocarbon Fuels: Production, Properties and Performance of Liquids and Gases*. New York, NY: John Wiley & Sons, 1975.
- Greeley, W. (U.S. Forest Service). "The Relation of Geography to Timber Supply." *Economic Geography* 1. 1925.
- Griffin, R. "CO₂ Release from Cement Production 1950-1985." Ed. G. Marland et al. Oak Ridge, TN, Oak Ridge National Laboratory, 1987.
- Grubb, M.J. "On Coefficients for Determining Greenhouse Gas Emissions from Fossil Fuel Production and Consumption." London, UK: Royal Institute of International Affairs, Energy and Environmental Programme, 1989.
- Guerra, C.R., Kelton, K., and Nielsen, D.C. "Natural Gas Supplementation with Refinery Gases and Hydrogen." *New Fuels and Advances in Combustion Technologies*. Chicago, IL: Institute of Gas Technology, 1979.
- Guthrie, V.B., Ed. *Petroleum Products Handbook*. New York, NY: McGraw-Hill, 1960.
- Hadaller, O.J., and Momenthy, A.M. "Conventional Jet Fuels." *The Characteristics of Future Fuels*. Part 1. Seattle, WA: Boeing Corp., September 1990.
- Harrison, M.R., and Cowgill, R.M. *Tier 2 Summary of Methane Emissions from the Natural Gas Industry*. Draft Final Report Prepared for the Gas Research Institute and the U.S. Environmental Protection Agency. Washington, DC, January 1996.
- Hashimoto, A.G., Varel, V.H., and Chen, Y.R. "Ultimate Methane Yield From Beef Cattle Manure: Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." *Agricultural Wastes* 3. 1981.
- Heath, L.S., Birdsey, R.A., and Row, C. "Carbon Pools and Flux in U.S. Forest Products." *The Role of Forest Ecosystems and Forest Resource Management in the Global Carbon Cycle*. NATO ASI Series. Germany: Springer-Verlag, 1995.
- "HFC Shortage Looms Because of Producers' Fears." *Chemical Market Reporter*. April 26, 1999.
- "HFC-134a Prices Rise As Market Tightens." *Chemical Market Reporter*. March 15, 1999.
- Hill, D.T. "Methane Productivity of the Major Animal Types." *Transactions of the ASAE* 27. 1984.
- Holzappel-Pschorn, A., and Seiler, W. "Methane Emission During a Cultivation Period from an Italian Rice Paddy." *Journal of Geophysical Research* 91. October 1986.
- Hong, B.D., and Slatick, E.R. "Carbon Dioxide Emission Factors for Coal." Energy Information Administration. *Quarterly Coal Report*, January-March 1994. Washington, DC, 1994.
- Houghton, R.A., et al. "The Flux of Carbon from Terrestrial Ecosystems to the Atmosphere in 1980 Due to Changes in Land Use: Geographic Distribution of the Global Flux." *Tellus* 39. 1987.

- Hunt, J.M. *Petroleum Geochemistry and Geology*. San Francisco, CA: W.H. Freeman, 1979.
- Intergovernmental Panel on Climate Change. *Climate Change: The IPCC Scientific Assessment*. Cambridge, UK: Cambridge University Press, 1990.
- Intergovernmental Panel on Climate Change. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Cambridge, UK: Cambridge University Press, 1992.
- Intergovernmental Panel on Climate Change. *Climate Change 1994: Radiative Forcing of Climate Change*. Cambridge, UK: Cambridge University Press, 1995.
- Intergovernmental Panel on Climate Change. *Climate Change 1995: The Science of Climate Change*. Cambridge, UK: Cambridge University Press, 1996. Summary available at web site www.ipcc.ch.
- Intergovernmental Panel on Climate Change. *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Vol. 3. (Paris, France, 1997). Web site www.iea.org/ipcc/invs6.htm.
- Intergovernmental Panel on Climate Change. *IPCC Guidelines for National Greenhouse Gas Inventories*. Vols. 1-4. Paris, France, 1994-97.
- Intergovernmental Panel on Climate Change. *Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control*. Proceedings, Research for Man and Environment. Bilthoven, Netherlands, February 1993.
- Jaques, A., Neitzert, F., and Boileau, P. *Trends in Canada's Greenhouse Gas Emissions (1990-1995)*. Ottawa, Canada: Environment Canada, October 1997.
- Keeling, C.D., and Whorf, T.P. "Atmospheric CO₂ Records From Sites in the SIO Air Sampling Network." 1993.
- Kirchgessner, D., Cowgill, R.M., Harrison, M., and Campbell, L.M. "Methods for Estimating Methane Emissions from the Domestic Natural Gas Industry." Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Air Pollution Prevention Division, June 1995.
- Kirchgessner, D.A., Piccot, S.D., and Chadha, A. "Estimation of Methane Emissions from A Surface Coal Mine Using Open-Path FTIR Spectroscopy and Modeling Techniques." *Chemosphere*. Special Methane Edition. 1993.
- Ko, M.K.W., Sze, N.D., Wang, W.C., Shia, G., Goldman, A., Murcray, F.J., Murcray, D.G., and Rinsland, C.P. "Atmospheric Sulfur Hexafluoride: Sources, Sinks, and Greenhouse Warming." *Journal of Geophysical Research* 98.
- Kostick, D. "Soda Ash, Sodium Bicarbonate, and Sodium Sulfate." *Mineral Facts and Problems*. 1985 ed. Washington, DC, 1985.
- Kostick, D. "Sodium Compounds." *Minerals Yearbook, 1987*. Washington, DC, 1987.
- Kramlich, J.C., and Linak, W.P. "Nitrous Oxide Behavior in the Atmosphere, and in Combustion and Industrial Systems." *Progress in Energy and Combustion Science* 20. 1994.
- Landau, C.W., and Bolich, P.K. "Methane Emissions from Louisiana First and Ratoon Crop." *Soil Science* 156. 1993.
- Leutwyler, K. "No Global Warming?" *Scientific American*. February 1994.
- Li, C., Frohling, S., and Harriss, R. "Modeling Carbon Biogeochemistry in Agricultural Soils." *Global Biogeochemical Cycles* 8. September 1994.
- Liss, W.E., et al. *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*. GRI-92/0123. Chicago, IL: Gas Research Institute, October 1992.
- Mann, L.K. "Changes in Soil Carbon Storage After Cultivation." *Soil Science* 142. November 1986.
- Mannsville Chemical Corporation. "Adipic Acid." *Chemical Products Synopsis*. Asbury Park, NJ, June 1990.
- ManTech Environmental Technology, Inc. *Impact of Conservation Tillage on Soil and Atmospheric Carbon in the Contiguous United States*. PB92-113448. Prepared for the Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency. September 1991.
- Marland, G., and Pippin, A. "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy* 14. 1990.
- Marland, G., and Rotty, R. "Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982." *Tellus* 36B. 1984.
- Marland, G., et al. *Estimates of CO₂ Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data*. Oak Ridge, TN: Oak Ridge National Laboratory, 1989.

