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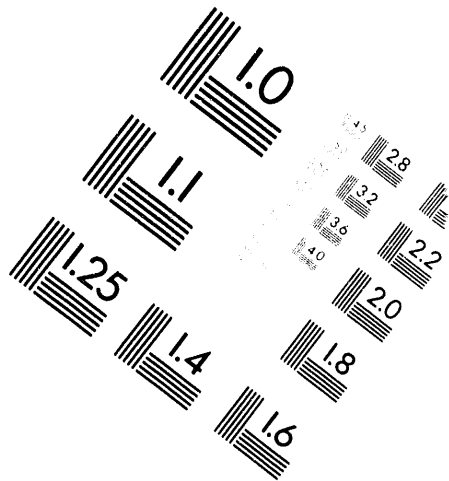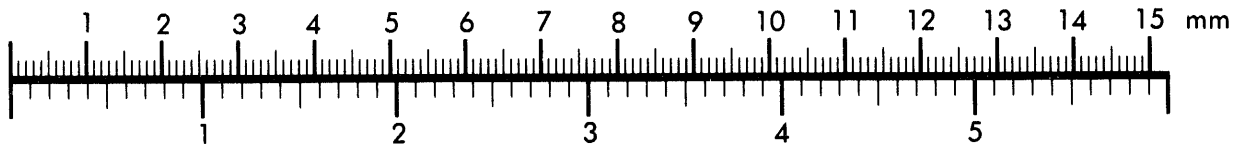**Association for Information and Image Management**
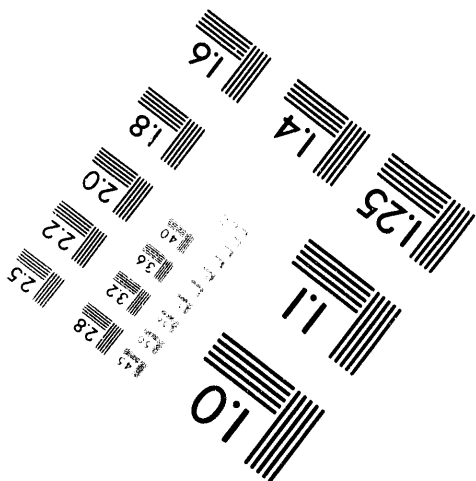
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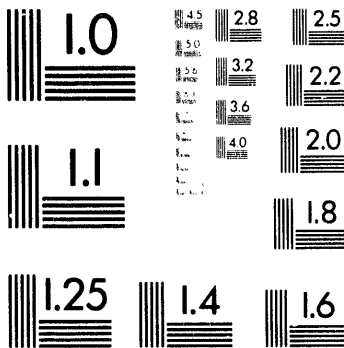
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Emissions of Greenhouse Gases in the United States 1985-1990

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Contacts

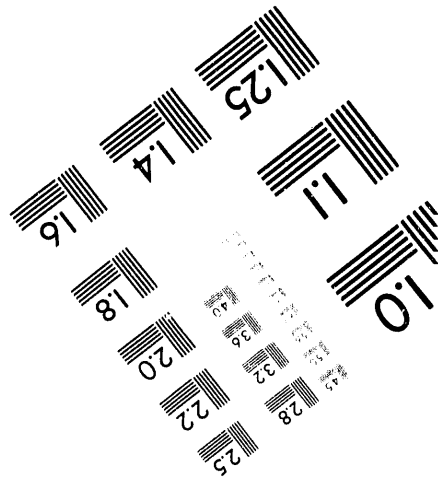This report, *Emissions of Greenhouse Gases in the United States 1985-1990*, was prepared under the general direction of W. Calvin Kilgore, Director of the Office of Energy Markets and End Use, Energy Information Administration. General questions concerning the content of this report may be referred to Arthur T. Andersen, Director of the Energy Markets and Contingency Information Division (202/586-1441), or Mary E. Northup, Chief of the Financial Analysis Branch (202/586-1445). Specific technical information concerning the content of the report may be obtained from Arthur Rypinski (202/586-8425).

Preface

This report presents the Energy Information Administration's (EIA's) estimates of greenhouse gas emissions for carbon dioxide, methane, nitrous oxide, and other greenhouse gases.

The second printing of this report (November 1993) includes revisions of Table 8, page 13, and Appendix B Tables B-1 through B-4. These revisions correctly allocate emissions of carbon dioxide from electric utilities across economic sectors.

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Executive Summary

The Earth's capacity to support life depends on the moderating influences of gases that envelop the planet and warm its surface and protect it from harmful radiation. These gases are referred to as "greenhouse gases." Their warming capacity, called "the greenhouse effect," is essential to maintaining a climate hospitable to all plant, animal, and human life. Through much of the Earth's history, greenhouse gases have been emitted in amounts that maintained the natural balance required to regulate the temperature and climate at the planet's surface. In recent years, however, there has been increasing concern that human activity may be affecting the intricate balance between the Earth's absorption of heat from the sun and its capacity to reradiate excess heat back into space. Some scientists believe that the Earth's climate, and consequently, the future course of life on the planet, will be irrevocably changed if the emissions of greenhouse gases produced from human activities are not reduced.

Scientists now know more about the greenhouse effect, and the extent to which human activity influences that effect, than ever before. Yet even with rapid growth in information, knowledge in this area remains imperfect. How much global climate might change, and over what time period, is not known, in part because many feedback mechanisms within the atmosphere and between the atmosphere and the biosphere are not yet well understood. At this point, what is clear is that emissions of greenhouse gases from human activities may be an important mechanism that affects global climate. Thus, research is intensifying to improve our understanding of the role human activities might play in influencing atmospheric concentrations of greenhouse gases, and to identify a range of actions which might reduce the consequences of human actions. Because new scientific findings concerning global climate change may influence every facet of life on this planet, they are being closely followed by government policymakers, industrial managers, and concerned citizens alike.

On the basis of scientific findings of the past few decades, the U.S. Government and the international community at large are now taking steps toward stabilizing greenhouse gas emissions. This report contributes to that process. Mandated by Congress through Section 1605(a) of the Energy Policy Act of 1992 (Title XVI), this report provides estimates of U.S. emissions of the principal greenhouse gases—carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds. Estimates are for the period 1985 to 1990. Preliminary estimates for 1991 have also been included, whenever data were available. A summary of Energy Information Administration (EIA) estimates of U.S. greenhouse gas emissions appears in Table ES1. Appendix A discusses the uncertainties associated with these estimates.

Greenhouse Gases and Their Effects

Policymakers, scientists, and the public seek to understand two key relationships: how greenhouse gases affect global climate, and how human activity can increase or decrease levels of those gases. Both relationships are discussed in Chapter 1, which reports on known natural and man-made sources and sinks of greenhouse gases worldwide, and the known and assumed effects of individual gases. These data support the premise that human activities strongly affect greenhouse gas emissions and are contributing to observed increases in atmospheric concentrations. The data also show, however, that much remains to be learned about the relationship between human activities and the natural processes that either generate or absorb greenhouse gases.

Carbon Dioxide

Carbon dioxide (CO_2), which is one of the most important greenhouse gases, is the subject of Chapter 2. Emissions of this gas occur both anthropogenically—as a result of human activities—and naturally.

Anthropogenic carbon dioxide emissions result primarily from the combustion of hydrocarbon (fossil) fuels such as natural gas, petroleum, and coal. When one of these hydrocarbon fuels is burned, essentially all of the carbon in the fuel chemically combines with the oxygen in the air to form carbon dioxide. Typical hydrocarbon fuels contain from 75 percent carbon by weight (methane) to more than 90 percent carbon by weight (petroleum coke). Thus, for every ton of fossil fuel burned, at least three-quarters of a ton of carbon enters

Table ES1. Summary of Estimated U.S. Emissions of Greenhouse Gases, 1985-1990
(Million Metric Tons of Gas and Million Metric Tons of Carbon)

Greenhouse Gas	1985	1986	1987	1988	1989	1990
Carbon Dioxide	4,667.1 (1,272.9)	4,662.1 (1,271.5)	4,806.3 (1,310.8)	5,031.6 (1,372.3)	5,067.5 (1,382.1)	5,012.4 (1,367.0)
Methane	29.5 (22.1)	29.2 (21.9)	29.1 (21.8)	29.3 (22.0)	28.9 (21.7)	29.1 (21.8)
Nitrous Oxide	0.3	0.3	0.3	0.3	0.3	0.3
Carbon Monoxide	83.1 (35.6)	76.0 (32.6)	75.1 (32.2)	75.5 (32.4)	68.3 (29.3)	67.7 (29.0)
Nitrogen Oxides	19.4	18.8	19.0	19.7	19.3	19.4
Nonmethane VOCs	19.8	18.5	18.6	18.6	17.4	17.6
CFC-11, 12, 113	NA	NA	NA	NA	NA	0.2

NA = not available.

Note: Gases that contain carbon can be measured either in terms of the full molecular weight of the gas or just in terms of their carbon content. In this table, the full molecular weight is shown on the top line, and the smaller number, indicating the weight of just the carbon content, is shown in parentheses on the bottom line.

Sources: Carbon dioxide, methane, and nitrous oxide from estimates presented in this report. Carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds (VOCs) from estimates in 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).

the atmosphere in the form of carbon dioxide.[1] Because anthropogenic carbon dioxide emissions can be measured on the basis of the amounts of fuels burned, emissions estimates for this gas can be calculated with greater precision than for any of the other greenhouse gases.

As shown in Table ES1, EIA estimates that U.S. carbon emissions have averaged between 1.3 billion and 1.4 billion metric tons per year during the 1985 to 1990 period. According to EIA data, the United States is the world's largest source of energy-related carbon dioxide emissions, accounting for about 22 percent of worldwide emissions in 1990. The United States is, however, a relatively slow-growing source of emissions. In that same year, the former Soviet Union accounted for 17 percent of worldwide emissions, and its emissions were growing much more rapidly.

Because carbon emissions are caused primarily by the combustion of fossil fuels, carbon dioxide emissions share the same causal factors as energy consumption in general. For instance, unusually hot or cold weather can drive up consumption, and economic recessions,

booms, fuel price swings, and longer-run economic growth can cause consumption fluctuations. Over time, the U.S. economy has improved its energy use efficiency, and the growth in energy consumption has tended to reflect a shifting balance between economic and population growth—which tend to increase energy consumption—and improved energy efficiency—which reduces energy consumption.

The shift between the use of fossil versus nonfossil fuels as sources for energy also influences carbon emissions. In the United States, nuclear and large-scale hydroelectric power are the only two nonfossil energy sources now being used to any significant degree. A number of nuclear power plants came on line during the 1980s, which reduced the growth in fossil fuel consumption. Hydroelectric power has not had the same effect, however, because no new dams have been built in the United States, and output from existing dams, which is dependent on the amount of rain and snow that falls in the western States, has fluctuated.

It is because of all these factors that the volume of U.S. carbon dioxide emissions grew at an annual rate of

[1]There are two commonly used methods for measuring carbon dioxide emissions: in the form of carbon (i.e., measuring just the carbon content of carbon dioxide) and using the full molecular weight of the compound. Since carbon has an atomic weight of 12 and oxygen has an atomic weight of 16, the carbon content of carbon dioxide (CO_2) is 12 / (12 + 16 + 16), or 12 / 44. Thus, carbon dioxide emissions measured as carbon can be converted to carbon dioxide emissions measured as carbon dioxide by multiplying by 44 / 12.

only 1.4 percent during the 1985 to 1990 reporting period of this report. This rate of growth is less than both the rate of growth for the U.S. economy, which averaged 2.7 percent annually during the period, and the rate of primary energy consumption, which during the same time period averaged 1.9 percent per year. It is particularly interesting that real energy prices remained flat, and even experienced some declines, during this period—trends that usually predict increased consumption of fossil fuels.

Methane

Anthropogenic methane, the subject of Chapter 3, is emitted primarily as an unintended byproduct of fossil fuel production and consumption, decomposition of organic waste in sanitary landfills, and agricultural activities, primarily the decomposition of solid wastes and gaseous emissions from animals. It is a potent greenhouse gas; for example, considering only its heat absorption potential, one molecule of methane can have 20 times more effect on climate than one molecule of carbon dioxide.[2]

The volume of U.S. methane emissions is more difficult to compute because few direct means exist to measure emissions, and relatively few data are available upon which to base even indirect emissions estimates. Thus, methane emissions estimates are much less reliable than those for carbon dioxide. On the basis of available information, however, EIA estimates that methane emissions remained relatively constant, at about 29 million metric tons, during the reporting period, although some changes occurred in the composition of the emissions. For example, emissions from agricultural sources generally declined during the late 1980s because, as Americans chose to eat less red meat, the U.S. population of beef cattle shrank and the beef yield per cow increased. At the same time, however, U.S. production of coal and natural gas for energy consumption slowly increased, causing a corresponding rise in methane emissions from those sources.

Nitrous Oxide

Nitrous oxide (N_2O), commonly known as "laughing gas," is a potent greenhouse gas. It differs from nitrogen oxides (NO_x), which are unstable gases, formed mainly through reactions of atmospheric nitrogen and oxygen at the very high temperatures found inside the combustion chambers of engines. When emitted into the atmosphere, nitrogen oxides are very reactive, tend to leave the atmosphere quickly, and assist in the formation of ozone and other components

of urban smog. Nitrous oxide, in contrast, is a stable gas with a long atmospheric lifetime.

Atmospheric concentrations of nitrous oxide are increasing at a rate of 0.3 percent annually. There is, however, uncertainty about the mechanisms by which this gas is either created in the atmosphere (both by human activity and by natural sources) or removed. Chapter 4 discusses emissions of this gas.

Although automobiles are responsible for some nitrous oxide emissions, nitrogenous fertilizers are their principal source. Scientists are not yet clear on the extent of emissions from using these fertilizers, however, and as a result, there is greater uncertainty in estimating the volume of nitrous oxide emissions than in estimating methane emissions. Nitrogen fertilizer use has, however, remained relatively constant during the reporting period. EIA's estimate of a slight increase in nitrous oxide emissions was based instead on a rise in emissions from automobiles (recent-vintage automotive catalytic converters, although effective in reducing emissions of more harmful pollutants, apparently increase nitrous oxide emissions).

Chlorofluorocarbons and Related Compounds

Mounting scientific evidence links the use of chlorofluorocarbons (CFCs) and related compounds to the depletion of stratospheric ozone. Stratospheric ozone filters the ultraviolet radiation that, when it reaches the Earth's surface in excessive amounts, may promote cancer and cataracts in humans and damage a wide variety of flora and fauna. Emissions of these gases are discussed in Chapter 5.

Since the mid-1980s, chlorofluorocarbon sales (and presumably emissions) in the United States have declined substantially. These reductions are the direct result of a series of international agreements: the Montreal Protocol on Substances that Deplete the Ozone Layer, which was developed in 1987; the subsequent London Agreement; and the as yet-to-be-ratified Copenhagen Agreement. The Montreal Protocol called for a 50-percent reduction in the use of CFCs, using 1986 usage levels as a baseline, by 1992; and the London Agreement called for the complete elimination of chlorofluorocarbon use by the year 2000. The Copenhagen Agreement, if ratified, would accelerate the complete phaseout of CFCs to January 1, 1996. The Montreal Protocol was signed by the United States, and most other industrialized nations, in January 1989.

[2]D. Wuebbles and J.A. Edmonds, *Primer on Greenhouse Gases* (Chelsea, MI: Lewis Publisher, Inc., 1991), p. 15.

The EIA has not been able to locate any published time series of emissions estimates for CFCs and related compounds. This report republishes an estimate of 1990 emissions prepared by the U.S. Environmental Protection Agency (EPA), along with information on 1985 and 1986 sales of CFCs and halons previously published by the EPA.

Criteria Pollutants

Emissions of conventional, so-called "criteria," pollutants have an indirect impact on global climate change through their contribution to the manufacture of tropospheric ozone. Carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds are all considered criteria pollutants. Emissions estimates for these gases were previously published by the EPA.

Criteria pollutants are regulated under the Clean Air Act of 1970 and successive amendments. EPA estimates show a steady decline in emissions of this type, which is mainly the result of increasingly sophisticated pollution control equipment in the U.S. automobile fleet. This report does not provide detailed estimates of tropospheric ozone emissions or concentrations, because tropospheric ozone is the result of complex chemical interactions rather than direct anthropogenic emissions.

Land Use Changes

Natural sources and sinks tend to provide larger volumes of greenhouse gases than man-made sources. These natural sources, however, are often grounded in particular types of natural ecosystems. When humans modify natural ecosystems by reclaiming swamps, clearing land for agriculture, or logging forests, their actions have consequences for emissions and absorption of greenhouse gases.

Estimates of emissions and absorption of greenhouse gases resulting from changes in land use, which are described in Chapter 7, were the most difficult, complex, and uncertain of all the emission inventory calculations. Consequently, land-use emissions and sinks have not been added to estimates from other emissions sources.

U.S. forests absorb atmospheric carbon dioxide through photosynthesis and convert it into biomass, primarily wood. Thus, carbon sequestration from this source should be increasing, since U.S. forest area increased during the late 1980s. Quantifying the amount of carbon that is being sequestered presents difficult methodological problems, however, because it is not clear how much (if any) of this carbon should be considered anthropogenic, and how much should be considered natural.

Likewise, potential emissions resulting from the abandonment of farmland, which is another large-scale trend in U.S. land use, should enhance natural absorption of carbon dioxide and methane while reducing emissions of nitrous oxide. The methodological problems associated with estimating the extent of these effects are also substantial.

1. Greenhouse Gases and Global Climate Change

The Greenhouse Effect

Atmospheric composition is a primary determinant of global average temperature and climate which in turn establish the conditions—and the limits—for all life on Earth. Trace gases, including especially water vapor, carbon dioxide, and methane, help trap heat initially derived from solar radiation. Without the heat-trapping properties of these gases, the Earth's average temperature would be -60 degrees F (-16 degrees C), like the very cold surface of Mars, instead of the current average global temperature of 59 degrees F (15 degrees C). Almost 99 percent of the Earth's atmosphere is composed of gases that are transparent either to incoming solar radiation or outgoing reflected infrared heat radiation. So-called "greenhouse gases," comprising no more than 1 percent of the atmosphere, block infrared radiation to outer space and reradiate the captured heat to the atmosphere. The process of capturing reflected heat is referred to as the "greenhouse effect." This effect raises the Earth's average temperature.

The main greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (such as CFC-11 and CFC-12). With the exception of chlorofluorocarbons, all greenhouse gases occur naturally. Water vapor is by far the most important, with an atmospheric concentration of nearly 1 percent. Carbon dioxide concentration is less than 0.04 percent. Concentrations of other greenhouse gases are a fraction of that for carbon dioxide (Table 1).

Some greenhouse gases are more potent at affecting climate change than are others. As a result, comparable increases in concentration of different greenhouse gases can have vastly different heat-trapping effects. Among those identified, carbon dioxide is least effective as a greenhouse gas. Considering only heat-absorption potential, one molecule of methane can have 20 times more effect on climate than one molecule of carbon dioxide.[3]

The level of greenhouse gas concentrations in the atmosphere significantly affects the amount of heat captured in the greenhouse process. Studies of the planet Venus have helped make this proposition clear: the bright clouds of Venus reflect so much solar radiation that less solar energy reaches the surface of Venus than the surface of Earth, even though Venus is much closer to the sun. Nonetheless, the surface temperature of Venus is about 900 degrees F (482 degrees C), compared with an average temperature of 59 degrees F (15 degrees C) on Earth. The difference in temperature is attributable to very high concentrations of greenhouse gases in the atmosphere of Venus as compared with that found on Earth, enabling a higher proportion of reflected heat to be captured within Venus' atmosphere.

Human activities can affect the Earth's atmospheric chemistry, especially with regard to the level of greenhouse gas concentrations (Table 2). Fossil fuel burning releases carbon dioxide. Fuel use appears to be a major factor in the apparent 25-percent increase in atmospheric carbon dioxide concentration over the past

Table 1. Atmospheric Concentrations of Greenhouse Gases

Item	Carbon Dioxide	Methane	Nitrous Oxide	CFC-11	CFC-12
	(parts per million)			(parts per trillion)	
Preindustrial Atmospheric Concentration . . .	280	0.80	0.29	0	0
Current Atmospheric Concentration	353	1.72	0.31	280	484
Rate of Change (PPM or PPT per year) . . .	1.8	0.02	0.8	10	17

Source: R.T. Watson et al., "Greenhouse Gases: Sources and Sinks," in Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), pp. 31-42.

[3]D. Wuebbles and J.A. Edmonds, *Primer on Greenhouse Gases* (Chelsea, MI: Lewis Publisher, Inc., 1991), p. 15.

Table 2. Sources of Greenhouse Gases

Gases	Sources
Carbon Dioxide	Fossil fuels, industry, deforestation
Methane	Rice cultivation, domestic animals, biomass burning, coal mining, natural gas venting, wetlands, fossil fuel combustion
Nitrous Oxide	Nitrogen fertilizer use, adipic acid production, biomass burning
CFC-11, CFC-12	Refrigerants, propellants, solvents

Source: R.T. Watson et al., "Greenhouse Gases: Sources and Sinks," in Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), pp. 31-42.

century (Table 1). Deforestation also contributes to this trend: Forest destruction which involves widespread burning not only directly releases carbon dioxide into the atmosphere but also reduces the Earth's ability to remove carbon dioxide from the atmosphere through photosynthesis.

Emission of carbon dioxide is not the only way in which human activities affect atmospheric concentrations of greenhouse gases. Methane concentrations have apparently more than doubled over the past century as a result of emissions from wetlands, rice cultivation, increased animal husbandry (especially for cattle and sheep), and leakages from energy production.

Nitrous oxide can also exacerbate the greenhouse effect. Atmospheric concentrations have risen an estimated 8 percent relative to pre-industrial levels, and much of the increase is attributed to agricultural use of nitrogenous fertilizers.[4] Other sources are derived from various processes associated with fuel combustion.

Chlorofluorocarbons are man-made compounds known to adversely affect the stratospheric ozone. Chlorofluorocarbons are part of a class of compounds termed halocarbons, formed when hydrocarbon molecules are joined with either chlorine, fluorine, or bromine in varying combinations. The most important of these compounds are CFC-11 and CFC-12, which until recently were the preferred refrigerants in a host of industrial and consumer applications. Bromine-containing chemicals (trade name "halon") are used in fire extinguishers. The compounds are highly stable and break down only in the presence of solar radiation. Scientific observation has determined that most CFCs which enter the atmosphere migrate to the stratosphere (the upper atmosphere). It is here that as the compounds decay chlorine is released. The released chlorine is highly reactive with

ozone and the reaction tends to be self-sustaining, enabling any chlorine atom to destroy many molecules of ozone. Annual observations have revealed that ozone concentrations in the stratosphere are declining as the presence of CFC compounds grows.

Ozone in the stratosphere protects the Earth from the sun's ultraviolet radiation. Excessive ultraviolet radiation is destructive to biological processes. Thus, CFCs in the stratosphere are a hazard insofar as they reduce the level of ozone protection. Recognition of this danger led to the Montreal Protocol, a United Nations-sponsored agreement to scale back CFC production. As scientific concern continued to grow, this agreement was amended to call for the elimination of CFCs in the 1990s. As a result, CFC production has fallen sharply (see Chapter 6). In the United States, CFC production is to be phased out by 1995.

CFCs and all other halocarbons are also greenhouse gases which absorb infrared radiation in ways which strongly complement the absorptive capabilities of carbon dioxide. However, the current state of atmospheric science does not permit a precise determination of the greenhouse warming potential of CFCs because they interact chemically with ozone in the lower atmosphere (troposphere) where ozone also has infrared absorption capabilities. Thus an increase in one greenhouse gas (CFCs) can lead to a reduction of another (ozone) with an (as of now) unknown net effect.

The influences of human activity on the heat-trapping potential of the Earth's atmosphere extend beyond direct emissions of greenhouse gases and include the emissions of gases and aerosols that affect the atmosphere's chemical reactivity and reflectivity. For example, increasing emissions of nitrogen oxides and

[4]R.T. Watson et al., "Greenhouse Gases: Sources and Sinks," in Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), p. 37.

carbon monoxide, as well as of methane and non-methane hydrocarbons, cause increases in ozone (O_3) in the troposphere, where it is a highly effective greenhouse gas.

In the stratosphere, the production of ozone begins with the photodissociation of O_2 in the presence of ultraviolet light. The free oxygen then combines with undissociated O_2 to form ozone O_3. In the troposphere, ozone production is a product of catalytic reactions involving nitrogen oxides, carbon monoxide, methane, and CFCs.

Some man-made emissions counteract greenhouse gases. Sulfur-containing gases are emitted into the atmosphere when fuel containing sulfur is burned. These gases tend to reflect sunlight back into space directly or in the context of altered cloud formation. How powerful these man-made emissions are in countering the potential warming effects of greenhouse gas emissions is not known. It is known, however, that they could be significant, since volcanic emissions, primarily through emissions of sulfur dioxide into the lower stratosphere, can cool the climate for short periods.

Measuring Greenhouse Gas Concentrations and Emissions

Over the last several decades, the science of atmospheric chemistry and scientific measurement have achieved great advances. We now know that atmospheric concentrations of greenhouse gases are rising, and know the rate of change. Moreover, we can identify human activities which contribute to these changes.

Nonetheless, much remains to be learned. A major area of inquiry relates to the precise relationship between human activities which give rise directly or indirectly to greenhouse gas emissions and changes in atmospheric concentrations. At this time, we know most about carbon dioxide and the role fossil fuel use plays in causing carbon dioxide to be released into the atmosphere. However, as of now, we cannot connect, in a quantitative way, the relationship between man-made carbon dioxide emissions and changes in the atmospheric concentration of carbon dioxide. It is estimated that were there to be a one-to-one relationship between man-made carbon dioxide emissions and atmospheric concentrations of carbon dioxide, measured carbon dioxide concentrations would rise by twice the amount actually observed. This disparity has led to much scientific research on the way in which the total carbon

cycle, including absorption of carbon in oceans and in plants, operates. However large man-made carbon dioxide emissions are, they are small relative to natural carbon exchanges between the atmosphere and forests and oceans.[5]

Rising concentrations of methane have led to a search for man-made methane emissions. As of now, we have not been able to reconcile known data on anthropogenic methane emission rates and changes in atmospheric concentrations. The search has led to an ongoing effort to more carefully measure methane emissions associated with energy production and to measure the extent to which agricultural and other activities incidentally produce methane

Nitrous oxide concentrations have been rising worldwide at about 0.3 percent per year. Though potential man-made sources of nitrous oxide have been identified, the cause of increase in worldwide concentrations is uncertain. Agriculture again is thought to play a major role, through use of fertilizers, but reliable quantification has yet to be achieved.

In sum, human activities affect greenhouse gas emissions and contribute to observed increases in atmospheric concentrations. However, much remains to be learned about the relationship between human activities and natural processes which either generate or absorb greenhouse gases.

The following sections provide a summary overview of available data on worldwide sources and sinks of major greenhouse gases.

Carbon Dioxide

All life on Earth participates in a planetary carbon cycle. Vegetation uses solar energy (photosynthesis) to absorb carbon dioxide from the atmosphere and convert it into biomass in the form of vegetable matter, including leaves and wood. Vegetation decays, releasing some carbon back into the atmosphere, while the other carbon accumulates in soils. The ocean both absorbs and releases carbon on a huge scale.