References

- 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.
- Matthews, E., and Fung, I. "Methane Emissions From Natural Wetlands: Global Distribution, Area, and Environmental Characteristics." *Global Biogeochemical Cycles* 1. March 1987.
- Matthews, E., Fung, I., and Lerner, J. "Methane Emission From Rice Cultivation: Geographic and Seasonal Distribution of Cultivated Areas and Emissions." *Global Biogeochemical Cycles* 5. March 1991.
- Moore, T.R. and Knowles, R. "The Influence of Water Table Level on Methane and Carbon Dioxide Emissions From Peatland Soils." *Canadian Journal of Soil Science* 69. 1989.
- Mosier, A. "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.
- Mosier, A., et al. "Methane and Nitrous Oxide Fluxes in Native, Fertilized, and Cultivated Grasslands." *Nature* 350. 1991.
- Mosier, A., and Schimel, D. "Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide." *Chemistry & Industry* 2. December 1991.
- Mosier, A., Parton, W.J., and Hutchinson, G.L. "Modeling Nitrous Oxide Evolution from Cropped and Native Soils." *Ecology Bulletin* 35. 1983.
- Nagy, B., and Columbo, U., eds. *Fundamental Aspects of Petroleum Chemistry*. New York, NY: Elsevier Publishing, 1967.
- National Institute of Petroleum and Energy Research. *Motor Gasoline, Summer and Motor Gasoline, Winter*. Various years.
- National Research Council. *Rethinking the Ozone Problem in Urban and Regional Air Pollution*. Washington, DC: National Academy Press, 1991.
- "Nationwide Survey: The State of Garbage in America." *Biocycle* (annual survey). Various years.
- Neue, H.H., and Scharpenseel, H.W. *Gaseous Products of Decomposition of Organic Matter and Rice*. Los Banos, Philippines, 1984.
- Oak Ridge National Laboratory. *Transportation Energy Data Book*. Oak Ridge, TN, various years. Web site www-cta.ornl.gov/cta/data/tebd.htm.
- Organization for Economic Cooperation and Development. *Estimation of Greenhouse Gas Emissions and Sinks*. Final Report. Paris, France, August 1991.
- Pacey, J. "Methane Recovery from Landfills." Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium. U.S. Environmental Protection Agency, Washington, DC, June 27-29, 1995.
- Pacey, J., Thorneloe, S.A., and Dorne, M. "Methane Recovery from Landfills and an Overview of EPA's Research Program for Landfill Gas Utilization." Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium, U.S. Environmental Protection Agency. Washington, DC, June 27-29, 1995.
- Parson, E.A., and Greene, O. "The Complex Chemistry of the International Ozone Agreements." *Environment* 37. March 1995.
- "PFCs Can Be Recycled with New Technology." American Institute of Chemical Engineers. Press Release. March 12, 1997.
- Piccot, S.D., Masemore, S.S., Ringler, E., and Kirchgessner, D.A. "Developing Improved Methane Emission Estimates for Coal Mining Operations." Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium, U.S. Environmental Protection Agency. Washington, DC, June 27-29, 1995.
- Powell, D.S., Faulkner, J.L., Darr, D.R., Zhu, Z., and MacCleery, D.W. *Forest Resources of the United States, 1992*. USDA Forest Service General Technical Report RM-234. Washington, DC, September 1993.
- Prather, M., et al. "Other Trace Gases and Atmospheric Chemistry." Intergovernmental Panel on Climate Change. *Climate Change 1994: Radiative Forcing of Climate Change*. Cambridge, UK: Cambridge University Press, 1995.
- Radian Corporation. *Global Emissions of Methane from Petroleum Sources*. Report prepared for the American Petroleum Institute. Research Triangle Park, NC, February 1992.
- Radian Corporation. *Nitrous Oxide Emissions from Adipic Acid Manufacturing*. Final Report prepared for U.S. Environmental Protection Agency, Office of Research and Development. Rochester, NY, January 1992.
- Railroad Commission of Texas. *Annual Summaries of Texas Natural Gas*. Various years.
- Reimer, R.A., Parrett, R.A., and Slaten, C.S., "Abatement of N₂O Emissions Produced in Adipic Acid." *Proceedings of the 5th International Workshop on Nitrous Oxide Emissions*. Tsukuba, Japan, July 1992.
- Rhodes, A.K. "U.S. Refiners Scramble To Meet Reformulated Gasoline Mandate." *Oil and Gas Journal*. January 27, 1992.
- Ringen, S., Lanum, J., and Miknis, F.P. "Calculating Heating Values from Elemental Compositions of Fossil Fuels." *Fuel* 58. January 1979.

- Rose, J.W., and Cooper, J.R. *Technical Data on Fuel*. London, UK: The British National Committee, World Energy Conference, 1977.
- Safley, L.M., Casada, M.E., Woodbury, J., and Roos, K.F. *Global Methane Emissions from Livestock and Poultry Manure*. EPA/400/1-91/048. Washington, DC: U.S. Environmental Protection Agency, Office of Air and Radiation, February 1992.
- Salthouse, R. *Making Clean Gasoline*. Logistics Management Institute, September 1992.
- Sampson, R.N., and Winnett, S.M. "Trees, Forests, and Carbon." *Forests and Global Change*, Vol. 1. Washington, DC, 1992.
- Sass, R.L., Fisher, F.M., and Harcombe, P.A. "Methane Production and Emission in a Texas Rice Field." *Global Biogeochemical Cycles* 4. March 1990.
- Sass, R.L., Fisher, F.M., Lewis, S., Jund, M., and Turner, F. "Methane Emissions from Rice Fields: Effect of Soil Properties." *Global Biogeochemical Cycles* 8. 1994.
- Sass, R.L., Fisher, F.M., and Wang, Y.B. "Methane Emissions from Rice Fields: The Effect of Floodwater Management." *Global Biogeochemical Cycles* 6. 1992.
- Schiff, D. and Sciannamea, M. "Greenlook." *Electronic Design*. December 15, 1997.
- Schlesinger, W.H. "Changes in Soil Carbon Storage and Associated Properties with Disturbance and Recovery." *The Changing Carbon Cycle: A Global Analysis*. Ed. J. Trabalka and D. Riechle. New York, NY: Springer-Verlag, 1986.
- Schmidt, P.F. *Fuel Oil Manual*. New York, NY: Industrial Press, 1969.
- Schutz, H., Seiler, W., and Conrad, R. "Processes Involved in Formation and Emissions of Methane in Rice Paddies." *Biogeochemistry* 7. 1989.
- Science Applications International Corporation. *Analysis of the Relationship Between the Heat and Carbon Content of U.S. Fuels: Final Task Report*. Report prepared for Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels. Washington, DC, 1992.
- Searls, J.P. "Sodium Compounds," *Minerals Yearbook, 1984*. Washington, DC: U.S. Bureau of Mines, 1984.
- Seiler, W., and Crutzen, P. "Estimates of Gross and Net Fluxes of Carbon Between the Biosphere and the Atmosphere from Biomass Burning." *Climatic Change* 2. 1980.
- Shine, K.P., Fouquart, Y., Ramaswamy, V., Solomon, S., and Srinivasan, J. "Radiative Forcing." *Climate Change 1994: Radiative Forcing of Climate Change*. Cambridge, UK: Cambridge University Press, 1995.
- Spicer, C.W., Holdren, M.W., Smith, D.L., Hughes, D.P., and Smith, M.D. "Chemical Composition of Exhaust from Aircraft Turbine Engines." *Journal of Engineering for Gas Turbines and Power* 114. January 1992.
- Stuedler, P.A., et al. "Influence of Nitrogen Fertilization on Methane Uptake in Temperate Forest Soils." *Nature* 341. September 28, 1989.
- Stevens, W.R. III. *Abatement of Nitrous Oxide Emissions Produced in the Adipic Acid Industry*. White House Conference on Global Climate Change, Nitrous Oxide Workshop. Wilmington, DE: Mimeo, The DuPont Company, June 11, 1993.
- Strehler, A., and Stutzle, W. "Biomass Residues." *Biomass: Regenerable Energy*. Ed. D.O. Hall and R.P. Overend. Chichester, UK: John Wiley and Sons, 1987.
- Takeshita, M., and Soud, H. *FGD Performance and Experience on Coal-fired Plants*. London, UK: IEA Coal Research, July 1993.
- Thiemens, M., and Trogler, W. "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide." *Science* 251. February 22, 1991.
- Thorneloe, S.A. "Landfill Gas Recovery/Utilization—Options and Economics." Paper presented at the Sixteenth Annual Conference by the Institute of Gas Technology on Energy from Biomass and Wastes, Orlando, FL, March 5, 1992.
- Thorneloe, S.A., Doorn, M.R.J., Stefanski, L.A., Barlaz, M.A., Peer, R.L., and Epperson, D.L. "Estimate of Methane Emissions from U.S. Landfills." Prepared for U.S. Environmental Protection Agency, Office of Research and Development. April 1994.
- Trevits, M.A., Finfinger, G.L., and LaScola, J.C. "Evaluation of U.S. Coal Mine Emissions." Society for Mining, Metallurgy and Exploration, *Proceedings of the Fifth U.S. Mine Ventilation Symposium*. Littlejohn, 1991.
- Turner, D.P., Lee, J.L., Koerper, G.J., and Barker, J.R., Eds. *The Forest Sector Carbon Budget of the United States: Carbon Pools and Flux under Alternative Policy Options*. EPA/600/3-93/093. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development, May 1993.
- U.S. Department of Agriculture, Crop Reporting Board, Statistical Reporting Service. *Commercial Fertilizers*. SpCr 7. Washington, DC, various years.
- U.S. Department of Agriculture, Forest Service. *AVHRR Forest Type Map, 1993 RPA Program, Forest Inventory and Analysis*. Starkville, MS, December 1992. Modified for printing by Pacific Meridian Resources, Emeryville, CA, 1996.

References

- U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch. *Cattle: Final Estimates, Sheep and Goats: Final Estimates, and Hogs and Pigs: Final Estimates*. Washington, DC, various years. Web site www.usda.mannlib.cornell.edu.
- U.S. Department of Agriculture, National Agricultural Statistics Service. *Crop Production*. Washington, DC, various years. Web site www.usda.gov/nass/pubs/dataprd1.html.
- U.S. Department of Agriculture, Soil Conservation Service (now the National Resources Conservation Service). *1991 Update of National Resources Inventory Wetlands Data for Non-Federal Rural Lands*. Washington, DC, not dated.
- U.S. Department of Agriculture, Soil Conservation Service (now the National Resources Conservation Service). *Summary Report: 1992 National Resources Inventory*. Washington, DC, July 1994. Web site www.ftw.nrcs.usda.gov/nri_data.html.
- U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division. *Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries*. Unpublished, various years.
- U.S. Department of Commerce, Bureau of the Census. *1990 Census of Population and Housing. Population and Housing Unit Counts, United States*. CPH-2-1. Washington, DC, 1993.
- U.S. Department of Commerce, Bureau of the Census. *Census of Manufacturers, 1992*. Washington, DC, 1995.
- U.S. Department of Commerce, Bureau of the Census. *Census of Mineral Industries, 1992*. Washington, DC, 1995.
- U.S. Department of Commerce, Bureau of the Census. *Current Industrial Reports: Annual Report on Fertilizer Materials*. MA28B. Washington, DC, 1992. Web site www.census.gov/econ/www/manumenu.html.
- U.S. Department of Commerce, Bureau of the Census. *Current Industrial Reports: Industrial Gases*. Washington, DC, various years.
- U.S. Department of Commerce, Bureau of the Census. *Current Industrial Reports: Quarterly and Annual Report on Fertilizer Materials*. MQ28B and MA28B. Washington, DC, various years. Web site www.census.gov/industry/mq28b974.txt.
- U.S. Department of Commerce, Bureau of the Census. *United States Census, 1980 and United States Census, 1990*. Washington, DC.
- U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census. *Census of Agriculture, United States Summary and State Data*. Vol. 1, "Geographic Area Series," Part 51. Washington, DC, 1982, 1987, and 1992.
- U.S. Department of Commerce, National Bureau of Standards. *Thermal Properties of Petroleum Products*. Miscellaneous Publication No. 97. Washington, DC, 1929.
- U.S. Department of Energy. *An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions*. DOE/NBB-0088P. Washington, DC, April 1990.
- U.S. Department of Energy. *Atmospheric Carbon Dioxide and the Global Carbon Cycle*. DOE/ER-0239. Ed. J.R. Trabalka. Washington, DC, 1985.
- U.S. Department of Energy. *Compliance Assessment of the Portsmouth Gaseous Diffusion Plant*. DOE/EH-0144. Washington, DC, April 1990.
- U.S. Department of Energy. *Energy Technology Characterizations Handbook: Environmental Pollution and Control Factors*, Third Edition. DOE/EP-0093. Washington, DC, March 1983.
- U.S. Department of Energy. *The Climate Change Action Plan: Technical Supplement*. DOE/PO-0011. Washington, DC, March 1994.
- U.S. Department of Energy and U.S. Environmental Protection Agency. *Report to the President on Carbon Dioxide Emissions From the Generation of Electric Power in the United States*. Draft Report. Washington, DC, September 29, 1999.
- U.S. Department of State. *Climate Action Plan*. Publication 10496. Washington, DC, July 1997.
- U.S. Department of State. *National Action Plan for Global Climate Change*. Publication 10026. Washington, DC, December 1992.
- U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Aluminum Report*. Washington, DC, various years. Web site <http://minerals.er.usgs.gov/minerals>.
- U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Cement Annual Report*. Washington, DC, various years. Web site <http://minerals.er.usgs.gov/minerals>.
- U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Crushed Stone Annual Report*. Washington, DC, various years. Web site <http://minerals.er.usgs.gov/minerals>.