However, increasing carbon dioxide concentrations in the atmosphere indicate that the natural carbon cycle may be out of balance. Table 3 summarizes what is known about both natural and man-made sources and sinks of carbon dioxide.

Sources and Sinks. Carbon dioxide has large natural sources and sinks, and smaller anthropogenic sources:

[5]D. Wuebbles and J.A. Edmonds, *Primer on Greenhouse Gases* (Chelsea, MI: Lewis Publisher, Inc., 1991), pp. 116-117.

Table 3. Worldwide Estimated Sources and Sinks of Carbon Dioxide
(Billion Metric Tons of Carbon per Year)

Sources and Sinks	Range
Sources	
Natural	
Biomass Respiration	22-65
Biomass Decay	18-55
Ocean Release	100-110
Anthropogenic (Man-Made)	
Fossil Fuel Burning	5.5-6.5
Industrial Sources	~0.1
Deforestation and Land Use Changes	1.1-3.6
Sinks (Natural)	
Biomass Photosynthesis	102.5-112.5
Uptake by the Ocean	40-120
Unidentified "Missing Sink"	2.2-3.7
Atmospheric Increase	3.2-3.6

Sources: D. Wuebbles and J.A. Edmonds, *Primer on Green-house Gases* (Chelsea, MI: Lewis Publisher, Inc., 1991), pp. 116-117; Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), pp. 31-34; and Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment* (Cambridge University Press, 1990), pp. 5, 13.

- **Biomass Photosynthesis, Respiration, and Decay.** Photosynthesis is believed to absorb some 110 billion metric tons of carbon from the atmosphere every year. This is approximately 40 times larger than carbon dioxide emissions from fossil fuels. However, natural emissions of carbon dioxide are of the same scale. Natural respiration by plants and animals on land emits some 60 billion metric tons of carbon dioxide, while the decay of land-based biomass releases another 50 billion metric tons.

- **Fossil Fuel.** Since 1860, global annual emissions of fossil fuel carbon dioxide have increased from 0.1 billion metric tons to approximately 5.9 billion metric tons of carbon per year in 1988. Fossil fuel carbon dioxide emissions in the United States accounted for more than 40 percent of global emissions in 1950; this share has steadily declined to 22 percent in 1990.[6]

- **Minor Industrial Sources.** Minor noncombustion sources of carbon dioxide occur, the most important

of which is the calcination of limestone to make cement.

- **Land-Use Changes (Deforestation).** Approximately 560 billion metric tons of carbon are currently stored in the form of terrestrial biomass, principally in forests. This mass is estimated to be about 15 to 20 percent (120 billion metric tons) less than was present in the mid-nineteenth century. Knowledge of the net annual emissions of carbon from land-use changes is far less certain than emissions estimates for fossil fuel use. In 1980, rates of deforestation were believed to be greatest for Brazil, Colombia, the Ivory Coast, Indonesia, Laos, and Thailand. Estimates of net carbon dioxide emissions from land-use change have increased for recent decades. Prior to 1950, significant deforestation is estimated to have occurred in the temperate latitudes as well as in the tropics.[7] Because carbon dioxide is a fertilizer for plants, the net increase in atmospheric carbon dioxide should in principle stimulate plant growth and add to the net carbon stock in the carbon dioxide fertilization effect.[8]

- **Uptake by the Ocean.** The ocean apparently is a net absorber of carbon dioxide from the atmosphere. Carbon dioxide, once dissolved in seawater, is used by marine life to construct such carbon-rich items as coral reefs and seashells. Carbon-containing debris continually rains down onto the sea floor, providing permanent carbon sequestration. However, the rate at which the ocean absorbs carbon, and the rate at which carbon dioxide in the ocean is converted to mineral carbon by marine life, are the focus of a continuing research effort.

Methane

Approximately 20 percent of methane emissions on a worldwide basis can be traced to energy use. Approximately 70 percent of the emissions of methane released into the atmosphere come from human-related activities. The major human-related sources include: ruminant animals (such as cows), rice paddies, biomass burning, natural gas production and distribution, coal mining, and solid waste disposal (landfills, etc.). Although the magnitude of the individual sources continue to have large uncertainty ranges, the human-related emissions have apparently increased dramatically in this century. For example, estimates show that total methane emissions from domestic animals have

[6]Energy Information Administration, *International Energy Outlook 1993*, DOE/EIA-0219(93) (Washington, DC, June 1993), p. 34.

[7]J.R. Trabalka (ed.), *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, DOE/ER-0239 (Washington, DC: U.S. Department of Energy, 1985).

[8]D. Wuebbles and J.A. Edmonds, *Primer on Greenhouse Gases* (Chelsea, MI: Lewis Publisher, Inc., 1991), p. 35.

increased by almost a factor of four over the past century.

Methane is produced naturally via anaerobic decomposition in biological systems. Wetlands provide the single largest source at 115 million metric tons of methane per year, but the uncertainty range on this estimate extends from 100 million to 200 million metric tons per year.

Estimated world annual emissions (source) and absorption or destruction (sinks) of methane each total about 500 million metric tons per year (Table 4), but the magnitude of individual sources of methane is highly uncertain. Total annual methane sources must equal the atmospheric sink of about 470 (420 to 520) million metric tons of methane per year, plus the possible soil (absorption) sink of about 30 (15 to 45) million metric tons of methane per year, and the annual growth of 28 million to 37 million metric tons of methane concentration in the atmosphere.

Natural Sources. Natural sources of methane include:

- **Wetlands.** Current estimates indicate a global flux of about 115 million metric tons of methane per year, with about 55 million tons of methane per year coming from tropical wetlands and 39 million metric tons of methane per year from high-latitude wetlands.[9]

- **Termites.** Termites digest wood by decomposing cellulose into methane. In temperate zones, termites are a trivial natural methane source. Termites are ubiquitous in the tropics, however, and when tropical forests are logged or burned, the vast quantities of dead wood created provide ideal conditions for termite population explosions. There is a large range in estimated fluxes of methane from termites; 10 million to 50 million metric tons of methane per year worldwide.[10] These values are based on laboratory experiments, applied to estimates of global termite populations and the amount of biomass consumed by termites in field experiments.

- **Ocean and Fresh Water.** Oceans and fresh waters are thought to be minor sources of atmospheric methane. Recent data from either the open oceans

Table 4. Worldwide Estimated Sources and Sinks of Methane
(Million Metric Tons of Methane per Year)

Sources and Sinks	Point Estimate	Range
Sources		
Natural		
Wetlands	115	(100-200)
Termites	20	(10-50)
Ocean	10	(5-20)
Freshwater	5	(1-25)
Methane Hydrate	5	(0-5)
Anthropogenic (Man-Made)		
Coal Mining, Natural Gas and Petroleum Industry	100	(70-120)
Rice Paddies	60	(20-150)
Enteric Fermentation	80	(65-100)
Animal Wastes	25	(20-30)
Domestic Sewage Treatment	25	?
Landfills	30	(20-70)
Biomass Burning	40	(20-80)
Sinks (Natural)		
Atmospheric (Tropospheric + Stratospheric) Removal	470	(420-520)
Removal by Soils	30	(15-45)
Atmospheric Increase	32	(28-37)

Source: Intergovernmental Panel on Climate Change, Climate Change 1992: The Supplementary Report to the IPCC Assessment (Cambridge University Press, 1992), p. 35.

[9]B.H. Svenson and T. Rosswell, "In Situ Methane Production from Acid Peat in Plant Communities with Different Moisture Regimes in a Subarctic Mire," Oikos, Vol. 43 (1984), pp. 341-350.

[10]R. Cicerone and R. Oremland, "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles, Vol. 2 (1988), pp. 299-327.

or coastal waters are inadequate to reduce the uncertainty in these estimates.[11]

Man-Made Sources. Man-made (anthropogenic) sources of methane emissions include:

- **Rice Paddies.** Rice paddies (a sort of artificial wetland) are believed to be an important source of methane. Estimates of the global flux range from 20 million to 150 million metric tons of methane per year. The flux of methane from rice paddies depends upon several factors, including: (1) agricultural practices (such as fertilization, water management, density of rice plants, double cropping system, application of manure or rice straw; (2) soil and paddy characteristics such as soil type, acidity, redox potential, temperature, nutrient availability, substrate, profile of anaerobic environment; and (3) time of season. Since 1940, the annual production of rice has approximately doubled as a result of double cropping practices and an increased area of cultivation. Methane emissions have likely increased proportionally.[12]

- **Biomass Burning.** Burning of biomass can occur naturally as in forest fires, or it can result from human activities such as land clearing for agriculture or burning agricultural wastes. Some fraction of the human contribution is the result of direct energy consumption, such as burning fuelwood. Biomass burning in tropical and subtropical regions is thought to be a significant source of atmospheric methane, with estimates of global emission rates ranging from 20 million to 80 million metric tons of methane per year.[13] Improved estimates require an enhanced understanding of both (1) methane emissions factors and (2) the amount and type of burning (smoldering versus flaming). Current estimates indicate that during the past century, the rate of forest clearing through burning has increased.[14]

- **Enteric Fermentation (Animals).** Methane emissions from enteric fermentation in ruminant animals, including all cattle, sheep, and wild animals, is estimated to provide an atmospheric source of 65 million to 100 million metric tons of methane per year.[15] Methane emissions depend upon animal populations, as well as the amount and type of food intake.

- **Landfills.** The anaerobic decay of organic waste in landfills may be a significant anthropogenic source of atmospheric methane—20 million to 70 million metric tons of per year.[16] Several factors must be studied (including amounts, trends, and types of waste materials and landfill practices) before the magnitude of this source can be precisely quantified.

- **Coal Mining.** Methane is released into the atmosphere from coal-mine ventilation and degassing from coal during transport to an end-use site. A recent unpublished study estimated that the flux of methane from coal mining for the top 20 coal-producing countries produced a global minimum emission of 70 million metric tons of methane per year.

- **Oil and Gas Drilling, Production and Distribution.** Because methane is the major component of natural gas, leakage from pipelines and venting from oil and gas wells could represent a significant source of atmospheric methane. One estimate of the global flux from these sources (not completely consistent with Table 4) is between 25 million and 50 million metric tons of methane per year.[17]

- **Combustion.** The combustion processes associated with the conversion of fossil fuel to thermal energy may be attended by the emission of some quantity of methane, depending upon the constituents of the fuel, the temperature of combustion, and the efficiency of the process.[18]

[11]R. Cicerone and R. Oremland, "Biogeochemical Aspects of Atmospheric Methane," *Global Biogeochemical Cycles*, Vol. 2 (1988), pp. 299-327.

[12]Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment* (Cambridge University Press, 1990), pp. 20-21.

[13]M.O. Andrae et al., "Biomass Burning Emissions and Associated Haze Layers over Amazonia," *Journal of Geophysical Research*, Vol. 93 (1988), pp. 1509-1527.

[14]H.G. Bingemer and P.J. Crutzen, "The Production of Methane From Solid Wastes," *Journal of Geophysical Research*, Vol. 92 (1987), pp. 2181-2187.

[15]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.

[16]H.G. Bingemer and P.J. Crutzen, "The Production of Methane From Solid Wastes," *Journal of Geophysical Research*, Vol. 92 (1987), pp. 2181-2187.

[17]R. Cicerone and R. Oremland, "Biogeochemical Aspects of Atmospheric Methane," *Global Biogeochemical Cycles*, Vol. 2 (1988), pp. 299-327.

[18]D. Wuebbles and J.A. Edmonds, *Primer on Greenhouse Gases* (Chelsea, MI: Lewis Publisher, Inc., 1991), p. 41.

Sinks. The major sink for atmospheric methane is a reaction with hydroxyl (OH) radicals in the troposphere, the hydroxyl concentration being controlled by a complex set of reactions involving methane, carbon monoxide, nonmethane hydrocarbons, nitrogen oxides, and tropospheric ozone.[19] Methane decays into carbon dioxide as it is oxidized. Because these reactions deplete the number of available hydroxyl radicals, increased methane concentrations are self-perpetuating. Reaction with hydroxyl radicals may also result in the production of tropospheric ozone.[20]

Nitrous Oxide

Total emissions are estimated to be between 10 million and 18 million metric tons of nitrogen per year (worldwide). Emissions rates are small relative to atmospheric burden. However, the atmospheric lifetime of nitrous oxide is uncertain within the range of 120 to 150 years. These estimates of sources and sinks that can be derived from atmospheric chemistry models are subject to substantial uncertainties. Estimates of the size of sources and of sinks obtained through direct experimental measurement are subject to even greater uncertainty.

The main sources of nitrous oxide emissions are thought to be biochemical activities (Table 5). Nitrous oxide is released both from cultivated and uncultivated soils. Combustion activities—including savanna burning, forest clearing, fuelwood use, and fossil-fuel combustion—also yield emissions. Other sources of emissions include oceans and contaminated aquifers.[21] The dominant human activities associated with nitrous oxide emissions are agricultural activity and energy use.

Sinks. The major atmospheric loss process for nitrous oxide is photochemical decomposition in the stratosphere, and is calculated to be 7 to 13 million metric tons of nitrogen per year. Tropospheric sinks such as surface loss in aquatic and soil systems are believed to be small.[22]

Ozone

Ozone is an extremely potent greenhouse gas that is both formed and destroyed in the atmosphere. Approx-

Table 5. Worldwide Estimated Sources and Sinks of Nitrous Oxide

(Million Metric Tons of Nitrogen per Year)

Sources and Sinks	Range
Sources	
Natural	
Oceans	1.4-2.6
Tropical Soils	--[a]
Wet Forests	2.2-3.7
Dry Savannas	0.5-2.0
Temperate Soils	--[a]
Forests	0.05-2.0
Grasslands	--[a]
Anthropogenic (Man-Made)	
Cultivated Soils	0.03-3.0
Biomass Burning	0.2-1.0
Stationary Combustion	0.1-0.3
Mobile Sources	0.2-0.6
Adipic Acid Production	0.4-0.6
Nitric Acid Production	0.1-0.3
Sinks (Natural)	
Removal by Soils	--[a]
Photolysis in the Stratosphere	7-13
Atmospheric Increase	3-4.5

[a]No scientific consensus yet exists on the volumes of gases.
Source: Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), p. 37.

imately 90 percent of all ozone is in the stratosphere. The remaining 10 percent is found in the troposphere. There are no direct emissions of ozone from anthropogenic sources. Concentrations of ozone are affected, however, by the indirect effects of several anthropogenic gases. In the troposphere, ozone concentrations rise due to increased levels of methane, nitrogen oxides, and volatile organic compounds. This is a cause for concern because tropospheric ozone is a strong absorber of infrared radiation, and in high concentrations causes respiratory distress in humans. In the stratosphere, chlorine and bromine from halocarbon compounds reduce ozone, which is also a concern because stratospheric ozone absorbs the ultraviolet radiation (UV-B) that would otherwise cause cancer, cataracts, and other illnesses.[23]

[19]Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment* (Cambridge University Press, 1990), p. 19.
[20]Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), pp. 19.
[21]D. Wuebbles and J.A. Edmonds, *Primer on Greenhouse Gases* (Chelsea, MI: Lewis Publisher, Inc., 1991), p. 44.
[22]Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment* (Cambridge University Press, 1990), p. 25.
[23]Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), p. 40.

CFCs and Related Compounds

CFC-11 and CFC-12 have atmospheric concentrations of 0.260 parts per billion by volume and 0.484 parts per billion by volume respectively, the highest concentrations of any of the chlorofluorocarbons. The growth in atmospheric concentrations of these CFCs has slowed to 1 to 2 percent per year since 1988.[24]

By themselves, CFCs have powerful direct effects on global warming because their unusual molecular size (not found in nature) blocks light "windows" that would otherwise be wide open enabling infrared radiation to escape to outer space. However, chlorine and bromine from CFCs destroy ozone, both in the stratosphere and closer to Earth's surface, tending to produce global cooling. CFCs tend to have relatively long lifetimes—the atmospheric lifetime for CFC-11 is estimated at 55 years and that of CFC-12 is estimated at 116 years. CFCs may cause warming in the beginning of their atmospheric lifetimes (as they absorb infrared radiation) and cooling later in their lifetimes as they break down and destroy ozone. This complicates their impact on global climates. Experts are currently divided over whether the net effect of atmospheric CFCs will be warming or cooling.

Nitrogen Oxides (NO_x) and Volatile Organic Compounds (VOCs)

These compounds have little direct effect on climate. However, they are important precursors of ozone, which is a greenhouse gas. There is no simple way to specify how emissions of a particular gas might contribute to ozone formation except in a specified airshed, under particular weather patterns, and with particular emissions of various anthropogenic and biogenic gases. Ozone formation, for example, is promoted by sunlight; thus, ozone concentrations will be much higher on sunny days than on overcast days. Thus, measures of ozone concentration in the troposphere are less subject to numerical evaluation than are local measures keyed to smog events and monitoring of progress associated with efforts to reduce urban air pollution.

Sulfur Oxides

Sulfur-containing gases are emitted into the atmosphere through natural and anthropogenic processes. It is estimated that more than half of all sulfur emissions on an annual basis are derived from fossil fuel burning.

Oceans and volcanic emissions are the most important natural sources. Sulfur oxides tend to promote cloud formation, which increases Earth's albedo (reflectivity) and consequently promotes global cooling. It is not known whether current sulfur oxide emissions and concentrations have acted to lower global temperatures as an offset to potential increases that might otherwise have occurred in the context of increased greenhouse gas concentrations described above.

Water Vapor

Water vapor is one of the primary absorbers of infrared radiation. Its concentration in the atmosphere currently is about 1 percent, varying with temperature and altitude. There are enormous natural sources and sinks of water vapor including evaporation from the oceans, precipitation, absorption and transpiration by plants, and glacial ice. Human activities have an insignificant impact on these natural processes.

As temperatures in the lower atmosphere increase, concentrations of atmospheric water vapor increase as well. This, in turn, enhances the greenhouse effect, leading to a warmer climate. Studies conducted in 1989 suggest that the positive water vapor feedback results in an amplification of the surface temperature by a factor of 1.6.[25] This water vapor feedback mechanism is one of the better understood interactions between atmospheric water vapor and climate.

Feedback mechanisms related to clouds are more complex and less well understood. Clouds absorb infrared radiation, thus contributing to global warming, but also reflect incoming solar radiation, producing a cooling effect. The net impact of these processes is unknown. Furthermore, changes in the type, amount, and altitude of clouds, as wells as cloud water content can all affect the extent of the cloud-climate feedback.[26]

Relative Forcing Properties

The contribution of a gas to the greenhouse effect depends on several factors, especially including concentration levels and the wavelengths at which the gas absorbs or raps infrared radiation. Carbon dioxide and water vapor absorb radiation at the same wavelength and block most potential radiation from being lost to outer space. If other greenhouse gases absorbed at the same wavelength as carbon dioxide and water vapor,

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[24]J.W. Elkins et al., "Decrease in Growth Rates of Atmospheric Chlorofluorocarbons 11 and 12," *Nature*, Vol. 364 (26 August 1993), pp. 780-783.

[25]Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment* (Cambridge University Press, 1990), p. 78.

[26]U.S. Department of Energy, Office of Environmental Analysis, *Limiting Net Greenhouse Gas Emissions in the United States, Volume II*, DOE/PE-0101 (Washington, DC, September 1991), p. 1.7.

increased concentrations would have little incremental greenhouse effect. However, most other greenhouse gases absorb radiation at wavelengths different from carbon dioxide and water vapor. Thus, increases in their concentrations enhance absorption of infrared radiation. The net result is that comparable increases in concentration of greenhouse gases have widely different effects on radiative forcing. All gases that absorb infrared radiation at wavelengths different from carbon dioxide and water vapor will contribute more to potential heat trapping than will increases in carbon dioxide.

In an effort to provide policymakers with a means for comparing the relative impact on global climate of a given greenhouse gas, the United Nations' Intergovernmental Panel on Climate Change (IPCC) devised the concept of Global Warming Potential (GWP). Patterned after the Ozone Depletion Potential concept developed as part of the Montreal Protocol, the GWP represents the radiative forcing (i.e., the extent of global temperature increase) from the instantaneous release of 1 kilogram of a greenhouse gas relative to the forcing expected from the instantaneous release of 1 kilogram of carbon dioxide within a given timeframe. As discussed above, because the atmospheric lifetimes of

greenhouse gases vary widely, the GWP of a gas depends on the selected time horizon.[27] The IPCC's latest set of GWPs provides estimates for time scales of 20, 100, and 500 years (Table 6).

Limitations in the method for calculating GWPs suggest that they are more useful as indicators of magnitude than as precise measurements. The GWP values in Table 6 are for direct effects only. The sign of the indirect effects is provided but the extent of these effects is unknown. In some cases (chlorofluorocarbons, for example), the indirect effects may outweigh the direct effects leading to an overall cooling effect. The indirect effects of methane as a hydroxyl scavenger, and as an ozone and water vapor precursor, amplify its radiative capacity as its concentration increases.[28]

GWPs are sensitive to the atmospheric lifetimes of the gases. Atmospheric lifetimes are uncertain and may vary with changes in atmospheric composition, location, and climate. This is a problem in the case of carbon dioxide particularly, because it is the reference gas. Because the carbon cycle is not well understood, the atmospheric lifetime of carbon dioxide may be prone to substantial revision.[29]

Table 6. Numerical Estimates of Global Warming Potential Relative to Carbon Dioxide

Gas	Lifetime (Years)	Direct Effect for Time Horizons of			Sign of Indirect Effect
		20 Years	100 Years	500 Years	
Carbon Dioxide	120	1	1	1	None[a]
Methane	10.5	35	11	14	Positive
Nitrous Oxide	132	260	270	170	Uncertain
CFC-11	55	4,500	3,400	1,400	Negative
CFC-12	116	7,100	7,100	4,100	Negative
CFC-113	110	4,600	4,500	2,500	Negative
CFC-114	220	6,100	7,000	5,800	Negative
CFC-115	550	5,500	7,000	8,500	Negative
HCFC-22	15.8	4,200	1,600	540	Negative
HFC-134a	15.6	3,100	1,200	400	None[b]
Halon 1301	77	5,600	4,900	2,300	Negative

[a]Carbon dioxide is not involved in chemical reactions affecting the concentration of radiatively active gases. However, it could affect the relevant chemical reactions through its influence on the atmospheric thermal structure.

[b]No currently known or negligible indirect effect.

Source: I.S.A. Isaksen et al., "Radiative Forcing of Climate," in Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), p. 56.

[27]Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment* (Cambridge University Press, 1990).

[28]Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992).

[29]Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992).

2. Carbon Dioxide Emissions

Overview

Most of the world'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 theory, if the amount of fuel burned and the amount of carbon in the fuel is 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 will be discussed throughout this chapter. Nonetheless, energy-related carbon dioxide emissions are known with greater reliability than other greenhouse gas emissions sources, and the uncertainty in the estimate is probably 10 percent or less. Appendix A 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 of 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 this chapter 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.

While most of the anthropogenic carbon dioxide emitted in the United States comes from energy consumption, there are several industrial processes which also emit carbon dioxide through noncombustion processes. The largest single source is the calcination of limestone in cement production, but other sources include lime production, steelmaking, and industrial carbon dioxide production.

Several emissions sources are excluded from this report, either due to the uncertainty of the estimates or because they are based on biomass combustion. Excluded sources are discussed in Appendix C.

Carbon dioxide emissions have been reported in many different units and formats by various researchers. Some U.S. firms calculate emissions in English units, while scientific researchers usually use metric units, though generally using terms not common even in foreign industry (for example, teragrams instead of the more familiar "million metric tons"). Another source of variation is whether to report carbon dioxide emissions in terms of the full molecular weight of the carbon dioxide, or just in terms of the carbon content. This report estimates carbon emissions in million metric tons of carbon. This set of units was chosen because persons more comfortable with English units can easily convert from metric tons to short tons (one short ton equals 0.9072 metric tons), and because carbon units can be conveniently compared with fuel units. Further, as noted above, carbon emissions can take several chemical forms (carbon dioxide, carbon monoxide, volatile organic compounds). Therefore, molecular weight estimates based solely on carbon dioxide can be imprecise. Estimates of carbon content can be converted to full molecular weight by multiplying by 44/12, or 3.6667.

Carbon Emissions from Energy Consumption

U.S. Carbon Emissions in a World Context

The Energy Information Administration (EIA) recently published a set of comparable worldwide estimates of energy-related carbon emissions in 1985 and 1990.[30] Since the report's estimates for the United States are made at a more aggregate level than those made in this report and exclude some industrial carbon sources, they are not directly comparable. However, the data provide

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[30]Energy Information Administration, *International Energy Outlook 1993*, DOE/EIA-0219(93) (Washington, DC, June 1993), p. 34.

an excellent source for observing broad trends in carbon emissions by country.

The United States is the world's largest source of energy-related carbon dioxide emissions, accounting for about 22 percent of worldwide emissions in 1990. However, the United States is a relatively slow-growing source of emissions. The second largest source of emissions is the former Soviet Union, which accounted for 17 percent of worldwide emissions in 1990, with emissions nearly as large (76 percent) as the United States, but growing much more rapidly. Since the Soviet economy in 1990 was a fraction of the size of the U.S. economy, the implication is that the Russians needed much more energy to produce a unit of GNP than did the United States. The third largest source of carbon dioxide emissions is China, which accounted for about 11 percent of world emissions in 1990 (about 48 percent of the U.S. level), with an economy that was perhaps one-fourteenth the size of the U.S. economy.[31] Chinese emissions have also grown very rapidly, increasing by 26 percent between 1985 and 1990.

In general, emissions of the industrialized countries of Europe are also growing slowly, though energy consumption per unit of GNP is lower than U.S. levels. Emissions in the developing world, while a relatively small part of the total, are rising rapidly, particularly in the Far East.

Emission Trends

Table 7 shows summary estimates of U.S. carbon dioxide emissions, both energy-related and from industrial sources. In 1990, the EIA estimates that anthropogenic carbon emissions were 1,367.0 million metric tons, declining to 1,351.7 million metric tons in 1991. Between 1985 and 1991, carbon emissions increased by about 80 million metric tons, at an annual rate of about 1 percent. This is much slower than the growth rate of the U.S. economy (2.0 percent per annum), or the growth rate of U.S. energy consumption (1.6 percent per annum) over the same period.