- U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Minerals Commodity Summaries*. Washington, DC, various years. Web site <http://minerals.er.usgs.gov/minerals>.
- U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Minerals Yearbook*. Washington, DC, various years. Web site <http://minerals.er.usgs.gov/minerals>.
- U.S. Department of the Interior, U.S. Geological Survey Minerals Information Service. *Soda Ash Annual Report*. Washington, DC, various years. Web site <http://minerals.er.usgs.gov/minerals>.
- U.S. Department of Transportation, Federal Highway Administration. *Highway Statistics*. Washington, DC, various years. Web site www.bts.gov/ntda/fhwa/prod.html.
- U.S. Environmental Protection Agency. *1995 Toxics Release Inventory: Public Data Release*. EPA-745-R-95-001. Washington, DC, April 1997. Web site www.epa.gov/opptintr/tri/pdr95/drhome.htm.
- U.S. Environmental Protection Agency. *1997 Toxics Release Inventory* (Washington, DC, May 1998). Web site www.epa.gov/opptintr/tri/pdr99/drhome.htm.
- U.S. Environmental Protection Agency. *Emissions of Nitrous Oxide From Highway Mobile Sources*. EPA-420-R-98-009. Washington, DC, August 1998. Web site www.epa.gov/oms/climate.htm.
- U.S. Environmental Protection Agency. *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*. Washington, DC, September 1994.
- U.S. Environmental Protection Agency. *Regional Interim Emission Inventories, 1987-1991*. Volume I, "Development Methodologies." EPA-454-R-93-021a. Research Triangle Park, NC, May 1993.
- U.S. Environmental Protection Agency, Environmental Research Laboratory. *The Impact of Conservation Tillage Use on Soil and Atmospheric Carbon in the Contiguous United States*. EPA/600/3-91/056. Corvallis, OR, November 1991.
- U.S. Environmental Protection Agency, Office of Air and Radiation. *Anthropogenic Methane Emissions in the United States: Estimates for 1990. Report to Congress*. Ed. Kathleen Hogan. Washington, DC, April 1993.
- U.S. Environmental Protection Agency, Office of Air and Radiation. *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*. EPA 430-R-97-020. Washington, DC, September 1997.
- U.S. Environmental Protection Agency, Office of Air and Radiation. *Methane Emissions from Coal Mining—Issues and Opportunities for Reduction*. EPA/400/9-90/008. Washington, DC, September 1990.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *Compilation of Air Pollutant Emission Factors*. AP-42, Fifth Edition. Vol. I: Stationary Point and Area Sources. Research Triangle Park, NC, September 1995. Web site www.epa.gov/ttn/chief/ap42.html.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *Compilation of Air Pollutant Emission Factors*. AP-42, Supplement D. Research Triangle Park, NC, September 1995. Web site www.epa.gov/ttn/chief/ap42.html.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Pollutant Emission Estimates 1980-1991*. EPA-454/R-92-013. Research Triangle Park, NC, October 1992.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Pollutant Emission Trends 1900-1994*. EPA-454-R-95-011. Research Triangle Park, NC, October 1995.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Pollutant Emission Trends 1900-1995*. EPA-454-R-96-007. Research Triangle Park, NC, October 1996. Web site www.epa.gov/airprog/oar/emtrnd/index.htm.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Pollutant Emissions Trends 1900-1996*. EPA-454-R-97-011. Research Triangle Park, NC, December 1997. Web site www.epa.gov/oar/emtrnd.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Pollutant Emission Trends Update, 1900-1997*. EPA-454-E-98-007. Research Triangle Park, NC, December 1998. Web site www.epa.gov/ttn/chief/trends97/emtrnd.html.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Quality and Emissions Trends Report, 1996*. EPA-454-R-97-013. Research Triangle Park, NC, January 1998. Web site www.epa.gov/oar/aqtrnd96.
- U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. *National Air Quality and Emissions Trends Report, 1997*. EPA-454-R-98-016. Research Triangle Park, NC, December 1998. Web site www.epa.gov/oar/aqtrnd97.
- U.S. Environmental Protection Agency, Office of Mobile Sources. *User's Guide to MOBILE 5: Mobile Source Emissions Model*. Ann Arbor, MI, 1993.

References

- U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation. *International Anthropogenic Methane Emissions: Estimates for 1990*. EPA 230-R-93-010. Washington, DC, January 1994.
- U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1993*. EPA 230-R-94-014. Washington, DC, September 1994.
- U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1994*. EPA 230-R-96-006. Washington, DC, November 1995.
- U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1996*. Draft Report. Washington, DC, March 1998.
- U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1997*. Draft Report. Washington, DC, March 1999.
- U.S. Environmental Protection Agency, Office of Research and Development. *The Forest Sector Carbon Budget of the United States: Carbon Pools and Flux Under Alternative Policy Options*. EPA-600-3-93-093. Washington, DC, May 1993.
- U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. *Characterization of Municipal Solid Waste in the United States: 1996 Update*. EPA-530-S-96-001. Washington, DC, May 1997.
- U.S. International Trade Commission. *Synthetic Organic Chemicals: United States Production and Trade*. USITC Publication 2720. Washington, DC, various years. Web site <http://205.197.120.5.80/wais/reports/arc/w2933.htm>.
- United Nations. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. FCCC/CP/1997/L.7/Add.1. 1997. Web site www.unfccc.de/index.html.
- United Nations. *Report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the Work of the Second Part of Its Fifth Session. Held at New York from 30 April to 9 May 1992*. UN Document A/AC.237/18, Part II. May 15, 1992.
- United Nations Environment Program. *Report of the Conference of the Parties on its First Session. Held at Berlin from 28 March to 7 April 1995. Addendum, Part Two: Action Taken by the Conference of the Parties at its First Session*. FCCC/CP/1995/7/Add.1. June 1995.
- United Nations Framework Convention on Climate Change. *Review of the Implementation of the Convention and of Decisions of the First Session of the Conference of the Parties: Ministerial Declaration*. FCCC/CP/1996/L.17. July 1996.
- Waddle, K.L., Oswald, D., Daniel, D., Powell, L., and Douglas, S. *Forest Statistics of the United States, 1987*. USDA Forest Service Resource Bulletin PNW-RB-168. Portland, OR: Pacific Northwest Research Station, 1989.
- Ward's Communications, Inc. *Ward's Automotive Yearbook*. Southfield, MI, 1999.
- Wassmann, R., Papen, H., and Rennenberg, H. "Methane Emissions from Rice Paddies and Possible Mitigation Strategies." *Chemosphere* 26. 1993.
- Wuebbles, D.J., and Edmonds, J. *Primer on Greenhouse Gases*. Chelsea, MI: Lewis Publishers, 1991.

Glossary

Acid stabilization: A circumstance where the pH of the waste mixture in an animal manure management system is maintained near 7.0, optimal conditions for methane production.

Aerobic bacteria: Microorganisms living, active, or occurring only in the presence of oxygen.

Aerobic decomposition: The breakdown of a molecule into simpler molecules or atoms by microorganisms under favorable conditions of oxygenation.

Aerosols: Airborne particles.

Afforestation: Planting of new forests on lands that have not been recently forested.

Agglomeration: The clustering of disparate elements.

Airshed: An area or region defined by settlement patterns or geology that results in discrete atmospheric conditions.

Albedo: The fraction of incident light or electromagnetic radiation that is reflected by a surface or body. See *Planetary albedo*.

Anaerobes: Organisms that live and are active only in the absence of oxygen.

Anaerobic bacteria: Microorganisms living, active, or occurring only in the absence of oxygen.

Anaerobic decomposition: The breakdown of molecules into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

Anaerobic lagoon: A liquid-based manure management system, characterized by waste residing in water to a depth of at least six feet for a period ranging between 30 and 200 days.

Anode: A positive electrode, as in a battery, radio tube, etc.

Anthracite: The highest rank of coal; used primarily for residential and commercial space heating. It is a hard, brittle, and black lustrous coal, often referred to as hard coal, containing a high percentage of fixed carbon and a low percentage of volatile matter. The moisture content of fresh-mined anthracite generally is less than 15 percent. The heat content of anthracite ranges from

22 to 28 million Btu per ton on a moist, mineral-matter-free basis. The heat content of anthracite coal consumed in the United States averages 25 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter). Note: Since the 1980's, anthracite refuse or mine waste has been used for steam electric power generation. This fuel typically has a heat content of 15 million Btu per ton or less.

Anthropogenic: Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation.

API Gravity: A scale expressing the density of petroleum products as established by the American Petroleum Institute.

Asphalt: A dark-brown to black cement-like material obtained by petroleum processing, containing bitumens as the predominant constituents. Includes crude asphalt as well as the following finished products: cements, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cutback asphalts.

Associated gas: Natural gas found mixed with crude oil in underground reservoirs, released as a byproduct of oil production.

Aviation gasoline (finished): 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. Note: Data on blending components are not counted in data on finished aviation gasoline.

Balancing item: A measurement of the difference between the reported amount of natural gas produced and the reported amount consumed.

Biofuels: Organic materials, such as wood, waste, and alcohol fuels, burned for energy purposes.

Biogas: The gas produced from the anaerobic decomposition of organic material in a landfill.

Biogenic: Produced by the actions of living organisms.

Biomass: Materials that are biological in origin, including organic material (both living and dead) from above and below ground, for example, trees, crops, grasses, tree litter, roots, and animals and animal waste.

Biosphere: The portion of the Earth and its atmosphere that can support life. The part of the global carbon cycle that includes living organisms and biogenic organic matter.

Bituminous coal: A dense coal, usually black, sometimes dark brown, often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing and to make coke. Bituminous coal is the most abundant coal in active U.S. mining regions. Its moisture content usually is less than 20 percent. The heat content of bituminous coal ranges from 21 to 30 million Btu per ton on a moist, mineral-matter-free basis. The heat content of bituminous coal consumed in the United States averages 24 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

BOD₅: The biochemical oxygen demand of wastewater during decomposition occurring over a 5-day period. A measure of the organic content of wastewater.

Bromofluorocarbons (halons): Inert, nontoxic chemicals that have at least one bromine atom in their chemical makeup. They evaporate without leaving a residue and are used in fire extinguishing systems, especially for large computer installations.

Bunker fuel: Fuel supplied to ships and aircraft, both domestic and foreign, consisting primarily of residual and distillate fuel oil for ships and kerosene-based jet fuel for aircraft. The term "international bunker fuels" is used to denote the consumption of fuel for international transport activities. *Note:* For the purposes of greenhouse gas emissions inventories, data on emissions from combustion of international bunker fuels are subtracted from national emissions totals. Historically, bunker fuels have meant only ship fuel. See *Vessel bunkering*.

Calcination: A process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled.

Calcium sulfate: A white crystalline salt, insoluble in water. Used in Keene's cement, in pigments, as a paper filler, and as a drying agent.

Calcium sulfite: A white powder, soluble in dilute sulfuric acid. Used in the sulfite process for the manufacture of wood pulp.

Capital stock: Property, plant and equipment used in the production, processing and distribution of energy resources.

Carbon black: An amorphous form of carbon, produced commercially by thermal or oxidative decomposition of hydrocarbons and used principally in rubber goods, pigments, and printer's ink.

Carbon budget: Carbon budget: The balance of the exchanges (incomes and losses) of carbon between carbon sinks (e.g., atmosphere and biosphere) in the carbon cycle. See *Carbon cycle* and *Carbon sink*.

Carbon cycle: All carbon sinks and exchanges of carbon from one sink to another by various chemical, physical, geological, and biological processes. See *Carbon sink* and *Carbon budget*.

Carbon dioxide (CO₂): A colorless, odorless, non-poisonous gas that is a normal part of Earth's atmosphere. Carbon dioxide is a product of fossil-fuel combustion as well as other processes. It is considered a greenhouse gas as it traps heat (infrared energy) radiated by the Earth into the atmosphere and thereby contributes to the potential for global warming. Other greenhouse gases are measured in relation to the global warming potential (GWP) of carbon dioxide, which by international scientific convention is assigned a value of one (1). See *Global warming potential (GWP)* and *Greenhouse gases*.

Carbon dioxide equivalent: The amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas. Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured (for example, methane) by its estimated global warming potential (which is 21 for methane). "Carbon equivalent units" are defined as carbon dioxide equivalents multiplied by the carbon content of carbon dioxide (i.e., 12/44).

Carbon flux: See *Carbon budget*.

Carbon intensity: The amount of carbon by weight emitted per unit of energy consumed. A common measure of carbon intensity is weight of carbon per British thermal unit (Btu) of energy. When there is only one fossil fuel under consideration, the carbon intensity and the emissions coefficient are the same thing. When there are several fuels, carbon intensity is based on their combined emissions coefficients weighted by their

energy consumption levels. See *Emissions coefficient* and *Carbon output rate*.

Carbon output rate: The amount of carbon by weight per kilowatt-hour of electricity produced.

Carbon sequestration: The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes.

Carbon sink: A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. The four sinks, which are regions of the Earth within which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels).

Catalytic converter: A device containing a catalyst for converting automobile exhaust into mostly harmless products.

Cesspool: An underground reservoir for liquid waste, typically household sewage.

Chlorofluorocarbons (CFCs): A family of inert, non-toxic, easily liquefied chemicals used in refrigeration, air conditioning, packaging, and insulation, or as solvents or aerosol propellants.

Clean Development Mechanism (CDM): A Kyoto Protocol program that enables industrialized countries to finance emissions-avoiding projects in developing countries and receive credit for reductions achieved against their own emissions limitation targets. See *Kyoto Protocol*.

Climate: The average course or condition of the weather over a period of years as exhibited by temperature, humidity, wind velocity, and precipitation.

Climate change: A term used to refer to all forms of climatic inconsistency, but especially to significant change from one prevailing climatic condition to another. In some cases, "climate change" has been used synonymously with the term "global warming"; scientists, however, tend to use the term in a wider sense inclusive of natural changes in climate as well as climatic cooling.

Clinker: Powdered cement, produced by heating a properly proportioned mixture of finely ground raw materials (calcium carbonate, silica, alumina, and iron oxide) in a kiln to a temperature of about 2,700°F.

Cloud condensation nuclei: Aerosol particles that provide a platform for the condensation of water vapor, resulting in clouds with higher droplet concentrations and increased albedo.

Coal coke: See *Coke (coal)*.

Coalbed methane: Methane produced from coalbeds in the same way that natural gas is produced from other strata. See "methane."

Coke (coal): A solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal from which the volatile constituents are driven off by baking in an oven at temperatures as high as 2,000 degrees Fahrenheit so that the fixed carbon and residual ash are fused together. Coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. Coke from coal is grey, hard, and porous and has a heating value of 24.8 million Btu per ton.

Coke (petroleum): A residue high in carbon content and low in hydrogen that is the final product of thermal decomposition in the condensation process in cracking. This product is reported as marketable coke or catalyst coke. The conversion is 5 barrels (of 42 U.S. gallons each) per short ton. Coke from petroleum has a heating value of 6.024 million Btu per barrel.

Combustion: Chemical oxidation accompanied by the generation of light and heat.

Combustion chamber: An enclosed vessel in which chemical oxidation of fuel occurs.

Conference of the Parties (COP): The collection of nations that have ratified the Framework Convention on Climate Change (FCCC). The primary role of the COP is to keep implementation of the FCCC under review and make the decisions necessary for its effective implementation. See *Framework Convention on Climate Change (FCCC)*.

Cracking: The refining process of breaking down the larger, heavier, and more complex hydrocarbon molecules into simpler and lighter molecules.