Conceptually, the level of U.S. energy-related carbon dioxide emissions can be viewed as the outcome of the interaction between three interrelated sets of factors:

- The growth of U.S. energy consumption, which is determined, among other things, by the rate of economic growth, changes in energy prices, weather fluctuations, and the rate of increase in the efficiency with which the economy uses energy

- Within energy consumption, the division between the use of fossil fuels and nonfossil fuels (since hydroelectric and nuclear power do not directly produce carbon emissions)

- Within fossil energy consumption, the division between types of fossil fuels, since coal produces

Table 7. U.S. Carbon Dioxide Emissions from Energy and Industry, 1985-1991
(Million Metric Tons Carbon)

Fuel Type or Process	1985	1986	1987	1988	1989	1990	1991
Energy Consumption							
Petroleum	544.1	566.1	571.0	596.4	596.6	583.2	562.7
Coal	442.2	434.5	453.5	478.7	479.1	480.4	474.9
Natural Gas	254.3	238.4	253.2	264.7	276.3	274.5	279.6
Total Energy Consumption	**1,240.6**	**1,239.0**	**1,277.6**	**1,339.8**	**1,352.0**	**1,338.0**	**1,317.2**
Adjustments to U.S. Energy							
U.S. Territories	10.0	9.5	10.1	8.6	9.6	9.4	10.8
Unmetered Gas	5.3	6.3	5.6	5.7	2.2	1.2	5.8
Total Adjustments	**15.3**	**15.8**	**15.7**	**14.3**	**11.8**	**10.6**	**16.6**
Other Sources							
Cement Production	9.6	9.7	9.6	9.5	9.5	9.5	8.8
Other Industrial	6.1	5.7	6.2	6.8	6.9	6.9	6.8
Gas Flaring	1.3	1.3	1.7	1.9	1.9	2.0	2.3
Total Other Sources	**17.0**	**16.7**	**17.5**	**18.2**	**18.3**	**18.4**	**17.9**
Total	**1,272.9**	**1,271.5**	**1,310.8**	**1,372.3**	**1,382.1**	**1,367.0**	**1,351.7**

Note: Includes emissions from bunker fuels.
Source: EIA estimates documented in this chapter.

[31]GNP estimates from World Bank, World Tables 1987, Fourth Edition (Baltimore, MD: Johns Hopkins University Press, 1987).

almost twice the carbon emissions per unit of energy that natural gas does, with petroleum products occupying an intermediate position.

As noted above, U.S. energy consumption has grown more slowly than the U.S. economy in recent years, even though real energy prices, in general, have declined considerably in recent years.

Nonfossil fuel sources grew during the 1980s, as many long-delayed nuclear power plants came on line. Hydroelectric power output fluctuates considerably from one year to the next, depending largely on precipitation in the western United States.

Table 8 illustrates the sectoral composition of carbon dioxide emissions. While the industrial sector is the largest source of carbon emissions, accounting for some 33 percent of total emissions in 1990, it has also had the slowest emissions growth rate, with emissions increasing at an annual rate of only 0.3 percent during the 1985-1991 period. The transportation sector, primarily gasoline consumption for automobiles and jet fuel for aircraft, had the fastest emissions growth rate. Appendix B presents detailed emissions estimates by fuel for each sector, covering an extended period, 1980-1991.

Estimating Emissions

Computations. EIA calculated its estimates of carbon emissions by multiplying energy consumption data by

fuel type with an associated carbon coefficient. The result was then modified by subtracting carbon sequestered by nonfuel use. An alternative approach would be to make similar estimates from energy production data accounting for trade, stock changes and losses. Although both approaches should produce similar results, the consumption approach provides much richer detail, and allows for information by end-use sector and detailed fuel type.

Data Sources. The energy consumption data used to make the estimates provided in this report have been taken from EIA's *State Energy Data Report 1991: Consumption Estimates*, where it is detailed by end-use sector (residential, commercial, industrial, and transportation), by fuel type (petroleum [distinguishing 11 products], coal, natural gas, and electricity), and by year. Coal consumption, disaggregated by rank, is estimated based on rank-specific information reported to the EIA for coal production, electric utility receipts, and industrial consumption.[32]

Estimates of emissions from noncombustion uses of fossil fuels leading to carbon sequestration are based on data provided in EIA's *Annual Energy Review 1992*, "Table 2.6. Fossil Fuel Consumption for Nonfuel Use, 1980-1992."[33] EIA used the Intergovernmental Panel on Climate Change (IPCC) methodology to interpret these data.[34] Energy for "nonfuel use" (Table 9) is understood to represent the potential energy with carbon sequestered. It is, however, generally accepted that

Table 8. U.S. Carbon Dioxide Emissions from Fossil Energy Consumption by End-Use Sector, 1985-1991
(Million Metric Tons of Carbon)

End Use	1985	1986	1987	1988	1989	1990	1991
Energy Consumption							
Residential	245.9	244.1	251.1	265.0	267.6	253.1	257.2
Commercial	189.7	190.5	197.2	207.7	210.1	206.7	206.4
Industrial	419.5	404.2	417.1	438.6	440.9	445.4	428.3
Transportation	385.4	400.1	412.2	428.4	433.4	432.9	425.2
Total Energy	**1,240.6**	**1,239.1**	**1,277.6**	**1,339.8**	**1,352.0**	**1,338.0**	**1,317.2**
Electric Utility	439.1	435.7	452.8	476.2	483.7	476.7	473.6

Note: Includes energy from petroleum, coal, and natural gas. Electric utility emissions are distributed across consumption sectors.
Source: EIA estimates documented in this chapter.

[32]See Energy Information Administration, *Coal Production*, DOE/EIA-0118 (Washington, DC), various issues, and *Annual Energy Review 1992*, DOE/EIA-0384(92) (Washington, DC, June 1993), for coal production information; and *Cost and Quality of Fuels for Electric Utility Plants*, DOE/EIA-0191 (Washington, DC), various issues, for electric utility receipts information. Industrial consumption by rank is derived from information published in Energy Information Administration, *Quarterly Coal Report*, DOE/EIA-0121 (Washington, DC), various issues, and unpublished information reported on Form EIA-3, "Quarterly Coal Consumption Report—Manufacturing Plants," for various years.

[33]This information is currently available only at the national level and for 1980-1991. Further disaggregation or development of earlier-year estimates would require new effort by EIA.

some energy for nonfuel use is oxidized rapidly in other chemical processes thus emitting carbon dioxide. For example, some of the carbon in petrochemical feedstocks and two-thirds of the carbon in natural gas used for fertilizer production is assumed to be oxidized. Carbon in this energy for nonfuel use, which undergoes rapid oxidation, is counted in emissions of carbon dioxide. Energy with, in fact, carbon sequestered, has

been subtracted from total energy consumption for final computations (Table 10).

In addition, based on Oak Ridge and IPCC methodologies, EIA has assumed that oxidation of fossil fuels during combustion is 99 percent complete and that 1 percent of the carbon remains sequestered. For convenience, this subtraction is made to the carbon

Table 9. U.S. Fossil Fuel Consumption for Nonfuel Use, 1985-1991
(Quadrillion Btu)

End Use	1985	1986	1987	1988	1989	1990	1991
Petroleum							
Asphalt and Road Oil	1.03	1.09	1.13	1.14	1.10	1.17	1.07
Liquefied Petroleum Gases ..	0.86	0.82	1.12	1.21	1.20	1.31	1.50
Lubricants	0.32	0.31	0.36	0.34	0.35	0.37	0.32
Industrial	0.17	0.16	0.18	0.18	0.18	0.19	NA
Transportation	0.16	0.15	0.17	0.17	0.17	0.18	NA
Petrochemical Feed	0.81	1.02	1.00	1.00	1.00	0.82	1.15
Petroleum Coke	0.14	0.13	0.20	0.20	0.19	0.23	0.22
Special Naphtha	0.16	0.13	0.14	0.11	0.11	0.11	0.09
Other (Waxes and Misc.)	0.15	0.14	0.16	0.17	0.18	0.16	0.19
Coal	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Natural Gas	0.54	0.47	0.49	0.53	0.57	0.64	0.61
Total	4.06	4.16	4.65	4.75	4.75	4.85	5.21

NA = not available.
Note: Asphalt and lubricants are as reported in *State Energy Data Report*. Some slight differences exist between this table and the *Annual Energy Review*.
Source: Energy Information Administration, *Annual Energy Review 1992*, DOE/EIA-0384(92) (Washington, DC, June 1992), Table 2.6, p. 33.

Table 10. U.S. Carbon Sequestered by Nonfuel Use of Energy, 19?/-1991
(Million Metric Tons of Carbon)

End Use	1985	1986	1987	1988	1989	1990	1991
Industrial							
Petroleum							
Asphalt and Road Oil	21.7	22.8	23.8	23.9	23.1	24.6	22.6
Liquefied Petroleum Gases .	11.9	11.3	15.5	16.7	16.6	18.1	20.7
Lubricants	1.8	1.7	1.9	1.9	1.9	2.0	1.8
Other	19.6	22.4	24.4	24.6	24.5	22.4	27.9
Petrochemical Feed	12.6	15.9	15.6	15.6	15.6	12.8	17.9
Petroleum Coke	3.8	3.6	5.5	5.5	5.2	6.3	6.0
Waxes and Misc.	3.2	2.9	3.4	3.6	3.8	3.4	4.0
Coal	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Natural Gas	2.6	2.3	2.4	2.5	2.7	3.1	2.9
Transportation							
Lubricants	1.7	1.6	1.8	1.8	1.8	1.9	1.7
Total	60.1	63.1	70.7	72.3	71.6	73.0	78.6

Source: EIA estimates, based on energy consumption data as shown in Table 9, and emissions coefficients shown in Table 11 of this report.

coefficient factors. Conceptually, fuel can be "lost" before combustion due to evaporation, leaks or spills, or subject to incomplete combustion, and vented to the atmosphere in the form of volatile organic compounds or particulates, or can remain at the site of combustion in the form of carbon-containing ash or soot.

Establishing carbon coefficient factors, which are used to associate thermal energy consumed with emissions of carbon in tons, has been the subject of work of Keeling, Rotty, Marland and Pippin at the Oak Ridge National Laboratory.[35] Factors in these estimates are based on factors found in Gregg Marland and Angela Pippin's report analyzing U.S. emissions and energy consumption (Table 11). Grubb has made additional studies.[36] EIA made estimates for individual fuels/ petroleum products when no factors were available from Oak Ridge or other research.

EIA's estimates of coefficient factors were based on estimates of the carbon content of each fuel. Combustion of hydrocarbons results in the production of

Table 11. Factors: Carbon Coefficients and Assumptions

Fuel Type	Million Metric Tons Carbon per Quadrillion Btu[a]	Million Metric Tons Carbon per Exajoule	Proportion of Nonfuel Use (If Any) Sequestered
Petroleum			
Motor Gasoline	19.23	18.41	--
LPG	17.09	16.36	0.80
Jet Fuel	19.27	18.45	--
Distillate Fuel	19.77	18.93	--
Residual Fuel	21.44	20.53	--
Asphalt and Road Oil[b]	20.83	--	1.00
Lubricants[b]	21.00	--	0.50
Petrochemical Feed[b]	19.25	--	0.80
Aviation Gas[b]	19.23	--	--
Kerosene	19.27	18.45	--
Petroleum Coke[b]	27.04	--	1.00
Special Naphtha[b]	19.23	--	0.00
Other: Waxes and Miscellaneous[b]	20.83	--	1.00
Petroleum Other[c]	NA	--	--
Coal[d]			
Anthracite Coal	27.85	--	0.75
Bituminous Coal	25.12	--	0.75
Subbituminous Coal	25.98	--	0.75
Lignite	26.35	--	0.75
Natural Gas			
Flare Gas[b]	15.06	--	--
Natural Gas	14.39	13.78	0.33

[a]Assumes conversion of 1 quadrillion Btu = 1.0551 exajoules and fraction combusted = 99 percent.
[b]Emissions coefficients are EIA estimates based on underlying chemical composition of the product.
[c]The carbon coefficient factor for "Petroleum Other" is a composite number, recalculated annually subject to variations in component products and assumptions about sequestration.
[d]Coal emissions factor is for 1990; varies by ±0.2 percent in other years.
NA = not available.
Source: G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol. 14, No. 4 (1990), p. 323. Coal emissions coefficients computed as a weighted average by State on a consumption basis, from Science Applications International Corp., *Analysis of the Relationship Between the Heat and Carbon Content of U.S. Coals* (Final Task Report, September 1992).

[35]Work at Oak Ridge National Laboratory has continued since the early 1970's. The report chosen for use in these EIA estimates is G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol. 14, No. 4 (1990), p. 323.

[36]See M.J. Grubb, "On Coefficients for Determining Greenhouse Gas Emissions from Fossil Fuel Production and Consumption," Energy and Environmental Programme, Royal Institute of International Affairs (London, England, April 1989, unpublished paper).

carbon dioxide, water vapor, and heat. Among hydrocarbons the value of the carbon coefficient depends on the relative density of carbon atoms in the molecular structure—molecules such as methane, for instance, in which each carbon atom is bonded to four hydrogen atoms, have a lower density of carbon atoms and thus less potential to yield carbon for creation of carbon dioxide during combustion. In contrast, hydrocarbons molecules like those found in coal have numerous carbon atoms bonded one to another and hence a greater potential to form carbon dioxide.

In practice this means that coal combustion emits almost twice as much carbon dioxide per unit of energy as does the combustion of natural gas. Crude oil combustion falls between coal and gas in this rating. These principles are an important underpinning for analysis because they enable development of carbon coefficient factors that can be applied to the data reported in thermal units which are commonly found in statistical reports on energy.

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 coefficients would be 5 percent to 10 percent larger, and the Btu content of the fuel would be 5 percent to 10 percent lower, but the carbon emissions estimate would be unchanged.[37]

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 emission estimates are the exact definition of "energy consumption" and the exact definition of "the United States" employed by researchers. Subtle differences in definition can produce variations of several percent in reported energy consumption, and hence in carbon emissions.

There are several anomalies in energy consumption data which contribute to the differences in energy-related carbon emissions made by different organizations. Some data, for instance, include energy consumption in U.S. territories such as Puerto Rico, or marine bunker fuel consumption, or include "unaccounted for" natural gas. Below is a discussion on each of these items and how they are treated in energy accounts.

Energy Consumption in U.S. Territories

EIA's energy data for the United States cover only the 50 States of the union and the District of Columbia. In contrast, energy data produced by the International Energy Agency for the United States cover the 50 States of the union plus U.S. territories, including Puerto Rico, the U.S. Virgin Islands, and Guam. Energy consumption of U.S. territories is only about 0.5 quadrillion Btu. Because U.S. territories are all islands, their consumption primarily consists of petroleum products. As a group, oil consumption for the territories range between 200,000 and 250,000 barrels per day, and coal consumption about 300,000 short tons per year.

Table 12 illustrates reported energy consumption in U.S. territories. These data have been published in EIA's *International Energy Annual* for various years. This table also draws on unpublished estimates of oil consumption for Wake Island, American Samoa, and the Pacific Trust Territories, which are included as "Other" in the Asia/Pacific region in the *International Energy Annual*.

Energy consumption for U.S. territories has been converted to carbon emissions using the same emission factors applied to U.S. energy data. Carbon emissions for U.S. territories ranged from 9 to 11 million metric tons per year (Table 13). Because a large portion of reported energy consumption in U.S. territories was from "other petroleum," this produces a degree of uncertainty about the correct emissions factor to be used in this area, as well as the reliability of underlying data.

International Bunker Fuels

The term "international bunker fuels" refers to fuel purchased by merchant ships in U.S. ports. By convention, trade statistics treat sales of bunker fuels as an export by the selling country because the purchaser promptly hauls the fuel outside of national boundaries. This convention is followed by those who prepare international energy statistics, such as the United Nations and the International Energy Agency.

[37]This is sometimes a source of discrepancy. See OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-12 to 2-15.

Table 12. Energy Consumption in U.S. Territories and International Bunkers, 1985-1991

(Quadrillion Btu)

Place	1985	1986	1987	1988	1989	1990	1991
U.S. Territories							
Puerto Rico	0.31	0.32	0.34	0.30	0.30	0.29	P 0.37
Virgin Islands	0.15	0.10	0.12	0.08	0.12	0.11	P 0.10
American Samoa	0.01	0.01	0.01	0.01	0.01	0.01	P 0.01
Guam	0.01	0.02	0.01	0.01	0.01	0.03	P 0.03
Micronesia	--	--	--	--	--	--	--
Wake Island	0.02	0.02	0.02	0.02	0.02	0.02	P 0.02
Total	**0.49**	**0.47**	**0.49**	**0.42**	**0.46**	**0.46**	**P 0.53**
U.S. Bunker Fuels	0.80	0.70	0.70	0.80	0.80	0.80	P 0.80

P = preliminary data.

Note: Energy consumption in Micronesia ranged from 0.002 to 0.004 quadrillion Btu.

Source: **U.S. Territories:** Energy Information Administration, *International Energy Annual*, DOE/EIA-0119 (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 1991 based on unpublished preliminary information. **Bunker Fuels:** Energy Information Administration, *International Energy Annual*, DOE/EIA-0119 (various years), table on "Disposition of Petroleum Products." Data for 1991 based on unpublished preliminary information.

Table 13. Carbon Emissions from U.S. Territories, International Bunkers, and Unmetered Gas Consumption, 1985-1991

(Million Metric Tons of Carbon)

Item	1985	1986	1987	1988	1989	1990	1991
U.S. Territories	10.0	9.5	10.1	8.6	9.6	9.4	P 10.8
Bunker Fuels	15.0	14.6	14.4	15.5	16.4	15.8	15.8
Unmetered Natural Gas Consumption	5.3	6.3	5.6	5.7	2.2	1.2	5.9

P = preliminary data.

Source: Estimates documented in Chapter 2 of the report *Emissions of Greenhouse Gases in the United States 1985-1990.*

Bunkers, however, are an export without a corresponding import because the purchasing ship generally burns the fuel on the high seas. EIA energy statistics, which are based on domestic sales of products, treat bunker fuels sales in the same way as sales of other fuels, i.e., as domestic energy consumption. Carbon emissions from bunker fuels are, therefore, already counted within the domestic energy consumption of the United States—primarily as transportation-related consumption of residual oil.

Those who wish to understand the differences between emissions inventories based on international energy statistics and EIA data will, however, need to know the amount of energy consumption and the amount of carbon emissions associated with international bunkers. Table 12 therefore shows U.S. international bunker fuel usage, based on data published in EIA's *International Energy Annual* in various years. The amount is about 0.8 quadrillion Btu (or 350,000 barrels per day), largely of

residual oil; it accounts for emissions of about 15 million metric tons of carbon annually (Table 13).

Unreported Natural Gas Consumption

Since EIA data on natural gas "consumption" stem from readings of customer natural gas meters by local gas distribution companies and other natural gas sellers, reported consumption in the United States is consistently 1 percent to 4 percent less than the amount of natural gas that reportedly enters pipeline service. This difference is called the "balancing item" in EIA's natural gas statistics. Because this gas is, by definition, "unaccounted for," there is no way of knowing the ultimate disposition of this gas for certain. Early studies of this issue suggested that much of the missing gas may have resulted from pipeline leaks, and that it entered the atmosphere in the form of methane. For safety, liability, and commercial reasons, however, gas transmission and distribution companies have aggres-

sive programs to find and fix leaks, and the handful of careful studies of existing pipeline systems tend to show that pipeline leaks are unlikely to account for as much as 0.5 percent of total natural gas consumption.

If leaks account for only a small portion of the missing gas, the balance must be accounted for by various accounting and tabulation errors and unreported consumption. Accounting and tabulation errors, should, in principle, randomly fluctuate between positive and negative values. Because unaccounted for gas always represents more than 1 percent of total consumption, the implication is that there is some unreported consumption. This may be due to systematic metering errors, or to underreporting of gas transported by one company for the account of another.[38]

EIA has assumed that the portion of the "unaccounted for" natural gas that cannot be attributed to pipeline leakage is actually consumption that has the same carbon characteristics as other gas consumption. Pipeline leakage is estimated using emissions coefficients based on studies of leakage from a sample of transmission and distribution pipelines.[39] These assumptions imply the combustion of approximately 0.4 quadrillion Btu per year, accounting for carbon emissions of between 5.0 and 6.0 million metric tons annually (Table 14). The exceptionally low carbon emissions from this source in 1989 and 1990 are due to low "unaccounted for" levels for those years.

Carbon Emissions from Energy Production

U.S. energy production processes also generate small volumes of carbon dioxide emissions. The two principal

sources of these emissions are flaring of natural gas and venting of the carbon dioxide that is produced in conjunction with natural gas.

Natural Gas Flaring

Natural gas venting and flaring is a temporary event that occurs early in the field development process— while gas handling facilities are under construction, when the volume of gas produced is very low, or when oil is being produced far from natural gas markets or pipelines. In the United States the strict regulations that control gas flaring together with the economics of a well-developed gas market ensure that only about 0.5 percent of gross production is vented or flared.[40]

Natural gas venting and flaring statistics are collected by State energy offices, and reported to the EIA. States use varying methods to compute venting and flaring, ranging from pro rata estimates based on State oil production, to requiring operators to fill out detailed reports. Operators rarely meter gas venting or flaring directly; consequently, the volumes disposed of are, at best, estimates.

For emissions purposes, it would be useful to know how much natural gas is vented, and how much flared, because flared gas produces carbon emissions, while vented gas produces methane emissions. Operators usually flare gas whenever possible, both because of legal requirements and because uncontrolled methane emissions are a major safety hazard. Venting occurs primarily when gas production is too low or too irregular to support a flare. Low-volume gas venting may go unreported by operators, and hence may not be accounted for in EIA statistics.

In 1990, the Department of Energy conducted a comprehensive examination of gas venting/flaring. For that

Table 14. U.S. Natural Gas Consumption and Balancing Item, 1985-1991

Item	1985	1986	1987	1988	1989	1990	1991
Gas Consumption (Trillion Cubic Feet)	17.28	16.22	17.21	18.03	18.80	18.72	19.13
"Balancing Item" (Trillion Cubic Feet)	-0.43	-0.49	-0.44	-0.45	-0.22	-0.15	-0.46
Estimated Gas Leakage (Trillion Cubic Feet)	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07
Unmetered Consumption (Trillion Cubic Feet)	-0.36	-0.43	-0.37	-0.38	-0.15	-0.08	-0.39
Estimated Unmetered Carbon Emissions (Million Metric Tons)	5.34	6.31	5.55	5.66	2.18	1.19	5.77

Sources: Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(93/07) (Washington, DC, July 1993), p. 76. Leakage estimates from this report (see Table 23). All gas in balancing item not attributed to leakage assumed as unreported consumption.

[38]Energy Information Administration, *Natural Gas Annual 1991*, DOE/EIA-0131(91) (Washington, DC, October 1992), p. 236.

[39]Emission coefficients modified from U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993). For a more detailed discussion of the method used see Chapter 3.

[40]Energy Information Administration, *Natural Gas Annual 1991*, DOE/EIA-0131(91) (Washington, DC, October 1992), p. 14.

study, every U.S. State energy office was asked to determine the proportion of venting and flaring in their State.[41] The results of the study suggested that 87 percent of natural gas was flared, while 13 percent was vented. Adjusting for incomplete combustion, these data suggest an 80 percent/20 percent split between flaring and venting. Thus, it is clear that most reported natural gas is flared.

Table 15 provides EIA estimates of carbon emissions from natural gas flaring. The composition of "wet" associated gas differs materially from the composition of "dry" pipeline-quality natural gas, in that it contains less methane and more natural gas liquids and inert

gases. The estimates presented here use Btu conversion factors for national "wet" natural gas.

Carbon Emissions from Industrial Sources

In addition to emissions from the combustion of fossil fuels, carbon is also emitted during noncombustion industrial processes (Table 16). Of these industrial processes, the most common is the calcination of limestone to manufacture lime. Although the cement industry is the largest user of lime, it is also used extensively in steelmaking, as a fertilizer, in flue gas

Table 15. U.S. Carbon Dioxide Emissions from Gas Flaring, 1985-1991

Item	1985	1986	1987	1988	1989	1990	1991
Basic Data							
Total Natural Gas Vented and Flared (Billion Cubic Feet)	94.78	97.63	123.71	142.53	141.64	150.42	169.85
Btu content of Flare Gas (Btu per Cubic Foot)	1,112	1,110	1,112	1,109	1,107	1,105	1,108
Carbon Emissions From Flaring (Million Metric Tons)	1.27	1.31	1.66	1.90	1.89	2.00	2.27

Sources: Natural gas vented and flared and Btu conversion factor from: Energy Information Administration, *Natural Gas Annual 1991*, DOE/EIA-0131(91) (Washington, DC, October 1992), p. 207. Carbon emissions calculated as 80 percent of gas "vented and flared" from 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).

Table 16. U.S. Carbon Dioxide Emissions from Industrial Sources, 1985-1991
(Million Metric Tons of Carbon)

Source	1985	1986	1987	1988	1989	1990	1991
Cement Manufacture	9.61	9.72	9.65	9.48	9.52	9.51	8.77
Lime Manufacture	3.05	2.81	3.06	3.31	3.33	3.39	3.26
Limestone in Steelmaking	0.08	0.09	0.10	0.10	0.13	0.08	0.09
Carbon Dioxide Manufacture	0.20	0.20	0.21	0.22	0.23	0.24	0.25
Soda Ash Manufacture	0.66	0.71	0.75	0.81	0.83	0.85	0.83
Soda Ash Consumption	0.32	0.32	0.34	0.35	0.34	0.33	0.31
Aluminum Production	1.77	1.53	1.69	1.99	2.03	2.04	2.07
Total	**15.68**	**15.38**	**15.80**	**16.26**	**16.41**	**16.44**	**15.58**

Source: Estimates computed by methods described in this chapter from cement production data from U.S. Department of the Interior, Bureau of Mines, "Cement," "Lime," and "Soda Ash" (April 1992), *Mineral Commodity Summaries* (1992), and "Cement" and "Soda Ash" chapters in *Minerals Yearbook* (1988). Limestone use in steelmaking from American Iron and Steel Institute, *Iron and Steel Annual Statistical Report*, various years. Carbon dioxide manufacturing computed from 1985 and 1990 estimates of non-enhanced oil recovery carbon dioxide consumption in The Freedonia Group, Inc., *Carbon Dioxide*, Business Report B286 (Cleveland, OH, November 1991), p. 20.

[41]U.S. Department of Energy, *An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions*, DOE/NBB-088P (Washington, DC, April 1990). See p. 3.7 for summary analysis of venting.

desulfurization, and for other processes. Carbon dioxide is also produced from carbon dioxide wells and gas treatment plants as an industrial gas for use in soft drinks and fire extinguishers, and to make dry ice.

Cement Manufacture

The cement production process is the largest nonenergy source of industrial carbon dioxide emissions. Carbon dioxide is created during the calcination process, when calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime (calcium oxide or CaO) and carbon dioxide. The lime ultimately combines with silicates to form dicalcium or tricalcium silicates, which are two of the four major compounds in powdered cement, or "clinker," and the carbon dioxide is released in the atmosphere.

The volume of carbon dioxide emitted during cement manufacturing is directly proportional to lime content, that is, one molecule of calcium carbonate decomposes into one molecule of carbon dioxide and one molecule of calcium oxide. Because cement production utilizes nearly all of the lime obtained from calcination, measuring lime content in finished cement is an effective means for determining the amount of carbon dioxide emitted.[42]

In the United States, most of the structural cement produced is Portland cement, which, although it has no set value for lime content, typically contains 60 percent to 67 percent of lime by weight. EIA has assumed an average lime content of 63.5 percent, based on the midpoint of this range, for its carbon dioxide emissions estimates from this source. This same approach was followed by Griffin[43] and Marland et al.[44] According to Griffin, there are more uncertainties in cement production figures than in the assumed lime content.[45] There are also nonhydraulic cements, such as natural cement, but the production of these do not result in the release of carbon dioxide into the atmosphere because production processes do not involve calcination.