Criteria pollutant: A pollutant determined to be hazardous to human health and regulated under EPA's National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act require EPA to describe the health and welfare impacts of a pollutant as the "criteria" for inclusion in the regulatory regime.

Crop residue: Organic residue remaining after the harvesting and processing of a crop.

Cultivar: A horticulturally or agriculturally derived variety of a plant.

Deforestation: The net removal of trees from forested land.

Degasification system: The methods employed for removing methane from a coal seam that could not

otherwise be removed by standard ventilation fans and thus would pose a substantial hazard to coal miners. These systems may be used prior to mining or during mining activities.

Degradable organic carbon: The portion of organic carbon present in such solid waste as paper, food waste, and yard waste that is susceptible to biochemical decomposition.

Desulfurization: The removal of sulfur, as from molten metals, petroleum oil, or flue gases.

Diffusive transport: The process by which particles of liquids or gases move from an area of higher concentration to an area of lower concentration.

Distillate fuel: A general classification for one of the petroleum fractions produced in conventional distillation operations. It includes 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. Products known as No. 1, No. 2, and No. 4 fuel oils are used primarily for space heating and electric power generation.

Efflux: An outward flow.

Electrical generating capacity: The full-load continuous power rating of electrical generating facilities, generators, prime movers, or other electric equipment (individually or collectively).

EMCON Methane Generation Model: A model for estimating the production of methane from municipal solid waste landfills.

Emissions: Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).

Emissions coefficient: A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., pounds of carbon dioxide emitted per Btu of fossil fuel consumed).

Enteric fermentation: A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

Eructation: An act or instance of belching.

Ethyl tertiary butyl ether (ETBE): A colorless, flammable, oxygenated hydrocarbon blend stock.

Ethylene: An olefinic hydrocarbon recovered from refinery or petrochemical processes.

Ethylene dichloride: A colorless, oily liquid used as a solvent and fumigant for organic synthesis, and for ore flotation.

Facultative bacteria: Bacteria that grow equally well under aerobic and anaerobic conditions.

Flange: A rib or a rim for strength, for guiding, or for attachment to another object (e.g., on a pipe).

Flared natural gas: Natural gas burned in flares on the well site or at gas processing plants.

Flatus: Gas generated in the intestines or the stomach of an animal.

Flue gas desulfurization: Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Also referred to as scrubbers. Chemicals such as lime are used as scrubbing media.

Fluidized-bed combustion: A method of burning particulate fuel, such as coal, in which the amount of air required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of mineral ash in the proportions of 1 part fuel to 200 parts ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid.

Flux material: A substance used to promote fusion, e.g., of metals or minerals.

Fodder: Coarse food for domestic livestock.

Forestomach: See *Rumen*.

Fossil fuel: Any naturally occurring organic fuel formed in the earth's crust, such as petroleum, coal, or natural gas.

Framework Convention on Climate Change (FCCC): An agreement opened for signature at the "Earth Summit" in Rio de Janeiro, Brazil, on June 4, 1992, which has the goal of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent significant anthropogenically forced climate change. See *Climate change*.

Fuel cycle: The entire set of sequential processes or stages involved in the utilization of fuel, including extraction, transformation, transportation, and combustion. Emissions generally occur at each stage of the fuel cycle.

Fugitive emissions: Unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels.

Gasification: A method for exploiting poor-quality coal and thin coal seams by burning the coal in place to produce combustible gas that can be collected and burned to generate power or processed into chemicals and fuels.

Gate station: Location where the pressure of natural gas being transferred from the transmission system to the distribution system is lowered for transport through small diameter, low pressure pipelines.

Geothermal: Pertaining to heat within the Earth.

Global climate change: See *Climate change*.

Global warming: An increase in the near surface temperature of the Earth. Global warming has occurred in the distant past as the result of natural influences, but the term is today most often used to refer to the warming predicted to occur as a result of increased anthropogenic emissions of greenhouse gases. See *Climate change*.

Global warming potential (GWP): An index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time, such as 100 years.

Greenhouse effect: The result of water vapor, carbon dioxide, and other gases trapping radiant (infrared) energy, thereby keeping the earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap this radiation, which would otherwise escape into space, and subsequent re-radiation of some of this energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent. See *Greenhouse gases*.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave radiation, thus preventing long-wave radiant energy from leaving the atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

Gross gas withdrawal: The full-volume of compounds extracted at the wellhead, including nonhydrocarbon gases and natural gas plant liquids.

Gypsum: The most common sulfate mineral. Used in wallboard.

Halogenated substances: A volatile compound containing halogens, such as chlorine, fluorine or bromine.

Halons: See *Bromofluorocarbons*.

Heating degree-day: The number of degrees per day that the average daily temperature is below 65 degrees Fahrenheit.

Herbivore: A plant-eating animal.

Hydrocarbon: An organic chemical compound of hydrogen and carbon in either gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simple (e.g., methane, a constituent of natural gas) to the very heavy and very complex.

Hydrochlorofluorocarbons (HCFCs): Chemicals composed of one or more carbon atoms and varying numbers of hydrogen, chlorine, and fluorine atoms.

Hydrofluorocarbons (HFCs): A group of man-made chemicals composed of one or two carbon atoms and varying numbers of hydrogen and fluorine atoms. Most HFCs have 100-year Global Warming Potentials in the thousands.

Hydroxyl radical (OH): An important chemical scavenger of many trace gases in the atmosphere that are greenhouse gases. Atmospheric concentrations of OH affect the atmospheric lifetimes of greenhouse gases, their abundance, and, ultimately, the effect they have on climate.

Intergovernmental Panel on Climate Change (IPCC): A panel established jointly in 1988 by the World Meteorological Organization and the United Nations Environment Program to assess the scientific information relating to climate change and to formulate realistic response strategies.

International bunker fuels: See *Bunker fuels*.

Jet fuel: See *Kerosene-type jet fuel* and *Naphtha-type jet fuel*.

Joint Implementation (JI): Agreements made between two or more nations under the auspices of the Framework Convention on Climate Change (FCCC) whereby a developed country can receive "emissions reduction units" when it helps to finance projects that reduce net emissions in another developed country (including countries with economies in transition).

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 has a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent

recovery point, a final boiling point of 572 degrees Fahrenheit, and a minimum flash point of 100 degrees Fahrenheit. Included are No. 1-K and No. 2-K, the two grades recognized by ASTM Specification D 3699 as well as all other grades of kerosene called range or stove oil, which have properties similar to those of No. 1 fuel oil. See *Kerosene-type jet fuel*.

Kerosene-type jet fuel: A kerosene-based product having a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point and a final maximum boiling point of 572 degrees Fahrenheit and meeting ASTM Specification D 1655 and Military Specifications MIL-T-5624P and MIL-T-83133D (Grades JP-5 and JP-8). It is used for commercial and military turbojet and turboprop aircraft engines.

Kyoto Protocol: The result of negotiations at the third Conference of the Parties (COP-3) in Kyoto, Japan, in December of 1997. The Kyoto Protocol sets binding greenhouse gas emissions targets for countries that sign and ratify the agreement. The gases covered under the Protocol include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride.

Ketone-alcohol (cyclohexanol): An oily, colorless, hygroscopic liquid with a camphor-like odor. Used in soapmaking, dry cleaning, plasticizers, insecticides, and germicides.

Leachate: A liquid produced as water percolates through wastes, collecting contaminants.

Lignite: The lowest rank of coal, often referred to as brown coal, used almost exclusively as fuel for steam-electric power generation. It is brownish-black and has a high inherent moisture content, sometimes as high as 45 percent. The heat content of lignite ranges from 9 to 17 million Btu per ton on a moist, mineral-matter-free basis. The heat content of lignite consumed in the United States averages 13 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

Liquefied petroleum gases (LPG): Ethane, ethylene, propane, propylene, normal butane, butylene, and isobutane produced at refineries or natural gas processing plants, including plants that fractionate new natural gas plant liquids.

Lubricant: A substance used to reduce friction between bearing surfaces or as a process material, either incorporated into other materials used as aids in manufacturing processes or as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Other substances may be added to impart or improve useful properties. Does not

include byproducts of lubricating oil from solvent extraction or tars derived from de-asphalting. Lubricants include all grades of lubricating oils from spindle oil to cylinder oil and those used in greases. Lubricant categories are paraffinic and naphthenic.

Methane (CH₄): A hydrocarbon gas that is the principal constituent of natural gas. Methane has a 100-year Global Warming Potential of 21.

Methanogens: Bacteria that synthesize methane, requiring completely anaerobic conditions for growth.

Methanol: A light alcohol that can be used for gasoline blending. See oxygenate.

Methanotrophs: Bacteria that use methane as food and oxidize it into carbon dioxide.

Methyl chloroform (trichloroethane): An industrial chemical (CH₃CCl₃) used as a solvent, aerosol propellant, and pesticide and for metal degreasing.

Methyl tertiary butyl ether (MTBE): A colorless, flammable, liquid oxygenated hydrocarbon containing 18.15 percent oxygen.

Methylene chloride: A colorless liquid, nonexplosive and practically nonflammable. Used as a refrigerant in centrifugal compressors, a solvent for organic materials, and a component in nonflammable paint removers.

Mole: The quantity of a compound or element that has a weight in grams numerically equal to its molecular weight. Also referred to as gram molecule or gram molecular weight.

Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer (1987). An international agreement, signed by most of the industrialized nations, to substantially reduce the use of chlorofluorocarbons (CFCs). Signed in January 1989, the original document called for a 50-percent reduction in CFC use by 1992 relative to 1986 levels. The subsequent London Agreement called for a complete elimination of CFC use by 2000. The Copenhagen Agreement, which called for a complete phaseout by January 1, 1996, was implemented by the U.S. Environmental Protection Agency.

Motor gasoline (finished): 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. Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 to 158 degrees Fahrenheit at the 10 percent recovery point to 365 to 374 degrees Fahrenheit at the 90 percent recovery point. "Motor Gasoline"

includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline, but excludes aviation gasoline. Note: Volumetric data on blending components, such as oxygenates, are not counted in data on finished motor gasoline until the blending components are blended into the gasoline.

Multiple cropping: A system of growing several crops on the same field in one year.

Municipal solid waste: Residential solid waste and some nonhazardous commercial, institutional, and industrial wastes.

Naphtha: A generic term applied to a petroleum fraction with an approximate boiling range between 122 and 400°F.

Naphtha-type jet fuel: A fuel in the heavy naphtha boiling range having an average gravity of 52.8 degrees API, 20 to 90 percent distillation temperatures of 290 degrees to 470 degrees Fahrenheit, and meeting Military Specification MIL-T-5624L (Grade JP-4). It is used primarily for military turbojet and turboprop aircraft engines because it has a lower freeze point than other aviation fuels and meets engine requirements at high altitudes and speeds.

Natural gas: A mixture of hydrocarbons and small quantities of various nonhydrocarbons in the gaseous phase or in solution with crude oil in natural underground reservoirs.

Natural gas liquids (NGLs): Those hydrocarbons in natural gas that are separated as liquids from the gas. Includes natural gas plant liquids and lease condensate.

Natural gas, pipeline quality: A mixture of hydrocarbon compounds existing in the gaseous phase with sufficient energy content, generally above 900 Btu, and a small enough share of impurities for transport through commercial gas pipelines and sale to end-users.

Nitrogen oxides (NO_x): Compounds of nitrogen and oxygen produced by the burning of fossil fuels.

Nitrous oxide (N₂O): A colorless gas, naturally occurring in the atmosphere. Nitrous oxide has a 100-year Global Warming Potential of 310.

Nonmethane volatile organic compounds (NMVOCs): Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Octane: A flammable liquid hydrocarbon found in petroleum. Used as a standard to measure the anti-knock properties of motor fuel.

Oil reservoir: An underground pool of liquid consisting of hydrocarbons, sulfur, oxygen, and nitrogen

trapped within a geological formation and protected from evaporation by the overlying mineral strata.

Organic content: The share of a substance that is of animal or plant origin.

Organic waste: Waste material of animal or plant origin.

Oxidize: To chemically transform a substance by combining it with oxygen.

Oxygenates: Substances which, when added to gasoline, increase the amount of oxygen in that gasoline blend. Ethanol, Methyl Tertiary Butyl Ether (MTBE), Ethyl Tertiary Butyl Ether (ETBE), and methanol are common oxygenates.

Ozone: A molecule made up of three atoms of oxygen. Occurs naturally in the stratosphere and provides a protective layer shielding the Earth from harmful ultraviolet radiation. In the troposphere, it is a chemical oxidant, a greenhouse gas, and a major component of photochemical smog.

Ozone precursors: Chemical compounds, such as carbon monoxide, methane, nonmethane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone.

Paraffinic hydrocarbons: Straight-chain hydrocarbon compounds with the general formula C_nH_{2n+2}.

Perfluorocarbons (PFCs): A group of man-made chemicals composed of one or two carbon atoms and four to six fluorine atoms, containing no chlorine. PFCs have no commercial uses and are emitted as a by-product of aluminum smelting and semiconductor manufacturing. PFCs have very high 100-year Global Warming Potentials and are very long-lived in the atmosphere.

Perfluoromethane: A compound (CF₄) emitted as a byproduct of aluminum smelting.

Petrochemical feedstock: Feedstock derived from petroleum, used principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics. The categories reported are naphthas (endpoint less than 401°F) and other oils (endpoint equal to or greater than 401°F).

Petroleum: Hydrocarbon mixtures, including crude oil, lease condensate, natural gas, products of natural gas processing plants, refined products, semifinished products, and blending materials.

Petroleum coke: See *Coke (petroleum)*.

Photosynthesis: The manufacture by plants of carbohydrates and oxygen from carbon dioxide and water in the presence of chlorophyll, with sunlight as the energy source. Carbon is sequestered and oxygen and water vapor are released in the process.

Pig iron: Crude, high-carbon iron produced by reduction of iron ore in a blast furnace.

Pipeline, distribution: A pipeline that conveys gas from a transmission pipeline to its ultimate consumer.

Pipeline, gathering: A pipeline that conveys gas from a production well/field to a gas processing plant or transmission pipeline for eventual delivery to end-use consumers.

Pipeline, transmission: A pipeline that conveys gas from a region where it is produced to a region where it is to be distributed.

Planetary albedo: The fraction of incident solar radiation that is reflected by the Earth-atmosphere system and returned to space, mostly by backscatter from clouds in the atmosphere.

Pneumatic device: A device moved or worked by air pressure.