EIA employed the method recommended by OECD/IPCC to perform the calculations of the amount of carbon released from cement manufacturing.[46] This method applies an emissions factor, in tons of carbon released per ton of cement produced, to the annual cement output in the United States. The emissions factor is derived by multiplying the fraction of lime contained in the cement (63.5 percent) by a constant that reflects the mass of carbon released per unit lime (12 grams per mole carbon / 56.08 grams per mole CaO). Annual emissions from cement production, in tons of carbon, are then determined by multiplying the amount of cement manufactured in tons by 0.136 (Table 16).

Other Calcination Processes

Although cement production is the calcination process most commonly cited as a source of carbon emissions, lime is also manufactured for other purposes. In 1990, U.S. lime production was reported at 17.45 million short tons.[47] If this product was produced by calcining limestone, associated carbon emissions would have been 3.4 million metric tons. Table 16 presents estimates of carbon emissions from lime production.

Processed and raw limestone are also used in iron smelting and steelmaking. Each year, about 1 million tons of limestone is used in steelmaking, which results in carbon emissions of about 0.1 million metric tons.[48]

Carbon Dioxide Manufacture

Manufacture of carbon dioxide is modest. Statistics of carbon dioxide production are maintained by the U.S. Department of Commerce. Industrial carbon dioxide production was about 17.5 million short tons in 1990, equivalent to emissions of a potential 4.5 million metric tons of carbon. However, most industrial carbon dioxide is produced by oil companies for their own "captive" use in enhanced oil recovery. Carbon dioxide used for enhanced oil recovery is injected back into the

[42]R. Griffin, "CO₂ Release from Cement Production 1950-1985," in G. Marland et al. (eds.), *Estimates of CO₂ Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Estimates and U.S. Bureau of Mines Cement Manufacturing Data* (Oak Ridge, TN: Oak Ridge National Laboratory, 1989), p. 655.

[43]R. Griffin, "CO₂ Release from Cement Production 1950-1985," in G. Marland et al. (eds.), *Estimates of CO₂ Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Estimates and U.S. Bureau of Mines Cement Manufacturing Data* (Oak Ridge, TN: Oak Ridge National Laboratory, 1989), p. 658.

[44]G. Marland et al. (eds.), *Estimates of CO₂ Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Estimates and U.S. Bureau of Mines Cement Manufacturing Data* (Oak Ridge, TN: Oak Ridge National Laboratory, 1989).

[45]R. Griffin, "CO₂ Release from Cement Production 1950-1985," in G. Marland et al. (eds.), *Estimates of CO₂ Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Estimates and U.S. Bureau of Mines Cement Manufacturing Data* (Oak Ridge, TN: Oak Ridge National Laboratory, 1989), p. 658.

[46]OECD, "CO₂ Emissions from Cement Manufacturing," in *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 3-2 - 3-7.

[47]U.S. Department of Interior, *Mineral Commodity Summaries 1992* (Washington, DC, 1992), p. 102.

[48]Computing carbon dioxide emissions from calcining limestone, based on the initial weight of the limestone, can be done by multiplying tons of limestone by the carbon portion of the total weight, or 12/(56+44) = 0.12.

ground, and, as a first approximation, can be considered sequestered. A private market research firm has estimated that 1990 consumption of industrial carbon dioxide for purposes other than enhanced oil recovery was about 4.4 million short tons, equivalent to emissions of about 1.1 million metric tons of carbon.[49] This source also indicates that only about 20 percent of 1990 carbon dioxide production capacity was accounted for by dedicated carbon dioxide wells or as a byproduct from natural gas wells or natural gas processing. The balance of capacity was largely byproduct output from chemical plants, particularly ammonia plants, whose principal feedstocks are natural gas and naphtha. Thus, industrial carbon dioxide production for other than enhanced oil recovery purposes can largely be considered a nonfuel use of fossil fuels, but a nonfuel use that does not lead to sequestration. Pending a more detailed accounting of carbon flows through the chemical industry, emissions from this source have been estimated at a nominal 220,000 metric tons of carbon per year, based on the assumption that only 20 percent of non-enhanced oil recovery use is accounted for by carbon dioxide from wells or gas plants. The possible range of emissions from this source is 0 to 1 million metric tons.

Soda Ash Manufacture and Use

Soda ash is an alkali, used primarily as an input to the manufacture of glass but also for various other industrial processes and to make bicarbonate of soda, the "baking soda" found in many kitchens. Soda ash is also known as sodium carbonate ($NaCO_3$). About 90 percent of the soda ash manufactured in the United States is produced from trona ore ($2NaCO_3 \cdot NaHCO_3$).[50] Soda ash is made from trona ore by calcination (roasting), during which 1 mole of carbon dioxide is driven off for each mole of soda ash produced.

About 9 million short tons of soda ash are manufactured annually in the United States.[51] Trona ore is used to produce about 90 percent of this amount, which implies carbon emissions of about 0.85 million metric tons, annually.

As its chemical formula indicates, soda ash, once manufactured, still retains an additional carbon atom. Using one molecule of soda ash to neutralize acids would generally result in the release of this carbon atom in the form of carbon dioxide. Some 3 to 4 million metric tons of soda ash are used in the manufacture of glass. Since glass contains no carbon, the carbon in soda ash used

for glassmaking is released to the atmosphere. Thus, the range of possible estimates for carbon emissions from the use (as distinct from the manufacture) of soda ash would be 0.3 million metric tons (assuming only soda ash for glass manufacture produces carbon emissions) to about 0.6 million metric tons (assuming all soda ash consumed produces emissions). The minimum figure (0.3 million metric tons) is used in this report and shown in Table 16.

Carbon Emissions from Aluminum Production

A recent article in the scientific literature suggests that primary aluminum smelting is a source of carbon emissions.[52] In large part, this is due to the large volume of energy required for aluminum smelting. The energy consumed in smelting is captured under emissions for energy consumption from all sources. The author of the article also asserts, however, that the process of reducing alumina (aluminum oxide) to aluminum emits from 1.5 to 2.2 metric tons of carbon dioxide for each metric ton of aluminum produced. U.S. primary aluminum production in 1990 was 4.05 million metric tons, which implies annual emissions of between 1.7 and 2.4 million metric tons of carbon (Table 17). The principal source of carbon in aluminum smelting is anodes manufactured from petroleum coke. Anode manufacture is (or should be) counted as a nonfuel use of petroleum coke; thus, carbon emissions of this level would imply that 27 percent to 40 percent of total nonfuel use of petroleum coke is attributable to aluminum smelting, and is not actually sequestered.

Other Estimates of Energy-Related Carbon Emissions

Over the past 3 years, there have been several estimates of energy-related carbon emissions. Both the Energy Information Administration (EIA) and the Environmental Protection Agency (EPA) have produced estimates of carbon dioxide emissions for various years. Further, other organizations, such as the Oak Ridge National Laboratory (ORNL), have produced other estimates.

All of the carbon emissions estimates share a strong family resemblance, and they rarely differ by more than 5 percent or so. There are clear and unambiguous data

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[49]The Freedonia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), p. 3.

[50]D. Kostick, "Soda Ash, Sodium Bicarbonate, and Sodium Sulfate," in *Mineral Facts and Problems*, 1985 edition (Washington, DC: U.S. Department of the Interior, Bureau of Mines, 1985), p. 843.

[51]U.S. Department of the Interior, Bureau of Mines, "Soda Ash," in *Mineral Commodity Summaries* (Washington, DC, 1992).

[52]D. Abrahamson, "Aluminum and Global Warming," *Nature*, Vol. 356 (April 1992), p. 454.

Table 17. U.S. Primary Aluminum Production and Carbon Emissions from Aluminum Production, 1985-1991
(Million Metric Tons of Aluminum and Thousand Metric Tons of Carbon)

Item	1985	1986	1987	1988	1989	1990	1991
Primary Aluminum Production	3.50	3.04	3.34	3.94	4.03	4.05	4.10
Carbon Emissions (Low Estimate)	1.43	1.24	1.37	1.61	1.65	1.66	1.68
Carbon Emissions (Mid Estimate)	1.77	1.53	1.69	1.99	2.03	2.04	2.07
Carbon Emissions (High Estimate)	2.10	1.82	2.00	2.37	2.42	2.43	2.46

Sources: Primary aluminum production from U.S. Department of the Interior, Bureau of Mines, "Aluminum," *Mineral Commodity Summaries 1992* (Washington, DC, 1992), p. 22; and "Aluminum," *Mineral Commodity Summaries 1988*, p. 10. Low and high estimate emissions coefficients of 1.5 and 2.2 tons of carbon dioxide per ton of aluminum produced from D. Abrahamson, "Aluminum and Global Warming," *Nature*, Vol. 356 (April 1992), p. 484. Mid-estimate coefficient is the average of the low and high estimates.

for about 95 percent of U.S. energy consumption. The last 5 percent is neither clear nor unambiguous, and it is within this last 5 percent that different analysts can come to divergent conclusions. The primary reasons for these differences are:

- Differences in general approach—some reports using "apparent" consumption (defined as the sum of consumption, imports, and net stock withdrawals, minus exports) and others using reported consumption

- Differences in the treatment of carbon sequestered through the nonfuel use of fossil fuels

- Differing definitions of "consumption," leading to differing treatment of statistical discrepancies or "balancing items" in energy statistics

- Differences in carbon emissions coefficients for particular fuels and assignment of coefficients

- Differences in underlying energy data due to periodic revisions of the underlying data, differing definitions of aggregates such as "other petroleum," and differences introduced by differing conversion factors used to convert volumes of particular fuels into weights, and weights into energy content.

Table 18 summarizes several recent estimates.

The EPA estimate is based on energy data from the International Energy Agency (IEA) and uses an "apparent consumption" approach. IEA data are based on national data submissions, in this case from the United States, but are converted into units and data

Table 18. Comparison of Energy-Related Carbon Emissions Estimates, 1990 and 1987
(Million Metric Tons of Carbon)

Fuel Type or Process	1990			1987		
	EIA (1993)	EPA (June 1993)	CDIAC/ Oak Ridge (1993)[a]	EIA (1993)	CDIAC/ Oak Ridge (1993)[a]	Marland and Pippin (1990)
Petroleum	583.2	602.5	542.9	571.0	545.3	552.1
Coal	480.4	489.0	508.1	453.5	454.4	452.7
Natural Gas	274.5	275.7	247.9	253.2	233.9	251.7
Cement	9.5	8.9	9.5	9.6	9.6	9.6
Gas Flaring	2.0	1.8	1.9	1.7	1.8	1.8
Adjustments to U.S. Energy	10.6			15.7		5.3
Other Sources	6.9	--	--	6.2	--	--
Total Carbon Dioxide	**1,367.0**	**1,377.9**	**1,310.3**	**1,310.8**	**1,245.0**	**1,273.2**

[a]Unpublished.

Note: Includes emissions from bunker fuels.

Sources: **EIA:** Table 7 of this report. **EPA:** *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990* (Public Review Draft, Washington, DC, June 21, 1993). **CDIAC/Oak Ridge:** Companion diskettes to Oak Ridge National Laboratory, *Trends '91—A Compendium of Data on Global Change* (Oak Ridge, TN, December 1991). **Marland and Pippin:** G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol. 14, No. 4 (1990), pp. 319-336.

definitions standardized for the IEA. Review indicates that numerous small differences can be introduced into what ought to be identical data by this process of standardization.

The CDIAC/Oak Ridge estimate is the U.S. portion of a world estimate, based on an energy database maintained by the United Nations (UN). UN energy data are ultimately derived from national energy statistics, but differences can be introduced during conversion to units and data definitions standardized for the UN. No further details about these estimates or about their underlying methodology are presently published.

The Marland and Pippin estimate is based on analysis using reported consumption data found in U.S. data sources. By combining general information found in EIA's *State Energy Data Report* with more disaggregated data in two additional studies of the transportation and manufacturing sectors, this report examined subsector carbon emissions—for example, information by Standard Industrial Classification (SIC) code for the manufacturing sector.[53] However, introduction of such a complicated benchmarking between sources did lead to yet another set of definitions, so that the estimates are very similar, but not strictly comparable to those of the other reports in Table 18.

Petroleum

Differences between estimates of carbon emissions are a reflection of the complexity of the petroleum industry itself. Information is commonly reported for crude oil and some 15 finished products in the United States, as well as for refinery inputs and feedstocks to the petrochemical industry. Inherently, there are numerous opportunities for statistical error. Use of secondary sources of data, such as the IEA or UN data as described above, also can compound the error.

A review of these reports indicates that among the many opportunities, there are some common sources of differences between estimates. These sources are summarized below.

- **General Approach.** The "apparent consumption" approach (taken by EPA) does not include "unaccounted for" crude oil (the amount of crude oil input to refineries but not available from production, inputs, or stock withdrawals). The "reported consumption" approach (taken by EIA) does include this as carbon emitted from additional product supplied. IEA data also include U.S. territories as part of U.S. energy consumption, while this report adds them as an "adjustment to energy."

- **Nonfuel Use.** Carbon is sequestered by the nonfuel use of petroleum products. This affects emissions of asphalt and road oil, lubricants, petrochemical feedstocks, petroleum coke, special naphthas, waxes, and miscellaneous products. Information on nonfuel use is not directly reported to EIA; rather, EIA publishes estimates derived from available energy and industry statistics, such as trends in the sales of LPG to the chemical industry or production of fertilizer from ammonia. Since this information is derived (not reported), it has been the subject of independent interpretation by different analysts—both as to the amount of fuel that should be included for each product and the fraction of carbon sequestered. The EPA report does not include carbon sequestered from nonfuel use of petrochemical feedstocks other than naphtha, petroleum coke, or waxes and miscellaneous products, for example.

- **Carbon Coefficient Factors.** The assignment and accuracy of carbon coefficient factors is another area of disagreement. All the estimates agree that 99 percent of the fuel is oxidized during combustion, but some of the values for individual coefficients differ. The EPA report takes world coefficients from the IPCC methodology; EIA and Marland and Pippin use factors for the United States. Factors for all products are not widely published, so estimates are made for smaller products. Whereas the EIA provided estimates for individual products (see Table 11) as needed, the EPA assumed the same factor as for crude oil whenever a factor was missing. This produces differing factors for natural gas liquids and petroleum coke. The EPA report also used a single world average emissions factor for crude oil.

Coal

Each of the reports produced very similar, but slightly different, results. This is attributed to differences in estimates of energy consumption and carbon coefficient factors. Most of the reports used a single carbon coefficient factor for coal; the EPA used a world factor found in the IPCC methodology, whereas Marland and Pippin used a factor developed more specifically for U.S. coal. The EIA estimate used carbon coefficient factors distinguishing between ranks of coal.

Natural Gas

Carbon emissions from natural gas are almost identical. Most of the difference is attributed to the use of slightly different carbon coefficient factors and treatment of losses and statistical discrepancies between consumption and production.

[53]See S.C. Davis et al., *Transportation Energy Databook: Edition 10*, ORNL-6565 (Oak Ridge, TN, 1989); and R. Thoreson et al., "Industrial Fuel Use: Structure and Trends," *Annual Review of Energy*, Vol. 10 (1985), pp. 165-199.

3. Methane Emissions

Overview

Anthropogenic methane is emitted into the atmosphere as a byproduct of the production and combustion of fossil fuels, the decomposition of human and animal wastes, digestion processes in ruminant animals, and the decomposition of organic matter in rice paddies. In the United States, emissions from oil, gas, and coal production, collectively, account for approximately one-fourth of total estimated methane emissions (Table 19). Solid waste landfills account for about a third of the total—making waste landfills the largest single source. Agricultural activities, primarily cattle production, account for the remainder of the anthropogenic methane emissions.

In aggregate, the data indicate relative stability in overall emissions rates in the late 1980s. It should be noted, however, that estimated emissions from energy production have been rising relative to other sources. The rise in energy-related emissions relates primarily to increasing levels of coal and natural gas output. Methane emissions from landfills are in decline primarily because methane recovery from landfills for fuel use has become more prevalent. Agricultural sources of

methane have also trended downward. The ruminant animal population—primarily cattle—is in decline in the United States as the composition of American diets has shifted away from red meat to chicken and other white meat substitutes and to greater reliance on grains, fruits, and vegetables.

Methane emissions estimates are much more uncertain than carbon dioxide emissions estimates. Most carbon dioxide emissions can be computed with a fairly high degree of reliability based on the carbon content of the fuel consumed. The quantity of fuel consumed, in turn, is usually carefully measured by organizations which buy and sell fuel. In contrast, known anthropogenic methane emissions are produced as an unintended side-effect of energy production and consumption, municipal waste disposal, and animal husbandry. As a consequence, methane emissions are not metered, and must therefore be estimated indirectly from a small volume of experimental data, which may or may not be representative of the population of emitters. Emissions can then be estimated by multiplying the estimated coefficient by some known variable (such as tons of solid waste landfilled), which may be badly suited for the purpose of computing methane emissions.

Table 19. U.S. Methane Emissions from Anthropogenic Sources, 1985-1991
(Thousand Metric Tons of Methane)

Source	1985	1986	1987	1988	1989	1990	1991
Energy Sources							
Oil and Gas	2,850	2,860	3,000	3,110	3,110	3,190	3,280
Coal Mining	4,190	4,190	4,290	4,390	4,570	4,920	4,590
Transportation	323	309	297	286	276	264	248
Stationary Combustion	79	77	78	79	83	72	72
Area Sources							
Landfills	11,310	11,360	11,240	11,220	10,980	10,720	NA
Agricultural Sources							
Ruminant Animals	6,840	6,600	6,440	6,350	6,130	6,170	6,210
Animal Waste	3,685	3,586	3,594	3,585	3,497	3,527	3,604
Rice Paddies	209	197	195	243	225	236	232
Total	**29,486**	**29,179**	**29,134**	**29,263**	**28,871**	**29,099**	**NA**

NA = not available.
Source: Emissions estimates presented in this report.

Methane Emissions from Energy Production and Use

Coal Mining

Emission Trends. About three-fifths of all methane emissions from energy production are a byproduct of coal mine operations. Emissions of methane from coal mining and post coal mining activities amounted to 4.9 million metric tons in 1990, up from 4.2 million metric tons in 1985 (Table 20). This growth is attributed to significant expansion of U.S. coal production. Efforts to recover methane from coal mines for energy use have been increasing steadily since 1987, with approximately 250,000 metric tons being recovered annually by 1993.

Methane is produced as a byproduct of the chemical and physical processes that lead to the formation of coal. The quantity of methane in a coalbed is largely a function of rank, pressure and temperature.[54] Coal rank is a reflection of variations in coal formation (high ranks such as bituminous are likely to contain more methane than low coal ranks such as lignite). Coalbeds formed under higher pressures are apt to contain more methane and pressures increase with depth. Thus the amount of methane in coalbeds increases with depth.[55]

Methane is stored in a coalbed in two ways. It can either occupy fractures and cracks in the bed or it may be lodged in the pores of the coal itself.[56] Methane held in fractures and cracks by pressure will be emitted when pressure drops either because of erosion of the overlying strata or coal mining.[57] Methane may also be released from the coal itself as it is transported and pulverized for combustion.

Estimating Coal Mine Related Emissions. Because it is highly explosive in atmospheric concentrations of 5 to 15 percent, methane in underground coal mines presents a potentially fatal hazard for miners.[58] Consequently, the U.S. Mine Safety and Health Administration (MSHA) monitors mine methane levels and requires mine operators to ventilate their mines. MSHA conducts quarterly inspections of mine air quality and quantity. Recent efforts by the U.S. Environmental Protection Agency (EPA) to estimate methane emissions from coal mines have relied upon databases developed from these inspections.

In EPA's *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, published in April 1993, ventilation data from approximately 200 of the "gassiest" mines in the United States are used to

Table 20. Methane Emissions from Coal Mining and Post-Mining Activities, 1985-1991
(Million Metric Tons of Methane)

Source	1985	1986	1987	1988	1989	1990	1991
Coal Mining	3.75	3.74	3.86	3.95	4.12	4.45	4.20
Underground Mining	3.46	3.46	3.58	3.67	3.83	4.15	3.93
Surface Mining	0.28	0.28	0.28	0.28	0.29	0.29	0.27
Post-Mining Activities	0.45	0.45	0.46	0.47	0.49	0.52	0.49
Deep Coal	0.39	0.39	0.40	0.41	0.43	0.47	0.44
Surface Coal	0.06	0.06	0.06	0.06	0.06	0.06	0.05
Methane Recovered for Energy	(0.00)	(0.00)	(0.03)	(0.04)	(0.04)	(0.05)	(0.10)
Net Emissions	4.19	4.19	4.29	4.39	4.57	4.92	4.59

Note: 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). Methane recovery rates from J.J. Mulhern et al., "Mining Methane," in *Proceedings of the 1993 International Coalbed Methane Symposium*, May 17-21, 1993, p. 492. Calculations based on OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-80 - 2-88.

[54]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), p. 2.1.

[55]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), p. 2-80.

[56]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), p. 2.1.

[57]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), p. 2-80.

[58]U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 3-7.

generate an emissions estimate of methane from coal mining of between 3.3 and 5.2 million metric tons for 1988.[59]

An alternative methodology, developed for EPA's September 1990 report, Methane Emissions From Coal Mining: Issues and Opportunities for Reduction, was adopted by the Intergovernmental Panel on Climate Change (IPCC) in August 1991.[60] Applying this methodology to U.S. coal production data results in a much larger emissions estimate for 1988 of 7.7 million metric tons. This method constructs a relationship between ventilation data from 59 of the "gassiest" mines in the United States and the in situ methane content of the coal in those mines. In situ methane content is estimated on the basis of laboratory examination of coal samples from the various U.S. coal basins. The estimated in situ methane content of coal in these basins is shown in Table 21.[61]

The EPA/IPCC method extends the relationship between emissions from underground coal mines and in situ methane content to surface coal mines, with minor modifications. However, such a relationship may differ substantially in surface coal mines where methane in coalbed cracks and fractures has the opportunity to migrate into the atmosphere in the absence of mining. The relationship is further altered by the much lower in situ methane content of surface-mined coal. Thus, the EPA/IPCC method provides the high end of the range of emissions estimates.

By definition, methane emissions are a function of in situ methane content. Before it is combusted, all coal is pulverized, releasing any methane it may contain. Therefore, the methane emitted from coal mining is, at a minimum, equal to coal production multiplied by in situ methane content. In 1990, this minimum emissions level amounted to 2.05 million metric tons.

Table 21. Estimated Average In Situ Methane Content of U.S. Coal Basins and States
(Cubic Meters Methane per Metric Ton of Coal)

Basin or State	Methane Content	Reference
Underground Mined Coal		
Northern Appalachian	5.4	Kelefant, J.R., Wicks, D.E., and Kuuskraa, V.A., 1988
Central Appalachian	10.4	Kelefant, J.R., and Boyer, C.M., 1988
Warrior	10.0	Mcfall, K.S., Wicks, D.E., and Kuuskraa, V.A., 1986
Piceance	8.0	Mcfall, K.S., Wicks, D.E., Kuuskraa, V.A., and Sedwick, K.B., 1986
San Juan	7.1	Kelso, B.S., Wicks, D.E., Kuuskraa, V.A., 1988
Illinois	1.8	Mroz, T.H., Ryan, J.G., and Bryer, C.W., 1983
Uinta	1.3	Mroz, T.H., Ryan, J.G., and Bryer, C.W., 1983
Green River	1.3	Mroz, T.H., Ryan, J.G., and Bryer, C.W., 1983
Pennsylvania Anthracite Fields	4.4	Diamond, W.P., Lascola, J.C., and Hyman, D.M., 1986
Surface Mined Coal		
Appalachian (Including Warrior)	1.55	Diamond, W.P., Lascola, J.C., and Hyman, D.M., 1986
Illinois	1.22	Diamond, W.P., Lascola, J.C., and Hyman, D.M., 1986
Powder River	0.10	Diamond, W.P., Lascola, J.C., and Hyman, D.M., 1986
Arkoma	3.40	Diamond, W.P., Lascola, J.C., and Hyman, D.M., 1986
San Juan	0.48	Diamond, W.P., Lascola, J.C., and Hyman, D.M., 1986
Alaska	0.10	Extrapolated from Powder River Basin
Arizona	0.48	Extrapolated from San Juan Basin
Arkansas	1.22	Extrapolated from Illinois Basin
California	0.10	Extrapolated from Powder River Basin
Louisiana	0.10	Extrapolated from Powder River Basin
North Dakota	0.10	Extrapolated from Powder River Basin
Texas	0.10	Extrapolated from Powder River Basin
Washington	0.10	Extrapolated from Powder River Basin

Source: OECD, Estimation of Greenhouse Gas Emissions and Sinks (Final Report) (Paris, France, August 1991), p. 2-85.

[59]U.S. Environmental Protection Agency, Anthropogenic Methane Emissions in the United States: Estimates for 1990 (Washington, DC, April 1993), pp. 3-1 - 3-30.
[60]U.S. Environmental Protection Agency, Methane Emissions from Coal Mining: Issues and Opportunities for Reduction (Washington, DC, September 1990), pp. 36-48.
[61]OECD, Estimation of Greenhouse Gas Emissions and Sinks (Final Report) (Paris, France, August 1991), pp. 2-80 - 2-88.

Methane emissions are likely to exceed the in situ content of the coal mined because methane trapped in cracks and fractures within the coalbed is released as the bed is mined. Also, coal not recovered is disturbed by the mining process, releasing more methane. These additional emissions vary from mine to mine. For example, there are several mines in Alabama whose unusually high levels of methane cannot be attributed to depth or in situ methane content.

For this report, the relationship between emissions from coal mine ventilation and degasification systems and in situ methane content was estimated on the basis of emissions data reported in EPA's *Anthropogenic Methane Emissions in the United States: Estimates for 1990*.[62] For underground coal mines, emissions per metric ton of coal mined were estimated at two times the in situ methane content for all basins in the United States except the Warrior Basin, location of the Nation's "gassiest mines," where emissions were estimated at six times the in situ methane content.

Emissions from surface mines should represent a much smaller multiple of in situ methane content than those from underground mines because of increased coal recovery efficiency and reduced emissions from cracks and fractures. However, because methane from surface mines poses little threat to worker safety and cannot be collected for commercial sale, there have been few systematic efforts to measure it. Thus, this report adjusts its emissions multiple according to variations in recovery efficiency. In underground coal mines, recovery rates are in the neighborhood of 50 percent, while surface mines have recovery rates around 80 percent. Adjusting emissions multiples to reflect this relationship yields emissions estimates from surface mines based on a multiple of 1.25 times in situ methane content.

Methane is also emitted as coal is transported and pulverized for combustion. These emissions are restricted to methane held in coal pores and are therefore a function of residual in situ methane content and production levels. It is estimated that 25 percent of the in situ methane is released during transportation and pulverizing.[63]

Recovery of methane for energy use takes place on a limited but growing basis. The bulk of this recovery takes place in five very "gassy" mines in Alabama. J.J. Mulhern of MSHA provides estimates of this recovery

for the years 1987, 1990, and 1993. Recovery efforts prior to 1987 either did not exist or are unknown. Estimates for the years 1988, 1989, and 1991 are interpolated from the existing data.[64]

Estimates of methane emissions from coal mining have a high degree of uncertainty due to the lack of data on surface mines and underground mines with inconsequential methane concentrations. However, a range of possible emissions can be constructed with a fair degree of confidence. The in situ methane content of coal mined represents the minimum level of emissions, and estimates derived from the EPA/IPCC methodology represent the plausible maximum. For 1990, the low end of the range of emissions was 2.05 million metric tons and the high end was 8.5 million metric tons. This report's estimate of 4.9 million metric tons is near the midpoint of that range.

Oil and Gas Production, Processing, and Distribution

Emission Trends. Methane, in the form of natural gas, is one of the principal products of the oil and gas industry. As the simplest hydrocarbon in chemical structure, it is an unintended byproduct of many different production and transportation activities. However, unintended emissions by industry are by their nature not measured. Hence, emissions estimates are highly uncertain. This section endeavors to break down methane emissions from the oil and gas production industry by activity, beginning with production, moving on to gas transmission and distribution, and then oil refining. Fugitive emissions from combustion of oil and gas by end users are treated in the following section. Table 22 summarizes oil and gas-related emissions. In total, these emissions account for 38 percent of all methane emissions estimated to derive from energy production and use. Nearly two-thirds of these emissions are associated with oil and gas production. Much of the balance is attributed to gas transmission and distribution losses. Since 1985, oil and gas related emissions have risen by about 15 percent. Most of the growth in emissions has come from estimated venting of associated gas, which has nearly doubled since 1985.

Oil and natural gas are found trapped beneath impermeable cap rock in underground reservoirs. Crude oil is generally found mixed with natural gas, often in the form of gas dissolved in the oil. Thus, when oil is produced, some volume of natural gas is generally

[62]U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-8 - 3-21.

[63]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), p. 2-87.

[64]J.J. Mulhern et al., "Mining Methane," in *Proceedings of the 1993 International Coalbed Methane Symposium*, May 17-21, 1993, p. 492.

Table 22. Methane Emissions from U.S. Oil and Gas Operations, 1985-1991
(Million Metric Tons Methane)

Source	1985	1986	1987	1988	1989	1990	1991
Oil and Gas Production							
Natural Gas Wellheads	0.21	0.21	0.22	0.22	0.23	0.23	0.24
Oil Wells	0.05	0.05	0.05	0.05	0.04	0.04	0.04
Gathering Pipelines	0.34	0.34	0.34	0.33	0.33	0.32	0.31
Gas Processing Plants	0.08	0.08	0.08	0.08	0.08	0.09	0.10
Heaters, Separators, Dehydrators	0.43	0.42	0.44	0.46	0.46	0.47	0.48
Total	**1.10**	**1.09**	**1.12**	**1.14**	**1.14**	**1.16**	**1.17**
Gas Venting	0.36	0.37	0.47	0.55	0.54	0.58	0.65
Gas Transmission and Distribution	1.31	1.31	1.33	1.34	1.35	1.37	1.38
Oil Refining and Transportation	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Total	**2.85**	**2.86**	**3.00**	**3.11**	**3.11**	**3.19**	**3.28**

Sources: U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, April 1993; *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 1992*, DOE/EIA-0384(92), May 1993; Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340, various years.

produced as a byproduct. The fate of this associated gas is generally based on commercial considerations. In the United States, where gas is a valuable commodity, associated gas is usually sold commercially. The production of oil and associated gas will produce fugitive methane emissions through leakage from valves, meters, and flanges.

When natural gas is produced by itself, there are similar fugitive emissions from pneumatic valves, meters, and flanges, as well as maintenance-related emissions from emptying pressure vessels and gathering systems. When gas is treated to remove heavy hydrocarbons and contaminants, the gas treatment and processing equipment produces fugitive and maintenance-related emissions. Finally, there are occasional accidents, both at wells and treatment plants, that may result in larger scale methane emissions. However, large-scale methane releases may result in fire and explosion, converting most of the methane to carbon dioxide.

Field Operations. The method used for the estimation of methane emissions from the natural gas system was derived largely from the work of the U.S. Environmental Protection Agency (EPA), in their report, *Anthropogenic Methane Emissions in the United States:*

Estimates for 1990.[65] The emissions factors developed by the EPA for fugitive emissions of methane at the natural gas wellhead, oil well, gathering pipeline, gas processing plants, and other field production equipment were adopted with minor modifications using EPA data.

Using detailed EPA data, a combined emissions factor for all equipment at natural gas wellheads and associated treatment facilities was developed. This factor was then multiplied by the number of U.S. gas wells in production as published in the Energy Information Administration's *Natural Gas Annual.*[66] A similar method was used to derive an oil well emission estimate. This included a single emissions factor multiplied by the number of U.S. oil wells in production as provided by *World Oil* magazine.[67]

The same approach was used to derive an emissions factor for gas processing plants with total U.S. throughput substituting for gross gas withdrawals as the denominator in the equation. Emissions factors for the components of gathering pipeline were aggregated and multiplied by pipeline miles as published by the American Gas Association in its annual *Gas Facts.*[68] In addition, EIA calculated an emissions factor for heaters, separators, and dehydrators, using the total emissions

[65]U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 2-1 - 2-52.
[66]Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years).
[67]*World Oil*, annual survey of state agencies, February issue, various years.
[68]American Gas Association, *Gas Facts*, various years.

estimate for 1990, provided by EPA, divided by gross gas withdrawals as published in EIA's *Natural Gas Annual*.

The underlying basis for the emissions factors used here is a small sample of model facilities where emissions were estimated for various components of the system. These model facilities were chosen on the basis of their accessibility for data collection and operator interviews as well as their size, process type, location and age. The estimates generalize the results of these analyses to the very diverse structural and operating conditions which exist in U.S. oil and gas production operations. Thus, a wide uncertainty range exists for emissions estimates within each component part.

Gas Venting. As noted in the previous chapter, this report assumes that some 20 percent of natural gas reported as "vented and flared" is actually vented. The estimate is based upon a Department of Energy report that surveyed individual State oil and gas offices responsible for collecting these data. The personnel at each office were asked about practices in their State.[69] Methane emissions from venting and flaring are estimated at 650,000 metric tons for 1991, up from 360,000 metric tons in 1985 (Table 22).

More than two-thirds of oil wells are so-called "stripper wells," which produce less than 10 barrels per day of oil, and account for about 14 percent of U.S. oil production. Associated gas production from stripper wells is usually at low pressures and volumes, and will often not be of commercial value. The associated gas vented from stripper wells may not be captured in any data series. In the absence of some basis for making estimates of the amount of unreported emissions, this potential source is ignored for the purposes of this report.

Natural Gas Transmission and Distribution. Emissions of methane are also associated with losses incurred during the transmission and distribution of natural gas. Since these losses are unmetered, there is no direct method of measuring the magnitude of these losses. A starting point for estimating the scale of these losses can be derived by examining how much natural gas turns up missing in national consumption statistics (Table 14, Chapter 2).

Over the past decade, the amount of gas that is not accounted for in consumption statistics has ranged from a low of 150 billion cubic feet in 1990 to a high of 700 billion cubic feet in 1983. This equates to a range of 0.8 percent to 4.2 percent of measured annual consumption. The primary short-run cause of the missing gas is believed to lie in timing differences in the measurement of gas production and consumption at different points in the system, and underreporting of gas transported by one company for the account of another. Other causes include leaks, unmetered consumption, the inherent error in gas metering equipment, and the sum of all metering, measurement, and reporting errors in the United States.

The balancing item does, however, set an upper limit on possible losses from the gas transmission and distribution system. The few careful studies of leaks from particular pipeline systems suggest that leaks are consistently much less than 0.5 percent of gas throughput.[70]

Therefore, this report employs an alternative methodology, largely based on the methods used by the U.S. Environmental Protection Agency (EPA) in their report, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*.[71] The EPA estimates methane emissions for transmission and distribution pipelines based on an examination of leaks, routine maintenance, and system upsets, along the pipelines. This report adopts EPA's emission factors for plastic and nonplastic pipelines within the distribution network.

EPA emissions factors for transmission system pipelines and for gate stations were modified slightly. Emissions factors for transmission system pipelines were calculated on a per mile of pipeline basis rather than the per pipeline component method employed by the EPA and chosen because data on miles of distribution are available for time-series use, while data on gate stations are not. The results of these calculations are summarized in Table 23.

It must be noted that there is considerable uncertainty in the emissions factors used. They were obtained through measurements on a small sample of pipeline that may or may not be representative of the larger system.

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[69]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). See p. 37 for summary analysis of venting and p. 30 for natural gas distribution and transmission.

[70]Interstate Natural Gas Association of America, *Global Warming and Methane Loss from Interstate Natural Gas Pipelines* (mimeo, August 1989), pp. 1-3.

[71]U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 2-28 - 2-36.

Table 23. Methane Emissions from U.S. Natural Gas Transmission and Distribution, 1985-1991
(Million Metric Tons of Methane)

Source	1985	1986	1987	1988	1989	1990	1991
Transmission Pipelines	1.01	1.01	1.02	1.02	1.03	1.04	1.05
Distribution Systems							
Plastic Distribution Pipelines	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Nonplastic Distribution Pipelines	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Gate Stations	0.10	0.11	0.11	0.11	0.12	0.12	0.12
Distribution System Upsets	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Distribution Systems Total	0.30	0.31	0.31	0.32	0.32	0.33	0.33
Total	1.31	1.31	1.33	1.34	1.35	1.37	1.38

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

Sources: Emissions factors derived from U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993). Pipeline mileage from American Gas Association, *Gas Facts*, various years.

Oil Refining and Transportation. Methane is emitted during transport of crude oil to the refinery and from refinery operations themselves. Methane emissions from the transportation phase occur when vapor is displaced during the loading and unloading of crude. Most crude oil produced in the United States, however, is transported via pipeline, which emits only minor amounts of fugitive methane. Accordingly, emissions from the transport of crude are relatively insignificant.

Methane is emitted during several phases of the refining process. When crude oil arrives at the refinery, it is loaded into storage tanks. Vapor displacement from these tanks results in methane emissions. During the refining process, methane is separated from the crude oil through vacuum or atmospheric distillation. Methane emissions occur during this stage from leaking

equipment components. Methane that is not destroyed during refinery flaring operations is also released to the atmosphere. In 1990, methane releases associated with oil refining and transport are estimated to total 83,000 metric tons, with the majority being fugitive emissions from refineries (Table 24). The estimate is based on the Radian Corporation's report, *Global Emissions of Methane From Petroleum Sources.*[72]

For transport, the Radian Corporation uses two emissions factors—one for tank truck and railcars and one for marine vessels. At present, there is no basis for determining the precise amount of crude that is transported by truck or rail to refineries, but the number is small. Accordingly, this report uses an emission factor attributed to transport on marine vessels. Radian's coefficient of 2.55×10^{-6} tons of methane per barrel

Table 24. Methane Emissions from U.S. Oil Refining and Transportation, 1985-1991
(Thousand Metric Tons of Methane)

Source	1985	1986	1987	1988	1989	1990	1991
Oil Refineries							
Fugitive Emissions	65.0	68.8	69.6	71.7	72.5	72.6	72.0
Tank Farms	1.7	1.8	1.9	1.9	1.9	1.9	1.9
Flaring	1.6	1.7	1.7	1.8	1.8	1.8	1.8
Total	68.3	72.4	73.1	75.4	76.3	76.3	75.7
Crude Transportation							
Marine Vessels	4.4	5.2	5.7	6.1	6.6	6.6	6.5
Total	72.7	77.6	78.9	81.5	82.9	82.9	82.2

Sources: Radian Corporation, *Global Emissions of Methane from Petroleum Sources* (Research Triangle Park, NC, February 1992); Energy Information Administration, *Annual Energy Review 1991*, DOE/EIA-0384(91) (Washington, DC, May 1993); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

[72]Radian Corporation, *Global Emissions of Methane From Petroleum Sources*, Report prepared for the American Petroleum Institute (Research Triangle Park, NC, February 17, 1992), pp. 5-2 - 5-4.

loaded was applied to the sum of annual crude oil imports, exports, and Alaskan production of crude. These categories should most accurately reflect the amount of crude subject to emissions from marine transport. It should be noted that Radian's methane emissions coefficient is based on Volatile Organic Compound (VOC) emissions factors published in EPA's *Compilation of Air Pollutant Emission Factors (AP-42)*[73] and assumes that 15 percent of the VOC vapor is methane. Radian's factor also assumes equal loading of oceangoing ships and in-river barges.

Combustion-Related Methane Emissions

Methane released through the combustion of fossil fuels is estimated to account for only 4 percent of energy-related methane emissions and 1 percent of total methane emissions (Table 19). Losses associated with the use of transport fuel account for most of these emissions. In aggregate, these emissions have declined by 23 percent between 1985 and 1991, largely due to improved performance of emissions control equipment on automobiles (Table 25).

Estimating Methane Emissions from Transportation

Much of the effort in controlling automobile emissions in recent years has focused on reducing emissions of so-called volatile organic hydrocarbons, including methane. Methane is emitted as a byproduct from the combustion of heavier hydrocarbons, particularly gasoline. When gasoline is burned in automobiles, complex hydrocarbons are broken down into simpler hydrocarbons, including methane. In common with other automotive emissions, it is not possible to directly measure automotive methane emissions from the more than 100 million automobiles registered in the United States. There have been, however, a number of studies of methane emissions from particular makes and models of automobiles in recent years, which are summarized in a 1990 Department of Energy report.[74] These studies tend to suggest that methane emissions from automobiles built in the 1970s (but tested in 1988) are on the order of 0.15 to 0.3 grams of methane per mile traveled. Older studies, using automobiles of similar vintage that were new or were tuned to factory specifications, produced methane emissions of 0.03 to 0.20 grams per mile, with post-1975 model year cars

Table 25. Estimated U.S. Transportation Methane Emissions, 1985-1991
(Thousand Metric Tons of Methane)

Item	1985	1986	1987	1988	1989	1990	1991
Motor Vehicles							
Passenger Cars	211	198	185	173	165	155	143
Buses	1	1	1	1	1	1	1
Motorcycles	5	5	5	5	6	5	5
Light Duty Trucks	68	67	68	68	67	65	62
Other Trucks	19	19	19	20	19	19	18
Total	304	290	278	267	257	245	229
Other Transport	19	19	19	19	19	19	[a]19
Total Transport	323	309	297	286	276	264	248

[a]EIA estimate. Underlying data not yet available.

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 OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-57 and 2-58. Distribution of passenger car and light duty truck fleet model years for 1983, 1985, 1988, and 1991 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.

[73]U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42 (Research Triangle Park, NC, September 1985), pp. 4.4-1 - 4.4-17.

[74]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), pp. 4.1-4.9.

turning in methane emissions uniformly less than 0.1 grams per mile. Tests of a set of 1980s vintage automobiles, performed in 1988, indicated a range of 0.05 to 0.09 grams per mile.

Properly maintained automobiles built since 1975 should usually produce emissions of less than 0.10 grams of methane per mile traveled, and might produce emissions as low as 0.03 grams of methane per mile. On the other hand, pre-1975 cars and badly maintained cars might produce emissions in the 0.15 to 0.30 grams per mile range.

EPA emissions factors for U.S. passenger cars, as reported to the Intergovernmental Panel on Climate Change, ranged from 0.03 grams per mile for post-1990 vehicles to 0.28 grams per mile for 1972 and prior vehicles.[75] These coefficients are generally consistent with the experimental data, though they are more consistent with a vehicle fleet composed largely of well-maintained vehicles.

This report uses methane emissions coefficients from the 1991 OECD/IPCC report, expressed in grams per kilometer traveled. In order to use these data, it is necessary to identify how many miles were driven by automobiles of various types and differing model years. This information is not collected directly. The Department of Transportation's Federal Highway Administration (FHWA) prepares annual estimates of vehicle miles traveled, divided by type of vehicle (cars versus trucks versus buses versus motorcycles).[76] These data are obtained by the FHWA from State transportation offices, which estimate it by varying methods, principally by traffic counts of selected roads. Data on vehicle miles traveled or fuel consumed by vehicle model year are also not collected directly. However, the Energy Information Administration conducts sample surveys of vehicle-owning households. Surveys were conducted in 1983, 1985, 1988, and 1991.[77]

This report uses a custom database sort from the EIA surveys to compute vehicle miles traveled for household-sector passenger cars and trucks by model year for 1983, 1985, 1988, and 1991. These surveys were used to compute a weighted average emissions coefficient for survey years. The weighted average coefficient was then applied to non-household-sector passenger cars

and light trucks (business-owned vehicles, fleets, rental cars, etc.) in survey years. The results are shown in Table 26. Emissions estimates for nonsurvey years were computed by interpolating between the weighted average estimates for survey years.

Table 25 illustrates methane emissions estimates by vehicle type for survey and nonsurvey years. There is a considerable degree of uncertainty in these estimates, since vehicle miles traveled data are inherently inaccurate. Overall, the real (unobservable) emissions figure is probably within 30 to 50 percent of the point estimate presented here.

Methane emissions from aviation are easily computed: jet fuel consumption of 1.47 million barrels per day can be multiplied by the OECD/IPCC emissions factor 0.087 grams per kilogram fuel. Aviation gasoline consumption is about 22,000 barrels per day, with an emissions factor of 2.6 grams per kilogram. These numbers produce less than 10,000 metric tons of methane emissions annually. Other vehicular uses (farm equipment, railroads, etc.) were computed using energy data from Oak Ridge's *Transportation Energy Data Book* plus the OECD/IPCC emissions coefficients. Note, however, that the underlying energy data are estimated using a variety of crude methods, and hence are not very reliable.

Estimating Methane Emissions from Stationary Sources

Unlike carbon dioxide, methane emissions from stationary source combustion of fossil fuels are relatively small (Table 27). Emissions are caused by the incomplete combustion of fuels: methane is a byproduct of this process and is thus released as an unburnt gaseous combustible.[78]

Emissions of methane depend on several factors including the fuel type, the temperature of combustion, the efficiency of the combustion process, and pollution control mechanisms. Emissions may also be affected by the type, size, and age of the combustion facility, as well as its maintenance, and operation.

Calculations of methane emissions from stationary sources were performed using EPA's *Compilation of Air*

[75]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-52 - 2-57.
[76]See Federal Highway Administration, *Highway Statistics 1988* (Washington, DC: U.S. Department of Transportation, 1990). This is an annual publication. Vehicle miles traveled are shown in Table VM-1 of this FHWA publication.
[77]See Energy Information Administration, *RTECS: Consumption Patterns of Household Vehicles 1983*, *RTECS: Consumption Patterns of Household Vehicles 1985*, and *Household Vehicles Energy Consumption 1988* (Washington, DC, 1985, 1987, 1990). Information on the 1991 survey will be published in October 1993.
[78]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), p. 2-25.

Table 26. U.S. Passenger Car and Light Truck Vehicle Miles Traveled, Emissions Coefficients, and Methane Emissions, 1983, 1985, 1988, and 1991

Model Year	CH₄ Coefficient (g/km)	1983 VMT	1983 CH₄	1985 VMT	1985 CH₄	1988 VMT	1988 CH₄	1991 VMT	1991 CH₄
Automobiles									
1977 and earlier	0.174	441.1	123.6	341.8	95.8	174.4	48.9	P 99.2	27.8
1978-1982	0.090	469.4	68.0	431.9	62.6	329.7	47.8	P 201.3	29.2
1983-1989	0.040	57.1	3.7	281.7	18.1	629.7	40.6	P 707.6	45.6
1990-1992	0.020	0.0	0.0	0.0	0.0	0.0	0.0	P 142.3	4.6
Other		5.0	1.0	3.8	0.6	0.0	0.0	P 0.0	0.0
Total		972.6	196.3	1,059.1	177.1	1,133.7	137.2	P 1,150.4	107.1
Other Passenger Vehicles .		225.4	45.5	201.5	33.7	295.6	35.8	P 383.3	35.7
Total Passenger		**1,198.0**	**241.8**	**1,260.6**	**210.8**	**1,429.3**	**172.9**	**1,533.7**	**142.8**
Light Duty Trucks									
1977 and earlier	0.174	130.7	36.6	102.1	28.6	78.6	22.0	P 57.3	16.1
1978-1982	0.090	100.3	14.5	98.4	14.3	84.2	12.2	P 56.0	8.1
1983-1989	0.070	12.5	1.4	90.8	10.2	214.9	24.2	P 271.3	30.6
1990-1992	0.040	0.0	0.0	0.0	0.0	0.0	0.0	P 67.4	4.3
Other		2.6	0.6	2.6	0.5	0.0	0.0	P 0.0	0.0
Total		246.2	53.1	293.8	53.6	377.6	58.4	P 452.0	59.1
Other Light Trucks		81.4	17.6	79.3	14.4	61.8	9.6	P 20.9	2.7
Total Light Trucks ..		**327.6**	**70.7**	**373.1**	**68.0**	**439.4**	**68.0**	**472.9**	**61.8**

P = preliminary data. VMT = vehicle miles traveled in billions of miles. CH₄ = methane emissions in thousand metric tons.
Note: Totals may not equal sum of components due to independent rounding.
Sources: Vehicle miles traveled by model year from the Energy Information Administration's Residential Transportation Energy Consumption database, custom database sort dated June 2, 1993. Total vehicle miles traveled from U.S. Department of Transportation, *Highway Statistics*, various years. Emissions coefficients by model year from OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-56 and 2-57.

Pollutant Emission Factors, which contains coefficients by fuel type for each end-use sector.[79] Emissions factors in pounds of methane per ton of fuel consumed were applied to fuel consumption data for each sector.

Consumption data for fossil fuels were taken from EIA's *State Energy Data Report 1991*, and data for wood consumption were taken from EIA's *Annual Energy Review 1992*. Data on wood used as fuel are reported for selected years only; the estimates shown are based on interpolation between years for which data were available.

Methane Emissions from Landfills

Emission Trends

Emissions from landfills are estimated to account for about one-third of all U.S. sources of methane. Emissions from this source declined by about 5 percent from

1985 to 1990 (Table 28). The main factor contributing to this decline is increased efforts to recover methane from landfills for fuel use.

Estimating Emissions

Methane is produced by the anaerobic decomposition of organic materials in landfills. Degradable carbon compounds in landfill waste are initially attacked by aerobic bacteria. These bacteria consume oxygen as they convert organic substances to carbon dioxide, heat and water. However, the oxygen in landfills is rapidly depleted, at which time decomposition continues via anaerobic bacteria. The resulting gas is estimated to consist of 50-percent carbon dioxide and 50-percent methane.[80] The lifetime of methane production in landfills may last anywhere from 10 to 60 years, with peak production believed to occur soon after the first or second years. The level of methane production in landfills is contingent on several factors. These factors include waste composition, moisture content, leachate

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[79] U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42 (Research Triangle Park, NC, September 1985), pp. 1.1-1 - 1.10-1.

[80] H.G. Bingemer and P.J. Crutzen, "The Production of Methane From Solid Wastes," *Journal of Geophysical Research*, Vol. 92 (1987), pp. 2181-2187.

Table 27. Methane Emissions from U.S. Stationary Combustion Sources, 1985-1991

(Thousand Metric Tons of Methane)

Source	1985	1986	1987	1988	1989	1990	1991
Residential							
Coal	0.04	0.04	0.04	0.04	0.03	0.04	0.03
Distillate Fuel	5.80	5.91	6.00	6.18	6.08	4.89	4.85
Natural Gas	5.43	5.29	5.29	5.68	5.86	5.38	5.58
LPG	0.43	0.42	0.46	0.46	0.51	0.47	0.50
Wood	[a]23.50	[a]23.00	22.49	[a]21.60	24.23	15.34	[a]15.30
Total	35.20	34.65	34.28	33.95	36.70	26.12	26.27
Commercial							
Coal	0.07	0.07	0.05	0.05	0.05	0.05	0.05
Fuel Oil	0.77	0.84	0.80	0.78	0.71	0.68	0.65
Natural Gas	2.98	2.84	2.98	3.27	3.33	3.22	3.35
LPG	0.07	0.07	0.08	0.08	0.09	0.08	0.09
Wood	[a]0.17	[a]0.17	[a]0.17	[a]0.17	[a]0.17	[a]0.17	[a]0.17
Total	4.06	3.99	4.08	4.36	4.36	4.20	4.31
Industrial							
Coal	1.58	1.51	1.53	1.61	1.59	1.57	1.48
Fuel Oil	2.47	2.44	1.98	1.87	1.45	1.46	1.20
Natural Gas	9.35	8.86	9.67	10.19	10.74	11.24	11.41
LPG	2.46	2.31	2.45	2.54	2.49	2.32	2.54
Wood	[a]13.10	[a]12.80	12.48	[a]12.80	13.25	13.26	[a]13.25
Total	28.96	27.91	28.11	29.00	29.53	29.85	29.89
Electric Utility							
Coal	9.45	9.33	9.78	10.32	10.45	10.54	10.51
Fuel Oil	0.85	1.15	0.98	1.22	1.29	0.97	0.91
Natural Gas	0.41	0.35	0.39	0.36	0.38	0.38	0.38
Wood	0.07[a]	0.07[a]	0.07	0.09[a]	0.10	0.10	0.09[a]
Total	10.79	10.91	11.22	11.99	12.22	11.98	11.90
Total All Fuels							
Coal	11.14	10.95	11.40	12.03	12.12	12.20	12.08
Fuel Oil	9.89	10.33	9.77	10.05	9.54	7.99	7.62
Natural Gas	18.18	17.34	18.33	19.49	20.31	20.22	20.72
LPG	2.96	2.80	2.99	3.08	3.09	2.88	3.13
Wood	36.84	36.04	35.21	34.66	37.75	28.86	28.81
Total	79.01	77.46	77.70	79.31	82.81	72.15	72.37

[a]Estimate. Underlying energy data not available.

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

Sources: U.S. Environmental Protection Agency, *Compilation of Air Pollutant Emission Factors*, AP-42 (Research Triangle Park, NC, 1985); Energy Information Administration, *State Energy Data Report*, DOE/EIA-0214(91) (Washington, DC, May 1993), and *Annual Energy Review 1992*, DOE/EIA-0384(92) (Washington, DC, June 1993).

acidity, and landfill temperature. Waste management techniques such as open dumping versus sanitary landfill also play a crucial role. Wastes disposed of using open dumping techniques decompose under aerobic conditions producing carbon dioxide, while waste disposal in tightly packed sanitary landfills like those used in the United States, are more conducive to anaerobic decomposition.[81]

There were two methodologies considered for calculating U.S. emissions from landfills. The first model assumes that methane is released into the atmosphere during the same year that the waste is landfilled.[82] The alternative includes time lag variables that account for the delay in the onset of anaerobic decomposition as well as the decreasing levels of methane production over time. The former was the preferred methodology

[81]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991).

[82]H.G. Bingemer and P.J. Crutzen, "The Production of Methane From Solid Wastes," *Journal of Geophysical Research*, Vol. 92 (1987), pp. 2181-2187.