Polystyrene: A polymer of styrene that is a rigid, transparent thermoplastic with good physical and electrical insulating properties, used in molded products, foams, and sheet materials.

Polyvinyl chloride (PVC): A polymer of vinyl chloride. Tasteless, odorless, insoluble in most organic solvents. A member of the family vinyl resin, used in soft flexible films for food packaging and in molded rigid products, such as pipes, fibers, upholstery, and bristles.

Post-mining emissions: Emissions of methane from coal occurring after the coal has been mined, during transport or pulverization.

Radiative forcing: A change in average net radiation at the top of the troposphere (known as the tropopause) because of a change in either incoming solar or exiting infrared radiation. A positive radiative forcing tends on average to warm the earth's surface; a negative radiative forcing on average tends to cool the earth's surface. Greenhouse gases, when emitted into the atmosphere, trap infrared energy radiated from the earth's surface and therefore tend to produce positive radiative forcing. See *Greenhouse gases*.

Radiatively active gases: Gases that absorb incoming solar radiation or outgoing infrared radiation, affecting the vertical temperature profile of the atmosphere. See *Radiative forcing*.

Ratoon crop: A crop cultivated from the shoots of a perennial plant.

Redox potential: A measurement of the state of oxidation of a system.

Reflectivity: The ratio of the energy carried by a wave after reflection from a surface to its energy before reflection.

Reforestation: Replanting of forests on lands that have recently been harvested or otherwise cleared of trees.

Reformulated gasoline: Finished motor gasoline formulated for use in motor vehicles, the composition and properties of which meet the requirements of the reformulated gasoline regulations promulgated by the U.S. Environmental Protection Agency under Section 211(k) of the Clean Air Act. Note: This category includes oxygenated fuels program reformulated gasoline (OPRG) but excludes reformulated gasoline blendstock for oxygenate blending (RBOB).

Renewable energy: Energy obtained from sources that are essentially inexhaustible (unlike, for example, the fossil fuels, of which there is a finite supply). Renewable sources of energy include wood, waste, geothermal, wind, photovoltaic, and solar thermal energy.

Residual fuel oil: 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. It 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 powerplants. 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.

Rumen: The large first compartment of the stomach of certain animals in which cellulose is broken down by the action of bacteria.

Sample: A set of measurements or outcomes selected from a given population.

Sequestration: See *Carbon sequestration*.

Septic tank: A tank in which the solid matter of continuously flowing sewage is disintegrated by bacteria.

Sinter: A chemical sedimentary rock deposited by precipitation from mineral waters, especially siliceous sinter and calcareous sinter.

Sodium silicate: A grey-white powder soluble in alkali and water, insoluble in alcohol and acid. Used to fireproof textiles, in petroleum refining and corrugated paperboard manufacture, and as an egg preservative. Also referred to as liquid gas, silicate of soda, sodium metasilicate, soluble glass, and water glass.

Sodium tripolyphosphate: A white powder used for water softening and as a food additive and texturizer.

Stabilization lagoon: A shallow artificial pond used for the treatment of wastewater. Treatment includes removal of solid material through sedimentation, the decomposition of organic material by bacteria, and the removal of nutrients by algae.

Still gas: Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. Principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Used as a refinery fuel and as a petrochemical feedstock.

Stratosphere: The region of the upper atmosphere extending from the tropopause (8 to 15 kilometers altitude) to about 50 kilometers. Its thermal structure, which is determined by its radiation balance, is generally very stable with low humidity.

Stripper well: A well that produces 60 million cubic feet of gas per day or less for a period of three consecutive months while producing at its maximum flow rate.

Styrene: A colorless, toxic liquid with a strong aromatic aroma. Insoluble in water, soluble in alcohol and ether; polymerizes rapidly; can become explosive. Used to make polymers and copolymers, polystyrene plastics, and rubber.

Subbituminous coal: A coal whose properties range from those of lignite to those of bituminous coal and used primarily as fuel for steam-electric power generation. It may be dull, dark brown to black, soft and crumbly, at the lower end of the range, to bright, jet black, hard, and relatively strong, at the upper end. Subbituminous coal contains 20 to 30 percent inherent moisture by weight. The heat content of subbituminous coal ranges from 17 to 24 million Btu per ton on a moist, mineral-matter-free basis. The heat content of subbituminous coal consumed in the United States averages 17 to 18 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

Sulfur dioxide (SO₂): A toxic, irritating, colorless gas soluble in water, alcohol, and ether. Used as a chemical intermediate, in paper pulping and ore refining, and as a solvent.

Sulfur hexafluoride (SF₆): A colorless gas soluble in alcohol and ether, and slightly less soluble in water. It is used as a dielectric in electronics. It possesses the highest 100-year Global Warming Potential of any gas (23,900).

Sulfur oxides (SO_x): Compounds containing sulfur and oxygen, such as sulfur dioxide (SO₂) and sulfur trioxide (SO₃).

Tertiary amyl methyl ether (TAME): An oxygenate blend stock formed by the catalytic etherification of isoamylene with methanol.

Troposphere: The inner layer of the atmosphere below about 15 kilometers, within which there is normally a steady decrease of temperature with increasing altitude. Nearly all clouds form and weather conditions manifest themselves within this region. Its thermal structure is caused primarily by the heating of the earth's surface by solar radiation, followed by heat transfer through turbulent mixing and convection.

Uncertainty: A measure used to quantify the plausible maximum and minimum values for emissions from any source, given the biases inherent in the methods used to calculate a point estimate and known sources of error.

Vapor displacement: The release of vapors that had previously occupied space above liquid fuels stored in tanks. These releases occur when tanks are emptied and filled.

Ventilation system: A method for reducing methane concentrations in coal mines to non-explosive levels by blowing air across the mine face and using large exhaust fans to remove methane while mining operations proceed.

Vessel bunkering: Includes sales for the fueling of commercial or private boats, such as pleasure craft, fishing boats, tugboats, and ocean-going vessels, including vessels operated by oil companies. Excluded are volumes sold to the U.S. Armed Forces.

Volatile organic compounds (VOCs): Organic compounds that participate in atmospheric photochemical reactions.

Volatile solids: A solid material that is readily decomposable at relatively low temperatures.

Waste flow: Quantity of a waste stream generated by an activity.

Wastewater: Water that has been used and contains dissolved or suspended waste materials.

Wastewater, domestic and commercial: Wastewater (sewage) produced by domestic and commercial establishments.

Wastewater, industrial: Wastewater produced by industrial processes.

Water vapor: Water in a vaporous form, especially when below boiling temperature and diffused (e.g., in the atmosphere).

Waxes: Solid or semisolid materials derived from petroleum distillates or residues. Light-colored, more or less translucent crystalline masses, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Included are all marketable waxes, whether crude scale or fully refined. Used primarily as industrial coating for surface protection.

Weanling system: A cattle management system that places calves on feed starting at 165 days of age and continues until the animals have reached slaughter weight.

Wellhead: The top of, or a structure built over, a well.

Wetlands: Areas regularly saturated by surface or groundwater and subsequently characterized by a prevalence of vegetation adapted for life in saturated-soil conditions.

Wood energy: Wood and wood products used as fuel, including roundwood (cordwood), limbwood, wood chips, bark, sawdust, forest residues, and charcoal.

Yearling system: A cattle management system that includes a stocker period from 165 days of age to 425 days of age followed by a 140-day feedlot period.