Table 28. Methane Emissions from U.S. Landfills, 1985-1990

(Million Metric Tons of Methane)

Type	1985	1986	1987	1988	1989	1990
Gross Emissions	11.91	12.15	12.08	12.17	12.16	11.96
Methane Recovery (Energy)	0.30	0.49	0.54	0.66	0.88	0.94
Methane Assumed Flared	0.30	0.30	0.30	0.30	0.30	0.30
Net Emissions	**11.31**	**11.36**	**11.24**	**11.22**	**10.98**	**10.72**

Source: Municipal solid waste landfilled from 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). Emissions calculations based on H.G. Bingemer and P.J. Crutzen, "The Production of Methane From Solid Wastes," *Journal of Geophysical Research*, Vol. 92 (1987), pp. 2181-2187. Recovery of methane estimates based on computations from Government Advisory Associates, *Methane Recovery from Landfill Yearbook*. Assumed flaring from U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 4-20.

because the latter requires supporting data on moisture content, acidity, landfill age, and time since closure. All of these data may be available for particular sites, but they are not available for national-level estimates.

To calculate U.S. emissions the following equation developed by Bingemer and Crutzen was used.

Methane Emissions = Total Municipal Solid Waste (MSW) generated × MSW landfilled (percent) × Degradable Organic Carbon (DOC) in MSW (percent) × Fraction Dissimilated DOC (percent) × 0.5 grams of methane in biogas × Conversion Factor (16 grams methane per 12 grams carbon) – Recovered methane

Data for total MSW landfilled in thousands of tons for the years 1985-1990 were obtained from Franklin Associates.[83] The results are summarized in Table 28.

The degradable organic carbon (DOC) content represents the organic carbon that is accessible to biochemical decomposition. A DOC of 21 percent was assumed for the years 1988-1990 based on Bingemer and Crutzen's work.[84] Noting the lower levels of organic material (particularly paper) in the waste stream prior to 1988, estimates of DOC were lowered to 20 percent for 1985-1987.

The percentage of DOC dissimilated is the portion of carbon that is converted to landfill gas. This fraction is highly dependent on the temperature of the anaerobic zone. Research has shown that at depths greater than two meters the temperature in landfills is independent

of ambient air temperatures. Temperatures in the anaerobic zone are likely to stabilize at 35 degrees C. At such a temperature approximately 77 percent of DOC is converted to biogas with a methane content of 50 percent.[85]

Data on methane recovered from landfills are poor. The actual quantity of MSW entering landfills on an annual basis is a calculated guess. No systematic reporting of landfill waste receipts by quantity and type exists. The age and depth of material placed in landfills is known for only a few sites. Additionally, the total number of landfill sites is not known. In the near future, data will improve as new regulations for landfills are implemented. For the purposes of this report a database of operating methane recovery for energy systems, and their throughput, prepared by Governmental Advisory Associates was used in combination with estimates of methane recovered and flared provided by the U.S. Environmental Protection Agency.

Agricultural Sources of Methane

Methane emissions from agricultural activities account for about one-third of all estimated U.S. emissions of methane. Three sources are identified. Methane from ruminant animals and animal waste are by far the most important contributing 98 percent of the total. The balance derives from methane emissions associated with wetland rice cultivation. In the 1980s, a downward

[83]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 (Washington, DC, July 1992), pp. 4-1 - 4-3.

[84]H.G. Bingemer and P.J. Crutzen, "The Production of Methane From Solid Wastes," *Journal of Geophysical Research*, Vol. 92 (1987), pp. 2181-2187.

[85]H.G. Bingemer and P.J. Crutzen, "The Production of Methane From Solid Wastes," *Journal of Geophysical Research*, Vol. 92 (1987), pp. 2181-2187; and OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991).

trend in emissions from agriculture is evident primarily because the population of ruminant animals (primarily cattle)—is in decline reflecting declining aggregate demand for beef.

Estimating Methane Emissions from Domesticated Animals

Ruminant animals such as cattle, buffalo, sheep, goats, and camels are substantial emitters of methane. In the United States, cattle are responsible for as much as 95 percent of methane emissions from enteric fermentation. The *rumen* is a large "forestomach," which hosts up to 200 species of microorganisms. A small fraction of these microorganisms are methanogenic bacteria. These methanogens are responsible for the removal of hydrogen produced in the rumen. Methane produced in the rumen is emitted through belching or as part of the flatus.[86]

As a product of the digestive process, the amount of methane emitted is contingent on the type of animal examined, the characteristics of the animal's feed, and the activity level of the animal. In order to calculate emissions from ruminant animals, the animals must be divided into distinct, relatively homogeneous groups. The food energy content and the percentage of that energy emitted as methane must then be estimated for a representative animal in each group. The resulting emissions for that representative animal is then multiplied by the total number in the group to establish an overall emissions estimate.

For the purposes of this report, emissions for cattle, sheep, and goats among ruminant animals were calculated. In addition, methane emissions from enteric fermentation in pigs and horses were judged large enough, because of their large populations, to warrant inclusion in this inventory. The results for the various animal types are summarized in Table 29.

The methodology chosen relies heavily on the work of Crutzen et al.[87] Cattle were divided into three groups: milk cows, cattle on feed, and cattle on range. Crutzen et al. offer daily gross energy intakes of 230 megajoules, 150 megajoules, and 110 megajoules respectively for each cattle class. These numbers correspond to 2.3, 1.75 and 1.3 times the maintenance requirements of each animal. Methane yields were drawn from the estimates of Blaxter and Clapperton.[88] They offer yields of 5.5 percent of gross daily energy intake for U.S. milk cows, 6.5 percent for cattle on feed, and 7.5 percent for cattle on range. Methane emissions can then be derived from these yields using the conversion factor 55.65 megajoules equals 1 kilogram of methane.

Data on U.S. cattle populations were provided by the U.S. Department of Agriculture's (USDA's) National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. The data were separated into cattle and milk cows. Cattle were further disaggregated into range cattle and cattle on feed.

The method for estimating emissions from sheep was similar to that of cattle. Estimates of daily gross energy

Table 29. U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1985-1991
(Million Metric Tons of Methane)

Animal Type	1985	1986	1987	1988	1989	1990	1991
Cattle	6.56	6.33	6.16	6.06	5.84	5.88	5.92
Sheep	0.14	0.13	0.14	0.14	0.14	0.15	0.15
Pigs	0.08	0.08	0.08	0.08	0.08	0.08	0.09
Goats	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Horses	0.04	0.04	0.04	0.04	0.05	0.05	0.05
Total	6.84	6.60	6.44	6.35	6.13	6.17	6.22

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

Sources: Cattle, sheep, and goat populations provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Service. Goat population figures extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982 and 1987. Emissions calculations based on 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.

[86]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), p. 5-3.

[87]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.

[88]K.L. Blaxter and J.L. Clapperton, "Prediction of the Amount of Methane Produced by Ruminants," *British Journal of Nutrition*, Vol. 19 (1965), pp. 511-522.

intake for adult sheep range from 30 to 40 megajoules. The midpoint of 35 megajoules per day was chosen. Immature sheep, those under one year old, have a gross energy intake of 20 to 25 megajoules daily. Again using the midpoint, 22.5 megajoules per day was chosen for the model. A mean methane yield of 6 percent was adopted, while the factor for converting energy intake to methane emitted remained the same.[89] Data on U.S. sheep populations, classified by age, were obtained from the National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch, U.S. Department of Agriculture.

The method for estimating emissions from goats differed from cattle and sheep. An annual methane yield per animal of 8 kilograms was assumed. This figure was chosen based on research on goats in India. Indian goats have an annual methane yield of 5 kilograms, comparable to sheep elsewhere in the developing world.[90] Sheep in the developed world have an estimated annual methane yield of 8 kilograms. Presuming that the relationship between sheep and goat yields is similar in the developing world, the 8 kilograms figure is used.

Population data for goats are restricted to the years 1982 and 1987 as documented in the Census of Agriculture.[91] Populations for the intervening years were estimated using straight line extrapolation. The population figures were multiplied by the 8 kilograms annual methane yield to determine the total emissions for goats.

Methane emissions estimates for the nonruminant animals (horses and pigs) were calculated using a method similar to that used for goats. Annual methane yields of 1.5 kilograms methane per animal for pigs and 18 kilograms per animal for horses were adopted based on the work of Crutzen et al.[92] Pig populations were provided by the National Agriculture Statistics Service, Livestock, Dairy and Poultry Branch, U.S. Department of Agriculture. Horse populations, similar to goat populations, were extrapolated from data available in the Census of Agriculture for the years 1982 to 1987.[93]

Methane Emissions from the Solid Waste of Domesticated Animals

Animal waste is primarily composed of organic material and water. When the organic material in the waste decomposes in an anaerobic environment, methane is produced. Because methane production only occurs under anaerobic conditions, the manner in which animal wastes are managed is a crucial determinant in the level of emissions. If the waste is left to dry in the fields in the presence of oxygen the production of methane will be minimal. If the waste is stored in a manner which prevents contact with oxygen methane production may be significant.[94]

To estimate U.S. emissions of methane from the solid waste of domesticated animals, the following equation outlined by Casada and Safley was used:[95]

$$TM_i = N_i \times TAM_i \times VS_i \times B_{oi} \times MCF_j \times WS\%_{ij}$$

where:

TM_i = Total methane emitted by the solid waste of a given animal group;

N_i = Total population of a given animal group;

TAM_i = Typical animal mass of a given animal;

VS_i = Average daily volatile solids production per unit of animal mass for a given animal;

B_{oi} = Maximum methane-producing capacity per unit of volatile solids for a given animal;

MCF_j = Methane Conversion Factor for each waste management system;

$WS\%_{ij}$ = Percentage of a given animal's waste handled using a given waste system.

There were ten groups of animals included in the emissions estimates. They were beef cattle on range, beef cattle on feed, milk cows including heifers for replacement, swine for market, swine for breeding, sheep, caged layer poultry, broiler poultry, goats, and horses. Estimates of emissions for these groups appear in Table 30.

All animal population data except those for horses and goats were acquired from the USDA's National Agricultural Statistics Service, Livestock, Dairy and Poultry

[89]K.L. Blaxter and J.L. Clapperton, "Prediction of the Amount of Methane Produced by Ruminants," *British Journal of Nutrition*, Vol. 19 (1965), pp. 511-522.

[90]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.

[91]U.S. Department of Commerce, Bureau of the Census, *1987 Census of Agriculture*, Volume 1, "Geographic Area Series."

[92]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.

[93]U.S. Department of Commerce, Bureau of the Census, *1987 Census of Agriculture*, Volume 1, "Geographic Area Series."

[94]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), p. 5-19.

[95]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. 17-46.

Table 30. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1985-1991
(Thousand Metric Tons of Methane)

Type of Animal	1985	1986	1987	1988	1989	1990	1991
Cattle	**2,300**	**2,226**	**2,154**	**2,118**	**2,063**	**2,071**	**2,073**
Beef On Feed	279	269	263	258	247	249	252
Beef On Range	891	859	838	824	788	795	804
Milk Cows	1,130	1,098	1,053	1,035	1,028	1,027	1,017
Swine	**1,111**	**1,083**	**1,155**	**1,179**	**1,143**	**1,158**	**1,226**
Market Swine	997	970	1,036	1,060	1,028	1,043	1,104
Breeding Swine	114	112	119	118	115	115	122
Poultry	**148**	**151**	**157**	**156**	**157**	**161**	**167**
Caged Layers	97	98	100	97	95	95	97
Broilers	51	53	57	59	63	67	70
Other Animals	**126**	**126**	**130**	**132**	**134**	**137**	**139**
Sheep	34	32	34	35	35	36	36
Goats	5	5	6	6	6	7	7
Horses	87	89	90	92	93	94	96
Total	**3,685**	**3,586**	**3,594**	**3,585**	**3,497**	**3,527**	**3,604**

Note: 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 and 1987. Population data for all other animals from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Typical animal mass and volatile solid production from American Society of Agricultural Engineers, *Manure Production and Characteristics Standards* (St. Joseph, MI, 1988). Maximum methane production, methane conversion factors, 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.

Service. Horse and goat data were acquired from the U.S. Department of Commerce.[96] These data only covered the years 1982 and 1987, and intervening years' populations were derived using straight-line extrapolation. This may be problematic as livestock populations tend to display a cyclical, rather than linear, growth path. Cattle populations were estimated using an average of the USDA's inventories for January 1, July 1, and December 31 of each year through 1988. For 1989-1991 USDA did not provide a July 1 inventory and only the January 1 and December 31 inventories were averaged. As broiler chickens only have approximately a 7-week life span, the total annual inventory of broilers slaughtered in the United States was multiplied by 0.1425, per the recommendation of Lawrence Witucki of the USDA's Economic Research Service, Commodity Economic Division, to yield an inventory of birds being raised at any given time.

Typical animal masses and volatile solids produced were taken from the American Society of Agricultural

Engineers', *Manure Production and Characteristics Standards*.[97]

This report adopted the maximum methane capacity estimates used by Casada and Safley in their 1990 report for the EPA (Table 31).[98] Maximum methane capacity is defined as the cubic meters of methane emitted from one kilogram of volatile solids in the solid waste of a given animal under optimal anaerobic conditions. The percentage of waste managed in a given system and each system's methane conversion factor were also adopted from Casada and Safley's work (Table 32).[99] The methane conversion factor represents the percentage of the maximum methane capacity realized using a given waste disposal system. It must be noted that the methane conversion factors are highly uncertain, and hence prone to revision.

Safley has recently developed updated methane conversion factors which have yet to be subjected to peer review. Their use is currently under consideration

[96]U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982 and 1987.

[97]American Society of Agricultural Engineers, *Manure Production and Characteristics Standards* (St. Joseph, MI, 1988).

[98]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.

[99]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. 28-32 and APP-81 - APP-98.

Table 31. Maximum Methane-Producing Capacity for U.S. Animal Wastes
(Cubic Meters of Methane per Kilogram of Volatile Solids)

Animal Category	Maximum Potential Emissions	Reference
Cattle		
Beef on Feed	0.33	Hashimoto, A.G., Varel, V.H., and Chen, Y.R., 1981
Beef on Range	0.17	Hashimoto, A.G., Varel, V.H., and Chen, Y.R., 1981
Dairy Cows	0.24	Morris, G.R., 1976
Swine		
Breeding Swine	0.36	Summers, R., and Bousfield, S., 1980
Market Swine	0.47	Chen, Y.R., 1983
Poultry		
Broilers	0.30	Safley, L.M., et al., 1992
Layers	0.34	Safley, L.M., et al., 1992, based on Hill, D.T., 1982 and 1984
Sheep	0.20	Weighted value based on Safley, L.M., et al., 1992
Goats	0.17	Safley, L.M., et al., 1992
Horses	0.33	Ghosh, S., 1984

Note: Maximum methane-producing capacity is defined as cubic meters of methane emitted from 1 kilogram of volatile solids in the solid waste of a given animal under optimal anaerobic conditions.

Table 32. Methane Conversion Factors for U.S. Livestock Waste Systems
(Percent of Maximum Methane-Producing Capacity)

| Waste System | EIA | | EPA | | |
	Methane Conversion Factor	Alternate Conversion Factor	Methane Conversion Factor at 30°C	Methane Conversion Factor at 20°C	Methane Conversion Factor at 10°C
Pasture	10.00	1.25	2.00	1.50	1.00
Daily Spread	5.00	0.30	1.00	0.50	0.10
Solid Storage	10.00	1.25	2.00	1.50	1.00
Drylot	10.00	1.25	5.00	1.50	1.00
Deep Pit Stacking	5.00	5.00	5.00	5.00	5.00
Litter	10.00	10.00	10.00	10.00	10.00
Paddock	10.00	1.25	2.00	1.50	1.00
Liquid Storage	20.00	22.50	65.00	35.00	10.00
Anaerobic Lagoon	90.00	90.00	90.00	90.00	90.00
Pit Storage < 30 days ..	10.00	11.50	33.00	18.00	5.00
Pit Storage > 30 Days ..	20.00	22.50	65.00	35.00	10.00
Other Systems	10.00	10.00	NA	NA	NA

NA = not applicable.
Note: Maximum methane-producing capacity is defined as cubic meters of methane emitted from 1 kilogram of volatile solids in the solid waste of a given animal under optimal anaerobic conditions. The methane conversion factors represent the percentage of those emissions realized under a given waste management system.

for future drafts of this report. In April 1993, the Environmental Protection Agency released a new report on U.S. anthropogenic methane emissions. In their section on methane emissions from the solid waste of livestock, they introduced new, lower estimates using substantially lower methane conversion factors than those used in this report. A comparison of emissions factors is shown in Table 32.

Table 33 illustrates an alternative emissions estimate based upon these lower factors, supplied to the U.S. Environmental Protection Agency in personal communications with Dr. Andrew Hashimoto, Department Chairman, Bioresource Engineering Department, Oregon State University. Dr. Hashimoto provided conversion factors applicable at temperatures of 10, 20, and 30 degrees Celsius. As virtually all livestock in the

Table 33. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1985-1991, Using Alternative Methane Conversion Factors

(Thousand Metric Tons of Methane)

Animal	1985	1986	1987	1988	1989	1990	1991
Cattle	**1,114**	**1,082**	**1,040**	**1,023**	**1,010**	**1,010**	**1,004**
Beef On Feed	39	37	37	36	34	35	35
Beef On Range	124	120	117	115	110	111	112
Milk Cows	951	925	887	872	865	865	857
Swine	**1,087**	**1,060**	**1,130**	**1,154**	**1,119**	**1,133**	**1,200**
Market Swine	976	950	1,014	1,038	1,007	1,021	1,081
Breeding Swine	111	110	116	116	113	113	119
Poultry	**149**	**152**	**158**	**157**	**159**	**163**	**168**
Caged Layers	99	99	101	99	96	96	98
Broilers	51	53	57	59	63	67	70
Other Animals	**24**	**24**	**26**	**26**	**26**	**27**	**27**
Sheep	7	6	7	7	7	7	7
Goats	1	1	2	2	2	2	2
Horses	16	17	17	17	17	18	18
Total All Animals	**2,375**	**2,318**	**2,353**	**2,359**	**2,313**	**2,332**	**2,398**

Note: 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 and 1987. Population data for all other animals from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch. Typical animal mass and volatile solid production from American Society of Agricultural Engineers, *Manure Production and Characteristics Standards* (St. Joseph, MI: 1988). 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. Methane conversion factors from U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 6-13.

United States are raised in climates with mean annual temperatures between 10 and 20 degrees C, a methane conversion factor using the mean value of the factors offered for 10 and 20 degrees C was adopted. Conversion factors for Litter and Deep Pit Stacking Systems continue to be drawn from the work of Safley et al.

Aside from the revised methane conversion factors for the various waste systems, the methodology used for the alternative estimates of emissions from the solid waste of domesticated animals was identical to that used for the original estimates. Totals for methane emissions shown in Table 33 are lower than those in Table 30 and Table 19 by one-third or more. The large disparity in the original and alternative estimates underscores the importance and potential variability of the methane conversion factors used in these emissions estimates. Unfortunately, this is only one element of uncertainty with regard to developing methane estimates derived from animal waste.

Estimating Methane Emissions from Wetland Rice Cultivation

Methane production in flooded rice fields results from the decomposition of organic material by methanogenic bacteria. A large part of the methane produced is oxidized by aerobic methanotropic bacteria, present in the surface layer of the submerged soil and in the soil surrounding the rice plant roots, and as such is not emitted to the atmosphere. The methane that is not oxidized is emitted from the paddy soil to the atmosphere via plant-mediated transport, and, to a lesser extent, diffusion through the floodwater, and ebullition (i.e. bubbling).[100]

Rice fields in dry, upland areas are not flooded and are, therefore, not believed to be sources of methane. Similarly, deepwater rice (greater than one meter floodwater depth) is not believed to be a significant source of methane, because the lower roots and stems of the rice

[100]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), p. 5-31.

plants are dead, blocking the primary methane transport pathway.

A number of environmental and managerial factors are believed to influence methane emissions from rice fields. Among these are soil acidity, temperature of the upper soil layer, application of commercial nitrogen and organic fertilizers, water management practices, and rice cultivar selection. Additionally, field experiments have shown large seasonal variations in methane emissions corresponding with the development of the rice plant.

Calculations of methane emissions from rice fields in the United States relied heavily on the method recommended by OECD/IPCC.[101] This method utilizes a daily emission rate range designed to capture some of the variability inherent in rice methane formation without requiring the level of data or the detailed calculations necessary to account for various environmental factors (e.g., soil acidity, temperature, fertilizer application). For this report, however, the OECD/IPCC document's recommended range, which is based on field experiments in China, was not used, in favor of a range that would more accurately reflect conditions in the United States. The range used for these calculations is based on the work of Sass et al. in Texas,[102] whose experiments yielded average daily emissions of 0.06 to 0.21 grams of methane per square meter per day. Similar experiments have been performed in California fields. This report uses the work of Sass. California accounts for less than 1 percent of the total rice area in the United States while Texas holds approximately 14 percent.[103] It was assumed that soil conditions in Arkansas, Louisiana, and Mississippi, which together

account for approximately 80 percent of the total U.S. rice area, would be more similar to those in Texas rather than in California. Table 34 displays low and high range estimates of methane emissions from flooded rice fields in the United States.

To calculate methane emissions, the emission rate range was applied to daily cultivated wetland rice area. The assumption was made that none of the rice area in the United States is either deepwater or upland. The daily cultivated area, therefore, is the product of the total number of hectares harvested annually and the number of days in the cropping cycle. According to Matthews et al.,[104] the length of the U.S. cropping cycle is approximately 153 days. The growing season may, in fact, be shorter than this but until more specific information regarding the cropping cycle can be obtained, calculations are based on a 153-day season.

Annual methane emissions are thus calculated:

1. Total number of hectares harvested × number of days in cropping cycle (153 days) = number of hectare-days harvested

2. Low estimate: number of hectare-days × (0.06 grams methane per square meter per day × 10,000 square meters per hectare)

   High estimate: number of hectare-days × (0.21 grams methane per meter per day × 10,000 square meters per hectare)

3. Multiply each estimate by (12 grams per mole carbon divided by 16 grams per mole methane) and divide each by 1,000,000 grams per metric ton to yield estimates in metric tons of carbon.

Table 34. Area of Land Harvested for Rice and Estimated U.S. Methane Emissions from Flooded Rice Fields, 1985-1991

Item	1985	1986	1987	1988	1989	1990	1991
Area Harvested (Thousand Hectares)	1,009.3	955.8	944.9	1,174.5	1,088.2	1,143.3	1,123.9
Methane Emissions-Low Estimate (Thousand Metric Tons)	92.7	87.7	86.7	107.8	99.9	105.0	103.2
Methane Emissions-High Estimate (Thousand Metric Tons)	324.3	307.1	303.6	377.4	349.6	367.3	361.1

Source: Rice area harvested data from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* annual reports. Emissions calculations based on OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), p. 5-35.

[101]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 5-28 - 5-44.

[102]R.L. Sass et al., "Methane Production and Emission in a Texas Rice Field," *Global Biogeochemical Cycles* Vol. 4, No. 1 (March 1990), pp. 47-68.

[103]Based on 1992 acreage figures.

[104]E. Matthews et al., "Methane Emission from Rice Cultivation: Geographic and Seasonal Distribution of Cultivated areas and Emissions," *Global Biogeochemical Cycles*, Vol. 5, No. 1 (March 1991), p. 10.

4. Nitrous Oxide Emissions

Overview

Nitrous oxide (N_2O), commonly known as "laughing gas," is a potent greenhouse gas. It is different from nitrogen oxides (NO_x), which are unstable gases, formed mainly through reactions of atmospheric nitrogen and oxygen at the very high temperatures found inside the combustion chambers of engines. Nitrogen oxides, when they are emitted into the atmosphere, are very reactive and tend to leave the atmosphere quickly, and assist in the formation of ozone and other components of urban smog.

By contrast, nitrous oxide is a very stable gas with a long atmospheric lifetime. It is a potent greenhouse gas, with a global warming potential range from 170 to 260 times the effect of carbon dioxide. Concentrations of nitrous oxide in the atmosphere are increasing at a rate of 0.3 percent annually. Unfortunately, scientists are highly uncertain about the natural and anthropogenic mechanisms that create nitrous oxide in the atmosphere and those by which it is removed from the atmosphere.

What is known is that certain bacteria react with nitrogen in the soil to create natural fluxes of nitrous oxide. Thus, even in the absence of human activity there would be background levels of emissions of nitrous

oxide.[105] Scientists also know that putting nitrogen fertilizer on the soil greatly increases natural fluxes of nitrous oxide. However, the actual degree of additional emissions varies.

Nitrous oxide and nitrogen oxides are also created through a reaction that occur between nitrogen in the air and oxygen during the combustion of fossil fuels. The Environmental Protection Agency (EPA) has computed emissions coefficients for nitrous oxide for emissions from motor vehicles and from numerous stationary sources. Recent research indicates that sampling errors have caused overestimates of earlier emissions factors for nitrous oxide emissions from stationary sources.[106]

There are also a handful of possible industrial sources for nitrous oxide: minuscule amounts are produced for medical use, and larger volumes are released into the atmosphere as a byproduct of adipic acid production. (Adipic acid is an intermediate product in the manufacture of nylon.)

Table 35 presents EIA's point estimates for nitrous oxide emissions. Although the uncertainty for industrial and transportation emissions is comparable to those for similar methane-related activities, the uncertainty for

Table 35. Estimated U.S. Nitrous Oxide Emissions, 1985-1991
(Thousand Metric Tons of Nitrous Oxide)

Item	1985	1986	1987	1988	1989	1990	1991
Fertilizer Emissions (1991 Methodology, Median Estimate)	124	108	106	107	108	109	117
Adipic Acid Emissions	[a]51	54	56	57	53	55	57
Transport-Related Emissions	81	93	106	121	127	133	136
Stationary Combustion Emissions	47	49	48	49	46	46	44
Total Emissions	**303**	**304**	**316**	**334**	**334**	**343**	**354**

[a]1985 data unavailable, EIA estimate is an average of 1984 and 1986 data.
Source: Estimates presented in this chapter.

[105]See A. Mosier et al., "Methane and Nitrous Oxide Fluxes in Native, Fertilized, and Cultivated Grasslands," *Nature*, Vol. 350, No. 6316 (March 28, 1991), pp. 330-332.
[106]See the discussion in OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-41 and 2-42.

nitrous oxide emissions for fertilizer use is considerably larger: as much as one order of magnitude.

Total nitrous oxide emissions have increased steadily since 1985, primarily because of developments in the transportation sector. Growth in emissions from transport is a byproduct of the imposition of emission controls for criteria pollutants—nitrogen oxides, carbon monoxide, and nonmethane volatile organic compounds. Between 1983 and 1989, automobiles equipped with three-way catalytic converters emitted 9.2 times more nitrous oxide gas than did automobiles that entered service before 1977. Agricultural emissions declined steadily from 1985 to 1990, primarily because of reductions in the amount of land in cultivation. Emissions from fertilizer use are highly uncertain, as discussed in the next section of this chapter.

Nitrous Oxide Emissions from Nitrogen Fertilizer Use

Results

Table 36 presents estimates of nitrous oxide emissions from the use of nitrogenous fertilizer. EIA used two methods to compute these estimates: the first is based on the IPCC 1991 draft methodology, while the second is based on discussions of an IPCC working group held in 1992. The difference between the two methods reflects the inherent uncertainty of agricultural nitrous oxide emissions.

Nitrous oxide emissions occur when soil bacteria act on nitrogen compounds in the soil. Several scientific studies have shown that when nitrogenous fertilizers are added to the soil a surge of nitrous oxide emissions, which lasts several months, occurs.[107] The range of observed nitrous oxide emissions is large, however, and

actual nitrous oxide emissions are greatly affected by soil type, soil temperature, type of crop planted, type of fertilizer used, and other, yet more obscure, factors.

The 1991 Methodology

The 1991 IPCC emissions methodology was primarily based on a large number of scientific papers that showed significant variations in nitrous oxide emissions by fertilizer type. The fertilizer types included: anhydrous ammonia, aqua ammonia, nitrogen solution, ammonium nitrate, ammonium sulfate, urea, sodium nitrate and nitrate limestone mix.

Historical fertilizer consumption data—for the period 1980 to 1992—were used in conjunction with the calculated N_2O-N coefficients from the OECD/IPCC report.[108] Nitrogen content by fertilizer type was calculated on an annual basis by dividing nitrogen nutrient by type of fertilizer into nitrogen fertilizer type consumed annually. The annual historical data for fertilizer consumption and nitrogen content were drawn from the USDA Statistical Reporting Service and the Tennessee Valley Authority's *Commercial Fertilizer Reports* for the period 1981 to 1992.

For each fertilizer type, emissions of nitrous oxide were estimated by multiplying the nitrogen content of each fertilizer type by its corresponding emissions factor, summing over all types, and then converting the estimate to units of nitrous oxide. The emissions coefficients, the percentages of total fertilizer nitrogen that evolves as nitrous oxide, are each presented as a range and as the median of the range.

The 1993 Proposed Methodology

In 1993, an OECD/IPCC working group considered contributed papers which suggested that the method of using different emissions coefficients for different types

Table 36. U.S. Nitrous Oxide Emissions from Nitrogen Fertilizer, 1985-1991
(Thousand Metric Tons of Nitrous Oxide)

Item	1985	1986	1987	1988	1989	1990	1991
Low Estimate	59.6	51.8	51.3	51.6	52.0	52.1	56.1
Median Estimate	124.3	107.7	106.5	107.6	108.4	109.4	117.0
High Estimate	810.2	717.0	703.2	724.3	724.6	749.2	782.3

Sources: Estimates described in this chapter, based on nitrogenous fertilizer consumption from Tennessee Valley Authority, *Commercial Fertilizers* (various years), and U.S. Department of Agriculture, Crop Reporting Board, Statistical Reporting Service, *Commercial Fertilizers, Consumption for Years Ended June 30, 1981 - June 30, 1985.*

[107]M. Eichner, "Nitrous Oxide Emissions from Fertilized Soils: Summary of Available Data," *Journal of Environmental Quality,* Vol. 19 (1990), pp. 272-280.
[108]N_2O-N refers to nitrous oxide emissions, measured in tons of the nitrogen content of nitrous oxide.

of fertilizer was not adequately supported by the scientific literature.[109] Although researchers had found that emissions varied according to fertilizer types, the findings were not based on a consistent set of controlled experiments. Thus, there was no basis for determining whether the observed variations were caused by variations in fertilizer type or by some uncontrolled variable, such as soil type, weather, crop, or temperature. The authors ultimately decided that the most that they could say is that about 1 percent of the nitrogen put on the soil as fertilizer is eventually emitted into the atmosphere as nitrous oxide, and that their confidence interval was plus or minus an order of magnitude, or between 0.1 percent and 10 percent. This method is currently under review and, as of this writing, has not been accepted by the IPCC working group. The results of the proposed methodology would indicate a range of emissions from 14,000 to 1.4 million metric tons per year.

In reviewing the proposed methodology, it appears that the high range (10 percent) coefficient is excessive. When EIA calculated nitrous oxide emissions for nitrogen fertilizer for total world consumption for 1990, it was found that approximately 12.4 million metric tons of nitrogen would have been emitted using the "high" coefficient in the revised methodology. In comparing nitrous oxide emissions from total nitrogen fertilizer with the total world estimated sources of nitrous oxide, the "high" emissions estimate for world nitrogen fertilizer alone would represent approximately 77 percent of estimated total nitrous oxide sources.

Nitrous Oxide Emissions from Fossil Fuel Combustion

Transportation

Fuel combustion in motor vehicle engines, like other combustion processes, may produce small amounts of nitrous oxide through reactions with atmospheric nitrogen. Research also indicates that the catalytic converters installed to reduce vehicular emissions of ordinary pollutants may promote the formation of nitrous oxide. As catalytic converter-equipped vehicles have increased their share in the U.S. motor vehicle fleet, estimated emissions of nitrous oxide from this source have increased rapidly. This pattern is in sharp contrast to emissions of criteria pollutants, such as carbon monoxide, nitrogen oxides, and volatile organic compounds. Estimated emissions per vehicle of these pollutants have been sharply reduced as a result of the introduction of catalytic converters.

Motor Vehicles. EIA has used emissions coefficients from the 1991 OECD/IPCC report to estimate vehicular emissions of nitrous oxide.[110] These coefficients, which were provided by EPA for U.S. vehicles, are the same ones the agency uses to estimate vehicular emissions of criteria pollutants. The coefficients express nitrous oxide emissions for various vehicle types and model years in grams per mile traveled and in grams per kilogram of fuel consumed. There is some uncertainty about whether these coefficients truly represent the performance of the U.S. motor vehicle fleet, because they tend to be based on tests of properly maintained new cars and only include data from small samples of vehicles actually in service. The coefficients indicate that pre-1977 passenger cars emit 0.007 grams per kilometer of nitrous oxide, while 1983 to 1989 model year vehicles emit 0.063 grams per kilometer—a ninefold increase. Post-1990 vehicles are reported to emit less nitrous oxide: 0.041 grams per mile.

Automobiles typically remain in service for many years, thus conceptually, average U.S. automobile nitrous oxide emissions per vehicle mile traveled should have risen rapidly after 1977, and peaked in 1990 or 1991. Unit emissions should decline through the 1990s, as new vehicles replace 1980s vintage vehicles.

Estimating aggregate U.S. emissions of nitrous oxide from vehicular sources requires, in addition to emissions factors, an estimate of equipment use: i.e., miles traveled by vehicles of different types and model years. This information is not collected directly, but the U.S. Department of Transportation's Federal Highway Administration (FHWA) prepares annual estimates of vehicle miles traveled, categorized by type of vehicle (cars, trucks, buses, and motorcycles).[111] The FHWA obtains its data from State transportation offices, which in turn make their estimates through a variety of methods, principally by conducting traffic counts on selected roads.

[109]A.R. Mosier, *Nitrous Oxide Emissions from Agricultural Soils* (mimeo, February 1993); and A.R. Mosier and A.F. Bouwman, *Working Group Report: Nitrous Oxide Emissions from Agricultural Soils* (prepared for International Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control) (mimeo, 1993).

[110]See the discussion in OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-41 and 2-42.

[111]See Federal Highway Administration, *Highway Statistics 1988* (Washington, DC: U.S. Department of Transportation, 1990). This is an annual publication. Vehicle miles traveled are shown in Table VM-1 of the FHWA report.

Data on vehicle miles traveled or fuel consumed by vehicle model year are also not collected directly. EIA has conducted sample surveys of vehicle-owning households in 1983, 1985, 1988, and 1991,[112] and has used a custom database from the surveys to compute vehicle miles traveled for household-sector passenger cars and trucks by model year for 1983, 1985, 1988, and 1991 and to compute a weighted average emissions coefficient. The weighted average coefficient was then applied to non-household-sector passenger cars and light trucks (business-owned vehicles, fleets, rental cars, etc.). Table 37 shows the miles traveled data for those years and the computation of nitrous oxide emissions from the data. Emissions estimates for nonsurvey years were computed by interpolating emissions coefficients between the weighted average for survey years. Emissions for nonsurveyed vehicles (buses, motorcycles, and heavy trucks) were computed by multiplying FHWA vehicle miles traveled estimates by estimated weighted average coefficients for model years. Table 38 illustrates nitrous oxide emissions estimates by vehicle type for nonsurvey years.

Other Forms of Transportation. There are no nitrous oxide emissions factors for aircraft, although there are factors for other forms of transportation such as railroads, farm equipment, barges, and oceangoing ships, which are mostly diesel powered. The numbers are very small (i.e., less than 10,000 metric tons).

Stationary Sources

Nitrous oxide is produced during stationary source combustion of fossil fuels. Until recently, flask samples taken from combustion experiments led researchers to believe that combustion activities represented a major anthropogenic source of nitrous oxide emissions. Studies indicated that nitrous oxide emissions were related both to NO_x emissions and to the nitrogen content of the fuel. A recent discovery of a possible sampling error, which produced nitrous oxide in the flask between the time the sample was taken and the time the flask was analyzed, has brought the accuracy of these experiments into question. Researchers now believe that combustion activities may be a relatively

Table 37. U.S. Passenger Car and Light Truck Vehicle Miles Traveled, Emissions Coefficients, and Nitrous Oxide Emissions, 1983, 1985, 1988, and 1991

Model Year	N_2O Coefficient (g/km)	1983 VMT	1983 N_2O	1985 VMT	1985 N_2O	1988 VMT	1988 N_2O	1991 VMT	1991 N_2O
Automobiles									
1977 and earlier	0.005	441.1	3.6	341.8	2.8	174.4	1.4	P 99.2	0.8
1978-1982	0.027	469.4	20.4	431.9	18.8	329.7	14.3	P 201.3	8.8
1983-1989	0.046	57.1	4.2	281.7	20.9	629.7	46.6	P 707.6	52.4
1990-1992	0.019	0.0	0.0	0.0	0.0	0.0	0.0	P 142.3	4.4
Other	0.005	5.0	0.0	3.8	0.0	0.0	0.0	P 0.0	0.0
Total		972.6	28.2	1,059.1	42.5	1,133.7	62.4	1,150.4	66.3
Other Passenger Vehicles		225.4	6.6	201.5	8.1	295.6	16.3	P 383.3	22.1
Total Passenger		1,198.0	34.9	1,260.6	50.6	1,429.3	78.6	1,533.7	88.4
Light Duty Trucks									
1977 and earlier	0.006	130.7	1.3	102.1	1.0	78.6	0.8	P 57.3	0.6
1978-1982	0.031	100.3	5.0	98.4	4.9	84.2	4.2	P 56.0	2.8
1983-1989	0.063	12.5	1.3	90.8	9.2	214.9	21.8	P 271.3	27.5
1990-1992	0.024	0.0	0.0	0.0	0.0	0.0	0.0	P 67.4	2.6
Other	0.006	2.6	0.1	2.6	0.1	0.0	0.0	P 0.0	0.0
Total		246.2	7.6	293.8	15.2	377.6	26.8	452.0	33.5
Other Light Trucks		81.4	2.5	79.3	4.1	61.8	4.4	P 20.9	1.5
Total Light Trucks		327.6	10.1	373.1	19.4	439.4	31.1	472.9	35.0

P = preliminary data. VMT = vehicle miles traveled in billions of miles. N_2O = nitrous oxide emissions in thousand metric tons.

Sources: Vehicle miles traveled by model year from the Energy Information Administration's Residential Transportation Energy Consumption database, custom database sort dated June 2, 1993. Total vehicle miles traveled from U.S. Department of Transportation, *Highway Statistics* (various years). Emissions coefficients by model year from OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-56 and 2-57.

[112]See Energy Information Administration, *RTECS: Consumption Patterns of Household Vehicles 1983, RTECS: Consumption Patterns of Household Vehicles 1985,* and *Household Vehicles Energy Consumption 1988* (Washington, DC, 1985, 1987, 1990). Information on the 1991 survey will be published in October 1993.

Table 38. Estimated U.S. Vehicular Nitrous Oxide Emissions, 1985-1991
(Thousand Metric Tons of Nitrous Oxide)

Item	1985	1986	1987	1988	1989	1990	1991
Motor Vehicles							
Passenger Cars	51	59	68	79	83	86	88
Buses	0	0	0	0	0	0	0
Motorcycles	0	0	0	0	0	0	0
Light Duty Trucks	19	23	27	31	33	34	35
Other Trucks	6	6	6	6	6	6	6
Total	76	88	101	116	122	127	130
Other Transport	5	[a]5	5	5	5	6	[a]6
Total Transport	81	93	106	121	127	133	136

[a]EIA interpolation based on prior and subsequent year's data. Actual value not available.

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 OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-57 and 2-58 (for passenger cars and light trucks in 1983, 1985, 1988 and 1991, see Table XIX). Distribution for passenger cars and light duty trucks in other years computed by interpolation. Distribution for bus and other truck fleet according to model year computed assuming 10-percent attrition of pre-1983 fleet for each year after 1984. "Other Transportation" calculated using fuel consumption data from S. Davis and M. Moore, *Transportation Energy Data Book*, ORNL-6710 (Oak Ridge, TN: Oak Ridge National Laboratory, March 1992), Edition 12, and prior issues.

minor source of nitrous oxide emissions, but this is by no means certain.[113] Thus, unknown factors in the process by which nitrous oxide is formed from stationary combustion sources make calculations of emissions uncertain.

EIA has employed the coefficients recommended by OECD to calculate nitrous oxide emissions from stationary sources. The IPCC believes that these coefficients are not affected by the sampling error.[114] These factors

were applied to energy consumption data taken from EIA's *State Energy Data Report*. Table 39 contains the results of these computations.

Nitrous Oxide Emissions from Adipic Acid Production

Adipic acid is a common industrial chemical with a number of uses, the most important of which is as an

Table 39. U.S. Nitrous Oxide Emissions from Stationary Combustion Sources, 1985-1991
(Thousand Metric Tons of Nitrous Oxide)

Source	1985	1986	1987	1988	1989	1990	1991
Commercial Sector							
Coal	6.69	6.68	6.20	6.38	5.47	5.80	5.27
Fuel Oil	21.53	24.10	22.73	22.46	20.17	19.52	18.45
Natural Gas	6.34	6.04	6.33	6.95	7.09	6.84	7.12
Total	34.57	36.81	35.26	35.80	32.74	32.15	30.84
Electric Utility (Coal)	12.32	12.18	12.77	13.42	13.51	13.59	13.53
Total All Fuels	46.89	48.99	48.03	49.22	46.25	45.74	44.37

Note: Columns may not add to totals due to independent rounding.

Sources: Emissions coefficients from OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-33 and 2-35. Energy consumption data from Energy Information Administration, *State Energy Data Report: Consumption Estimates 1960-1991*, DOE/EIA-0214(91) (Washington, DC, May 1993).

[113]See the discussion in OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-41 and 2-42.

[114]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 2-25 - 2-48.

intermediate product in the production of nylon. A 1991 article in *Science* suggests that the production of adipic acid may be an important source of nitrous oxide emissions.[115] The nature of the chemical reaction involved and laboratory studies suggest that about 1 mole of nitrous oxide is emitted for each mole of adipic acid produced. This is equivalent to about 0.3 grams of nitrous oxide per gram of adipic acid.

Monsanto, Du Pont, and Allied Chemical are the sole producers of adipic acid in the United States: all of their adipic acid production occurs in four plants.[116] Operators of the two plants that account for about 75 percent of capacity report that they currently destroy nitrous oxides before they can be emitted into the atmosphere. Of the remaining two plants, one (accounting for 22 percent of capacity) emits nitrous oxide into the atmosphere; the other, which accounts for 3 percent of capacity, did not provide information.[117] Table 40 lists estimated nitrous oxide emissions from adipic acid production.

Several uncertainties surround estimates of nitrous oxide emissions from adipic acid production:

- Although annual production levels of adipic acid in the United States are reported in trade journals, there is no authoritative, official source of production information. Thus, there is a degree of uncertainty about actual production.

- The coefficient used for calculating these emissions is based on laboratory studies and may differ for actual industrial processes.

- Both the share of production controlled and the actual level of control are uncertain.

Nitrous Oxide Emissions from Nitric Acid Production

A recent report by the Radian Corporation suggests that manufacture of nitric acid may cause emissions of

Table 40. Estimates of U.S. Adipic Acid Production and Nitrous Oxide Emissions from Adipic Acid, 1985-1991

Item	1985[a]	1986	1987	1988	1989	1990	1991
Adipic Acid Production (Thousand Metric Tons)	658	689	712	726	744	735	771
Share of Production Without Emissions Controls (Percent)	23	22	22	22	23	23	23
Emissions from Controlled Share (Thousand Metric Tons)	1	2	2	2	2	2	2
Emissions from Uncontrolled Share (Thousand Metric Tons)	50	53	54	55	52	53	55
Total Emissions (Thousand Metric Tons)	**51**	**54**	**56**	**57**	**53**	**55**	**57**

[a]1985 production data unavailable. EIA estimate made by interpolating between 1984 and 1986 production data.

Sources: Adipic acid production and plant capacity for 1985-1986 from Mannsville Chemical Products Corp., "Adipic Acid," in *Chemical Products Synopsis* (New Jersey, June 1990). Production for 1987 from "Growth Maintains a Strong Pace," *Chemical & Engineering News* (June 19, 1989), p. 39. Production for 1988-1989 from M. Reisch, "Top 50 Chemicals Production Resumed Growth Last Year," *Chemical & Engineering News* (April 8, 1991), p. 14. Production for 1990-1991 from M. Reisch, "Top 50 Chemicals Production Stagnated Last Year," *Chemical & Engineering News* (April 13, 1992), p. 16. Uncontrolled emissions assumed to be 0.3 grams nitrous oxide per gram of adipic acid, based on M. Thiemens and W. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251 (February 22, 1991), p. 933. Emissions controls assumed to be 99 percent effective, per telephone conversation with Monsanto.

[115]M. Thiemens and W. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251 (February 22, 1991), p. 932.

[116]Mannsville Chemical Products Corp., "Adipic Acid," in *Chemical Products Synopsis* (New Jersey, June 1990).

[117]ICF Inc., Memorandum of May 18, 1993, reporting telephone conversations with officials of Monsanto, Du Pont, and Allied Chemical.

nitrous oxide.[118] Nitric acid (HNO_3) is an inorganic compound used primarily to make ammonium nitrate fertilizer (65 percent), ammonium nitrate explosives (15 percent), aniline, and adipic acid (20 percent).[119]

The DuPont Company recently estimated U.S. nitrous oxide emissions from nitric acid manufacture at about 40,000 metric tons per year. These estimates were reported to the White House Conference on Global Climate Change, Methane and Other Gases Workshop.[120] In 1991, approximately 7.2 million metric tons of nitric acid were produced.[121] However, in the absence of more specific information about manufacturing processes and possible emissions controls, EIA is not able to present estimates of emissions from this source.

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[118]Radian Corporation, *Nitrous Oxide Emissions from Adipic Acid Manufacturing*, Final Report prepared for the U.S. Environmental Protection Agency, Office of Research and Development (Research Triangle Park, NC, January 1992), p. 15.

[119]Personal communication with Kevin Swift, Senior Economist, Chemical Manufacturers Association, Washington, DC, August 30, 1993.

[120]W.R. Stevens, III, *Abatement of Nitrous Oxide Emissions Produced in the Adipic Acid Industry* (prepared for White House Conference on Global Climate Change, Methane and Other Gases Workshop, June 11, 1993) (mimeo, The DuPont Company, Wilmington, DE).

[121]U.S. Department of Commerce, Bureau of the Census, *Current Industrial Reports: Annual Report on Fertilizer Materials*, MA28B (Washington, DC, 1992), Table 7.

5. Chlorofluorocarbons and Related Compounds

Chlorofluorocarbons

Worldwide sales of chlorofluorocarbons (CFCs) decreased by 24 percent from their peak of 1.28 million metric tons in 1988 to 872,000 metric tons in 1990. Sales of CFC-11, accounting for more than one-quarter of all CFC sales in 1990, dropped by 38 percent during the same period, from 376,000 metric tons to 233,000 metric tons. Sales of CFC-12, which represented one-third of all CFC sales in 1988, decreased by more than 45 percent, to 231,000 metric tons in 1990 (Table 41).

These reductions are the direct consequence of an international agreement, the Montreal Protocol on Substances that Deplete the Ozone Layer (1987). The Montreal Protocol called for a 50-percent reduction in use of CFCs compared to 1986 levels by 1992. The subsequent London Agreement called for complete elimination of the use of CFCs by 2000. The Copenhagen Agreement (not yet ratified) would accelerate the complete phaseout of CFCs to January 1, 1996.

The United States ratified the Montreal Protocol in January 1989. The motivation behind this international agreement was mounting scientific evidence linking the use of CFCs to the depletion of stratospheric ozone, which serves as a filter for the ultraviolet radiation that, in excessive amounts, may promote cancer and cataracts in humans and may damage a wide variety of flora and fauna.[122]

Although the data are unavailable, it is likely that U.S. sales of CFCs, like worldwide sales, were increasing through 1988, with all reductions in consumption occurring after the Montreal Protocol was ratified in 1989. U.S. sales of CFC-12, used as a refrigerant in automobile air conditioning, increased from 135,000 metric tons in 1985 to 143,000 metric tons in 1986 (Table 42).

Until recently, atmospheric concentrations of CFCs had been increasing at an annual rate of between 4 percent and 11 percent, depending on the specific compound.[123] As the production and use of CFCs are phased out pursuant to the Montreal Protocol, the rate of growth should slow. A recent report indicates that the growth rate of emissions of CFC-11 and CFC-12 has declined to 1 to 2 percent per year since 1988.[124] CFCs, however, have atmospheric lifetimes estimated to be between 75 and 380 years. Even when production of CFCs ceases, there will be a large inventory of the compounds trapped in insulation and used in cooling systems that will be emitted gradually over a period of

Table 41. World Chlorofluorocarbon Sales, 1985-1991
(Million Metric Tons)

CFC Compound	1985	1986	1987	1988	1989	1990	1991
CFC-11	0.327	0.350	0.382	0.376	0.302	0.233	0.213
CFC-12	0.376	0.398	0.425	0.421	0.380	0.231	0.225
CFC-113	0.187	0.197	0.226	0.247	0.251	0.175	0.148
CFC-114	0.017	0.019	0.017	0.016	0.015	0.008	0.007
CFC-115	0.010	0.012	0.013	0.014	0.014	0.011	0.012
HCFC-22	0.153	0.165	0.173	0.204	0.220	0.214	0.237
Total	1.070	1.141	1.236	1.278	1.182	0.872	0.842

Source: Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales, and Atmospheric Release of CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, and HCFC-22 Through 1991* (mimeo, September 1992).

[122]Energy Information Administration, *Potential Costs of Restricting Chlorofluorocarbon Use*, SR/ED/89-01 (Washington, DC, August 1989), p. 1.

[123]U.S. Environmental Protection Agency, Office of Policy Planning and Evaluation, *Policy Options for Stabilizing Global Climate*, Draft Report to Congress (Washington, DC, February 1989), p. IV-34.

[124]J.W. Elkins et al., "Decrease in Growth Rates of Atmospheric Chlorofluorocarbons 11 and 12," *Nature*, Vol. 364 (26 August 1993), p. 782.

Table 42. U.S. Chlorofluorocarbon and Halon Sales and Emissions for Selected Years
(Million Metric Tons)

Compound	Sales					1990 Emissions
	1985	Percent of Reported World Sales	1986	Percent of Reported World Sales		
CFC-11	0.075	23	0.090	26		0.056
CFC-12	0.135	36	0.143	36		0.113
CFC-113	0.073	39	0.078	40		0.053
CFC-114	NA	NA	0.004	21		0.005
CFC-115	NA	NA	0.010	83		0.003
Halon 1211	0.003	NA	0.003	NA		0.001
Halon 1301	0.005	NA	0.005	NA		0.002
Total	NA	NA	0.333	NA		0.233

NA = not available.

Sources: World sales figures from the Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of CFC-113, CFC-114, CFC-115, CFC-11, and CFC-12 Through 1991* (mimeo, September 1992). 1985 U.S. sales figures from U.S. Environmental Protection Agency, *Policy Options for Stabilizing Global Climate*, Draft Report to Congress (Washington, DC, February 1989). 1986 U.S. sales figures from U.S. Environmental Protection Agency, *Federal Register*, Vol. 53, No. 156 (August 12, 1988), p. 30599; and Putnam, Hayes and Bartlett, Inc. 1990 U.S. emissions figures from U.S. Environmental Protection Agency, *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990*, Review Draft (Washington, DC, June 21, 1993).

many years. Thus, CFC concentrations may continue to rise for some years after production ceases.

Efforts to curb the use of CFCs, originally implemented to protect stratospheric ozone, have important implications for global climate. CFCs are powerful greenhouse gases, with global warming potentials estimated to be larger than that of carbon dioxide by several orders of magnitude. However, because CFCs destroy ozone and stratospheric ozone is also a greenhouse gas, there is a countervailing effect of CFCs that may be equal to or larger than their direct radiative forcing effect. The net climate impact of these two forces is beyond current scientific understanding.

All signatories of the Montreal Protocol are required to report production and consumption of the eight CFCs controlled under the agreement to the United Nations Environmental Program (UNEP). In addition, the Chemical Manufacturers Association (CMA) collects production and sales data on CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, and HCFC-22 from most of the CFC-producing companies in the industrialized world. The four U.S. producers reporting to CMA are Allied Signal, Ausimont USA, E.I. du Pont de Nemours, and Elf Atochem North America.[125] While both the CMA

and UNEP provide aggregated world data, country-specific data are held in confidence to protect the proprietary interests of companies in nations that have a limited number of producers. EPA has published sales data for the United States for 1985 and 1986 (Table 42).

Emissions of CFCs usually are not a direct consequence of their consumption. Rather, they occur gradually over time through leakage, servicing, and disposal of materials and equipment in which CFCs are used. Because of this time lag, emissions are likely to be lower than consumption when CFC inventories are increasing (as they were during the 1980s) and greater than consumption as production and sales are phased out.

The precise timetable of emissions is a function of the end use in which a CFC is applied. For example, CFC emissions from home refrigerators come primarily from disposal, which may take place decades after production. In contrast, emissions from automobile air conditioners are predominantly due to servicing requirements, which arise in the near term.[126]

Using a model that incorporates release tables by end use, the EPA developed estimates of U.S. CFC emis-

[125]AFEAS, *Production, Sales and Atmospheric Release of CFC-11 and CFC-12 Through 1991*, Schedules 7 and 8 (Washington, DC, September 1992).

[126]Energy Information Administration, *Potential Costs of Restricting Chlorofluorocarbon Use*, SR/ED/89-01 (Washington, DC, August 1989), p. 43.

sions for 1990. A summary of those estimates is shown in Table 42.[127]

Related Compounds

A large body of man-made chlorocarbons and related compounds are not addressed in detail in this report, because their effects on global climate are either limited or unknown. Most prominent among these are HCFC-22, methyl chloroform, and carbon tetrachloride. These compounds differ from CFCs in that they contain no fluorine. However, like CFCs, they pose a threat to stratospheric ozone and are regulated by the EPA.[128]

HCFC-22 is the most commonly used of a class of compounds known as hydrochlorofluorocarbons, or HCFCs. HCFCs are less stable than CFCs, and are more prone to decay in the troposphere.[129] HCFCs thus have much shorter atmospheric lives than CFCs, and hence, less impact on stratospheric ozone and global warming. Worldwide production of HCFC-22 was 236,000 metric tons in 1991.[130] The EPA has estimated U.S. emissions of HCFC-22 at 82,000 metric tons in 1990.[131] HCFC-22 is commonly used as a refrigerant, and it is likely to be an important near-term replacement for CFCs in many applications. HCFC-22 has an atmospheric concentration of about 0.11 parts per billion, and, as of 1989, concentrations were increasing at a rate of 4 to 5 percent per year.[132]

Methyl chloroform is used extensively as a cleaning solvent. U.S. production was 364,000 metric tons in 1990.[133] The EPA estimates that emissions of methyl chloroform were in excess of 300,000 metric tons in 1990.[134] Atmospheric concentrations of methyl chloroform have been growing by about 5 percent annually.[135] However, relative to other CFCs this compound is of lesser importance as a greenhouse gas because of its lower Global Warming Potential (GWP) and short atmospheric lifetime of 6 to 7 years.[136]

Carbon tetrachloride has a much higher GWP and a longer atmospheric lifetime than methyl chloroform. Because of its toxicity, it is used in the United States primarily as a feedstock in the production of CFC-11 and CFC-12.[137] This production process destroys most of the carbon tetrachloride, leaving emissions of only 30,000 metric tons in 1990.[138] This low rate of emissions reduces the importance of this compound as a greenhouse gas.

Carbon tetrafluorine (CF_4) and CFC-116 (C_2F_6) may have the greatest consequences on radiative forcing on a per-molecule basis of any of the CFC-related compounds. Sources of these compounds are not well understood, although it is known that they are emitted as byproducts of aluminum production. Estimates of their atmospheric lifetimes exceed 10,000 years, and their GWPs are estimated to be greater than those of both CFC-11 and CFC-12.[139]

[127]U.S. Environmental Protection Agency, *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990*, Review Draft (Washington, DC, June 21, 1993), p. 25.

[128]U.S. Environmental Protection Agency, Office of Policy Planning and Evaluation, *Policy Options for Stabilizing Global Climate*, Draft Report to Congress (Washington, DC, February 1989), p. IV-33.

[129]Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), p. 56.

[130]AFEAS, *Production, Sales and Atmospheric Release of HCFC-22 Through 1991*, (Washington, DC: September 1992), p. 7.

[131]U.S. Environmental Protection Agency, *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990*, Review Draft (Washington, DC, June 21, 1993), p. 25.

[132]Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), p. 38.

[133]Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1992* (Washington, DC, 1992), p. 48.

[134]U.S. Environmental Protection Agency, *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990*, Review Draft (Washington, DC, June 21, 1993), p. 25.

[135]Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), p. 38.

[136]D. Wuebbles and J.A. Edmonds, *Primer on Greenhouse Gases* (Chelsea, MI: Lewis Publisher, Inc., 1991), pp. 48 and 155.

[137]U.S. Environmental Protection Agency, Office of Policy Planning and Evaluation, *Policy Options for Stabilizing Global Climate*, Draft Report to Congress (Washington, DC, February 1989), p. IV-35.

[138]U.S. Environmental Protection Agency, *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990*, Review Draft (Washington, DC, June 21, 1993), p. 25.

[139]D. Abrahamson, "Aluminum and Global Warming," *Nature*, Vol. 356 (April 1992), p. 454.

6. Criteria Pollutants

Overview

Carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds (NMVOCs), commonly referred to as "criteria pollutants" because they are regulated under the 1970 Clean Air Act and successive amendments, also have an impact on global climate. The regulation of these pollutants has been effective, particularly in the cases of carbon monoxide and NMVOCs. Carbon monoxide emissions have decreased by approximately 25 percent, from 83 million metric tons in 1985 to 62 million metric tons in 1991, and emissions of NMVOCs have decreased from 19.8 million metric tons in 1985 to 16.9 million metric tons in 1991. Emissions of nitrogen oxides have remained stable during the same period.

The criteria pollutants have limited direct radiative effects on global climate. Instead, their effects are indirect, caused by their reaction with other chemical compounds. The most important of the indirect effects is their role as tropospheric ozone precursors, since tropospheric ozone is itself a greenhouse gas that may increase radiative forcing and alter the atmospheric lifetimes of other greenhouse gases. This report does not provide detailed estimates of tropospheric ozone emissions or concentrations, because tropospheric ozone is the result of complex chemical interactions rather than direct anthropogenic emissions.

It is impossible to discern a trend in tropospheric ozone concentrations using current methods. Large volumes of tropospheric ozone tend to form in and downwind of large urban areas.[140] The EPA monitors ozone levels in urban areas to gauge compliance with the National Ambient Air Quality Standards (NAAQS). EPA assesses ozone trends on the basis of the second-highest daily maximum 1-hour concentration during a given year. Because local levels of ozone are highly sensitive to meteorological variability (i.e., changes in sunlight, rainfall, wind, etc.), the available data are unreliable and cannot be generalized beyond the local

airshed. The urban "heat island" effect, which warms metropolitan areas compared to the surrounding countryside, also promotes local ozone formation.

The EPA has reported downward trends in nationwide average ozone concentrations, based on the method described above; however, it is difficult to be certain that this is the case. In 1987, there were 60 areas that did not meet the NAAQS for ozone, but by 1990 the number had risen to 98. Also, recent scientific evidence suggests that, among the criteria pollutants, nitrogen oxides play the most important role as ozone precursors, and emissions of nitrogen oxides have remained stable between 1985 and 1991.[141]

Carbon Monoxide

Although carbon monoxide absorbs a minimal amount of infrared radiation, it does not have a significant direct effect on climate. Carbon monoxide does, however, react with the hydroxyl radical (OH), which is an important chemical scavenger of many trace gases—most notably methane. Hydroxyl is a major vehicle for carbon monoxide oxidation. As carbon monoxide levels rise, less hydroxyl is available to oxidize methane, and methane concentrations increase.

Carbon monoxide also contributes to global warming as a precursor to tropospheric ozone. In the presence of high nitrogen oxide (NO_x) concentrations, carbon monoxide assists in the creation of ozone in the troposphere. In addition, carbon monoxide is ultimately oxidized to carbon dioxide, thus adding to the global carbon dioxide level. Because of the relatively high efficiency of most fossil fuel combustion processes, however, the contribution of carbon monoxide to carbon dioxide levels is small.[142] U.S. emissions of carbon monoxide in 1991 totalled 62 million metric tons, which represents a decline of roughly 25 percent from 1985 levels (Table 43).

[140]National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution* (Washington, DC: National Academy Press, 1991), pp. 1-29.

[141]National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution* (Washington, DC: National Academy Press, 1991), pp. 1-29.

[142]U.S. Department of Energy, Office of Environmental Analysis, *Limiting Net Greenhouse Gas Emissions in the United States, Volume II*, DOE/PE-0101 (Washington, DC, September 1991), p. 1.13.

Table 43. U.S. Carbon Monoxide Emissions, 1985-1991
(Million Metric Tons)

Source	1985	1986	1987	1988	1989	1990	1991
Transportation							
Highway Vehicles	56.31	51.58	49.01	46.34	42.06	41.32	36.11
Aircraft	1.09	1.08	1.06	1.05	1.07	1.08	1.06
Railroads	0.19	0.18	0.19	0.19	0.19	0.19	0.16
Vessels	1.40	1.50	1.56	1.62	1.66	1.72	1.72
Other Off-Highway	4.53	4.37	4.42	4.25	4.32	4.17	4.44
Total	63.52	58.71	56.24	53.45	49.30	48.48	43.49
Stationary Source Fuel Combustion							
Electric Utilities	0.29	0.28	0.30	0.31	0.32	0.31	0.31
Industrial	0.61	0.60	0.64	0.65	0.66	0.65	0.66
Commercial-Institutional	0.05	0.05	0.05	0.06	0.05	0.05	0.05
Residential	5.34	5.34	5.36	5.25	5.37	3.29	3.66
Total	6.29	6.27	6.34	6.27	6.40	4.30	4.68
Total Energy-Related Emissions	69.81	64.93	62.38	59.72	55.70	52.78	48.17
Industrial Processes	4.38	4.20	4.33	4.60	4.58	4.64	4.69
Solid Waste Disposal							
Incineration	0.99	0.86	0.86	0.86	0.85	0.84	0.89
Open Burning	0.86	0.84	0.84	0.84	0.84	0.86	1.17
Total	1.85	1.70	1.70	1.70	1.70	1.70	2.06
Miscellaneous							
Forest Fires	6.48	4.54	5.83	8.93	5.76	8.06	6.62
Other Burning	0.61	0.60	0.61	0.59	0.58	0.56	0.55
Total	7.09	5.15	6.44	9.51	6.34	8.62	7.18
Total All Sources	83.12	76.03	75.05	75.53	68.32	67.74	62.10
Carbon Content of Carbon Monoxide	35.62	32.58	32.16	32.37	29.28	29.03	26.61
Carbon Content of Energy-Related Carbon Monoxide	29.92	27.85	26.82	25.59	23.87	22.62	20.64

Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Estimates, 1900-1991*, EPA-454/R-92-013 (Research Triangle Park, NC, October 1992), Table B-1, p. 102.

Nitrogen Oxides

The oxides of nitrogen (NO and NO_2, referred to as NO_x) are radiatively interactive gases. In current concentrations they do not make a significant direct contribution to global warming. NO_x does, however, affect greenhouse warming through its effects on the reaction pathway for methane oxidation and is also an active catalyst in the oxidizing reactions that form tropospheric ozone. Increases in NO_x levels are expected to result in increased levels of ozone in the troposphere.[143] Like carbon monoxide, the bulk of NO_x emissions in the United States come from transpor-

tation sources. In 1991, EIA estimates that the United States emitted roughly 19 million metric tons of nitrogen oxides (Table 44).

Nonmethane Volatile Organic Compounds

As with the other criteria pollutants, nonmethane volatile organic compounds (NMVOCs) contribute to greenhouse warming as tropospheric ozone precursors. When NO_x concentrations are relatively high, increases

[143]Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment* (Cambridge University Press, 1992), p. 40.

Table 44. U.S. Nitrogen Oxide Emissions, 1985-1991
(Million Metric Tons)

Source	1985	1986	1987	1988	1989	1990	1991
Transportation							
Highway Vehicles	7.27	6.57	6.26	6.21	5.87	5.88	5.38
Aircraft	0.13	0.14	0.13	0.13	0.13	0.13	0.13
Railroads	0.54	0.52	0.53	0.55	0.55	0.54	0.46
Vessels	0.19	0.20	0.21	0.22	0.23	0.22	0.23
Other Off-Highway	1.03	1.06	1.00	1.09	1.08	1.06	1.06
Total	9.15	8.49	8.14	8.19	7.85	7.83	7.26
Stationary Source Fuel Combustion							
Electric Utilities	5.99	6.22	6.42	6.78	6.86	6.78	6.71
Industrial	2.81	2.75	3.04	3.09	3.13	3.32	3.33
Commercial-Institutional	0.22	0.22	0.23	0.25	0.23	0.22	0.21
Residential	0.36	0.36	0.36	0.40	0.37	0.31	0.33
Total	9.38	9.55	10.05	10.52	10.59	10.63	10.59
Total Energy-Related Emissions	18.53	18.04	18.19	18.71	18.44	18.46	17.85
Industrial Processes	0.56	0.56	0.56	0.58	0.59	0.59	0.60
Solid Waste Disposal							
Incineration	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Open Burning	0.06	0.06	0.06	0.06	0.06	0.06	0.08
Total	0.08	0.08	0.08	0.08	0.08	0.08	0.10
Miscellaneous							
Forest Fires	0.20	0.14	0.18	0.27	0.18	0.24	0.20
Other Burning	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	0.21	0.16	0.19	0.28	0.19	0.26	0.21
Total All Sources	19.39	18.83	19.03	19.65	19.29	19.38	18.76

Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Estimates 1900-1991*, EPA-454/R-92-013 (Research Triangle Park, NC, October 1992), Table B-3, p. 104.

in NMVOC levels lead to significant corresponding elevations of ozone in the troposphere. Increases in NMVOC emissions may also result in reduced hydroxyl concentrations. According to EPA, in 1991, U.S. emissions of NMVOCs totalled nearly 17 million metric tons (Table 45).[144]

[144]U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Estimates 1900-1991*, EPA-454/R-92-013 (Washington, DC, October 1992), Table B-7.

Table 45. U.S. Nonmethane Volatile Organic Compound Emissions, 1985-1991
(Million Metric Tons)

Source	1985	1986	1987	1988	1989	1990	1991
Transportation							
Highway Vehicles	6.26	5.64	5.34	4.98	4.18	4.27	3.82
Aircraft	0.19	0.19	0.19	0.19	0.19	0.19	0.18
Railroads	0.13	0.13	0.13	0.13	0.13	0.13	0.11
Vessels	0.41	0.45	0.47	0.48	0.49	0.51	0.51
Other Off-Highway	0.48	0.47	0.47	0.47	0.46	0.45	0.46
Total	7.47	6.88	6.59	6.26	5.45	5.54	5.08
Stationary Source Fuel Combustion							
Electric Utilities	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Industrial	0.13	0.13	0.14	0.14	0.14	0.13	0.13
Commercial-Institutional	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Residential	0.72	0.72	0.73	0.71	0.73	0.45	0.50
Total	0.90	0.89	0.90	0.89	0.91	0.62	0.67
Total Energy-Related Emissions	8.37	7.77	7.49	7.15	6.36	6.16	5.75
Industrial Processes	8.35	7.92	8.17	8.00	7.97	8.02	7.86
Solid Waste Disposal							
Incineration	0.30	0.28	0.28	0.28	0.28	0.28	0.28
Open Burning	0.30	0.30	0.30	0.30	0.30	0.30	0.41
Total	0.60	0.58	0.58	0.58	0.58	0.58	0.69
Miscellaneous							
Forest Fires	0.87	0.60	0.78	1.20	0.77	1.09	0.89
Other Burning	0.09	0.09	0.09	0.09	0.09	0.08	0.08
Miscellaneous Organic Solvent	1.53	1.49	1.53	1.59	1.59	1.65	1.61
Total	2.49	2.19	2.40	2.88	2.44	2.82	2.59
Total All Sources	19.80	18.45	18.64	18.61	17.35	17.58	16.88
Estimated Carbon Content of Energy-Related NMVOC's	6.95	6.45	6.22	5.93	5.28	5.11	4.77

Notes: Assumes a carbon coefficient of 0.83 metric tons of carbon per metric ton of NMVOC. 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 Estimates 1900-1991*, EPA-454/R-92-013 (Research Triangle Park, NC, October 1992), Table B-7, p. 108.

7. Land Use Issues

As discussed in Chapter 1, natural sources and sinks tend to provide larger volumes of greenhouse gases than man-made sources. These natural sources, however, are often grounded in particular types of natural ecosystems. When humans modify natural ecosystems by reclaiming swamps, clearing land for agriculture, or logging forests, their actions have consequences for emissions and sinks of greenhouse gases.

Some of the ways in which human activities have modified or transformed natural sources and sinks of greenhouse gases, together with estimates of the magnitude of these changes in the United States during the 1980s are considered in this chapter.

Estimates of emissions and sinks of greenhouse gases from land use changes are the most uncertain areas in emissions inventories. Data on land use changes in the United States are very general; moreover, emissions factors are derived from a small number of studies that were often conducted for other, very different, purposes than emissions estimates. Thus, the calculations in this chapter can only be considered very rough, "order of magnitude" estimates of emissions and sinks that can be illustrated through more detailed and careful study.

Finally, there are significant conceptual problems in attributing emissions and sinks of greenhouse gases to changes in land use in particular years, because a change in land use will produce changes in natural emissions patterns over a prolonged period of time.

Carbon Sequestration in Forests and Soils

Every green plant is, in effect, a solar-powered factory that extracts carbon dioxide from the atmosphere, separates the carbon atom from the oxygen atoms, returns oxygen to the atmosphere, and uses the carbon to make biomass in the form of roots, stems, and leaves. Thus, the most important natural process is photosynthesis.

Dead vegetation may accumulate as soil, sequestering additional mineral carbon in the ground.

Even without the gradual sequestration of carbon in the soil, the current inventory of biomass in the form of forests and natural vegetation contains enormous amounts of carbon. A recent study conducted by Richard Birdsey of the U.S. Forest Service, estimated that U.S. forest ecosystems contained 52.5 billion metric tons of carbon in 1987[145]—the equivalent of nearly 40 years of U.S. carbon emissions from fossil fuel consumption.

Forests grow, and as they grow, they absorb carbon from the atmosphere and incorporate it into biomass and soils. Birdsey estimated that U.S. forests absorbed 460 million metric tons of carbon in 1987—equivalent of an annual growth rate in sequestered carbon of 0.8 percent. After subtracting carbon lost through logging, burning, and land clearing (355 million metric tons), forests absorbed a net 106 million metric tons of carbon, which is equivalent to about 8 percent of energy-related carbon emissions. A later estimate, made in a report recently completed by the EPA, estimated net absorption from forested areas in the coterminous United States at 114 million metric tons for the year 1990.[146] This report also estimated total carbon storage in U.S. forestland at 38.5 billion metric tons, which illustrates some of the uncertainties associated with calculations of this sort.

While trees on existing acreage continue to absorb carbon, the acreage planted in forests can also expand or contract. Farm and pastureland can be converted to forestland, and forestland can be cleared and converted for other uses. Clearing forestland sets the stage for large-scale losses of carbon to the atmosphere, while allowing crop or pastureland to grow trees sets the stage for large-scale absorption of carbon.

Other types of land use conversion produce more ambiguous results. In general, converting pasturelands or grasslands into cropland probably produces emissions

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[145]R. Birdsey, *Carbon Storage and Accumulation in United States Forest Ecosystems* (U.S. Department of Agriculture, August 1992), p. 3.
[146]U.S. Environmental Protection Agency, *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), p. xiii.

of carbon through the destruction of biomass and loss of soil carbon. Typical estimates of the amount of soil carbon loss are approximately 30 percent of the amount in place at the time of conversion.[147] These losses can be expected to take place over a period of 20 years, or longer, following conversion. Similarly, abandoning cropland or converting it to pasture or forest should lead to net carbon sequestration through the creation of biomass and gradual additions to soil carbon.

Table 46 shows U.S. Department of Agriculture estimates of the major uses of land in the United States, which were developed through a periodic sample survey. Prepublication data indicate that the next survey will show that between 1987 and 1992 there was a net increase of forestland of 5 million acres.[148] Between 1982 and 1987 there was also a large net reduction in the amount of active cropland. The amount of land used for crops declined by 52 million acres, while the amount of idle cropland increased by 47 million acres. Although an exact figure is not yet

available, U.S. Department of Agriculture staff anticipate that 1992 data will show further reductions in cultivated cropland. These shifts should, in principle, generate additional carbon storage.

It is very difficult to be specific about how much carbon might be gained or lost through transformations of grasslands, pasturelands, or croplands. Although the amount of carbon in a square meter of forest might be on the order of 9 to 26 kilograms, depending on the condition of the forest and on the age and type of trees growing, typical estimates of carbon storage in cultivated lands range from 1 to 8 kilograms per square meter, and uncultivated (but cultivatable) lands range from 2 to 10 kilograms per square meter.[149] Thus, there is less carbon to be gained or lost, and the range of possible outcomes per unit of land is consequently smaller.

A recent study commissioned by the EPA estimated a current average soil carbon content for an area of 110

Table 46. Major Uses of Land in the United States
(Million Acres)

Land Use	1978	1982	1987	1992
Cropland	471	469	464	NA
Used for Crops	369	383	331	NA
Idle Cropland	26	21	68	NA
Pasture	76	65	65	NA
Grassland Pasture and Range	587	597	591	NA
Forest-Use Land	737	721	731	P 737
Grazed Land	172	158	155	NA
Special Use	34	66	83	NA
Other Use	531	497	493	NA
Special Use Areas	124	204	196	NA
Miscellaneous Other Land	345	274	283	NA
Total Land Area	**2,264**	**2,265**	**2,265**	**2,263**

NA = not available.
P = preliminary.
Sources: A. Daugherty, *Major Uses of Land in the United States: 1987*, Economic Research Service Report 643 (Washington, DC: U.S. Department of Agriculture, January 1991), p. 4. Forest area for 1992 provided by U.S. Department of Agriculture from pre-publication draft of *Forest Statistics of the United States 1992*. This figure is potentially subject to revision prior to final publication.

[147]Soils initially very low in carbon tend to gain slight amounts of carbon after cultivation, but richer soils tend to lose at least 20 percent of soil carbon after cultivation begins. See L.K. Mann, "Changes in Soil Carbon Storage After Cultivation," *Soil Science*, Vol. 142, No. 5 (November 1986), p. 279; and W.H. Schlesinger, "Changes in Soil Carbon Storage and Associated Properties with Disturbance and Recovery," in J. Trabalka and D. Riechle (eds)., *The Changing Carbon Cycle: A Global Analysis* (New York: Springer-Verlag, 1986), p. 212.

[148]The reported 10-million-acre increase in forest lands during 1982-1987 was due to a reclassification of existing land, rather than to a change in land use. See A. Daugherty, *Major Uses of Land in the United States: 1987*, Agricultural Economic Report Number 643 (Washington, DC: U.S. Department of Agriculture, Economic Research Service, January 1991), p. iii.

[149]See the scattergram in L.K. Mann, "Changes in Soil Carbon Storage After Cultivation," *Soil Science*, Vol. 142, No. 5 (November 1986), p. 284.

million hectares (272 million acres) of farmland in the United States at 4.8 to 7.9 kilograms per square meter.[150] The study estimated that 1.0 billion to 1.6 billion metric tons of soil carbon had been lost from the farmland since it had been placed in cultivation, equivalent to 16 percent of the estimated original carbon content of the soil. The study also noted, however, that land with a soil carbon content of less than 4 kilograms per square meter was generally not being cultivated at the time of the study. It would not be surprising if the least fertile farmland were the most likely to be removed from cultivation. Therefore, the carbon gains from idling cropland are likely to be small: if the gains are commensurate with the original losses, they would be on the order of 0.6 kilograms per square meter (2.4 metric tons per acre), accrued over 20 to 50 years. However, the small gain would be distributed over a large acreage, since, as noted above, some 47 million acres were withdrawn from cultivation between 1982 and 1987, implying eventual carbon storage of nearly 114 million metric tons, accrued at a rate of 2 million to 5 million metric tons per year. An estimate made for the year 1930 suggested that carbon sequestration for the United States and Canada from the increase and abandonment of croplands was 3 million metric tons.[151]

Similarly, converting land to forest should produce carbon gains, both through the addition of biomass (i.e., carbon stored in trees) and through the accretion of carbon into the soil, as dead limbs and trees pile up and gradually decay. On average, the amount of carbon stored in U.S. forests is 17.7 kilograms per square meter of forestland (using the Birdsey/USDA estimate for storage), or 13 kilograms per square meter (using the EPA estimate). The range in forest storage across States is very large: from 9 kilograms per square meter in Nevada to 26 kilograms per square meter in Alaska, according to Birdsey. As a crude numerical example, converting former cropland to forest might sequester approximately 10 kilograms per square meter over a 70-year period. (The actual amount would depend on the soil fertility and original carbon content of the land, the type of trees planted, and other factors specific to a particular plot of land). This would produce 40.5 metric tons per acre over a 70-year period, or an average of 0.58 metric tons per year per acre. If the actual characteristics of the 5 million acres converted over the past 5 years match this example, the conversion will ultimately store about 205 million tons of carbon over the next 70 years, at an average rate of 2.9 million metric

tons per year. The actual annual rate could vary considerably from the average, since some species of trees grow much more rapidly in their early years than do others.

The examples above highlight two methodological problems common to adding carbon sources and sinks derived from land use data to more conventional greenhouse gas emissions.

Distinguishing Between Anthropogenic and Biogenic Activities. Human beings plant trees, but trees also reproduce themselves. Biomass, in general, tries to grow itself to limits of the capacity of the ecosystem. It is therefore difficult to determine which activities are biogenic and which are anthropogenic.

If humans plant forests and protect them as they grow, that is in principle an anthropogenic activity. Humans also abandon farmland, however, and trees can grow back by themselves, without human intervention. There are parts of the United States (national parks, or the interior of Alaska, for example) that remain close to their natural state and continue to add biomass without human intervention. It is less clear that this carbon sequestration should "count" as anthropogenic.

The broadest definition of anthropogenic would take the view that because humans control all land use in the United States, all land use decisions, whether of omission or commission, are anthropogenic acts. This argument might lead to the conclusion that by not cutting down and burning all its forests, the United States actually has saved 50 billion metric tons of carbon emissions in each year in which the forests were not cut down. Alternatively, too narrow a definition of anthropogenic could exclude unambiguous reforestation activities. There is no single universally acceptable definition of anthropogenic for the purpose of making an emissions inventory, and any decision that is made will inevitably be arbitrary to some degree.

Assigning Anthropogenic Emissions and Sinks to a Particular Calendar Year. When a tree is planted, it grows and sequesters carbon for many years. The period during which a tree grows to its full height varies from a few decades for the faster-growing species to more than a century for slower-growing species. Thus, trees planted in 1990 will absorb some amount of carbon dioxide from the atmosphere every

[150]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), p. 7.

[151]R.A. Houghton 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*, Vol. 39 (1987), p. 124.

year for decades to come. Similarly, trees planted in 1950 are absorbing carbon dioxide from the atmosphere today.

Unfortunately, the future carbon-absorbing properties of current tree planting depend on the preservation of the forest through time. Thus, attributing all of the carbon sequestration of the next 100 years to a tree planted today is to bet on a century of continued intent, and creates an opportunity for misstating the long-run sequestration potential of timberland that is repeatedly harvested. Alternatively, counting carbon sequestration only in the year in which it actually occurs requires accounting for changes in land use made decades ago for uncertain reasons.

Methane Emissions from Wetlands

As discussed in Chapter 1, there are numerous natural sources of methane. Anthropogenic land use changes inevitably affect these natural sources. One such natural source is wetlands. However, the stock of natural wetlands in the United States has diminished considerably over the past 2 centuries, which should, in principle, have reduced biogenic methane emissions. 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.[152] Remaining wetlands total 274 million acres: wetlands lost total 119 million acres.

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.[153] The report does not, however, provide information of the conversion of other land categories to wetlands during this period, so it is a gross, rather than a net, figure.

The range of observed methane fluxes from U.S. wetlands is enormous. One survey of experiments conducted entirely in the United States, for instance, found estimates ranging from a negative flux (methane absorption) to a flux of 213 grams of methane per square meter per year.[154] Thus, it is difficult to extrapolate from experimental data to large-scale emissions estimates.

Estimates of global methane fluxes from wetlands have tended to indicate 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.[155] The U.S. share of all temperate zone wetlands is about 57 percent, and temperate zone wetlands lost during the 1980s account for about 0.5 percent of U.S. wetlands at the beginning of the period. Consequently, the reduction in natural methane emissions from wetlands loss 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 Modification of Methane Sinks

The scientific literature suggests that grasslands and forestlands are both natural sinks for methane and 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.[156]

Exactly how much methane is absorbed by natural soils, and how much nitrous oxide emitted, is more difficult to estimate. One report, which was based on a few experiments, indicates that methane uptake in temperate evergreen and deciduous forests in the United States ranged from 0.19 to 3.17 milligrams (measured in carbon units) per square meter per day, which is equivalent to the uptake of from 36.8 to 624.4

[152]T. Dahl, *Wetlands Losses in the United States: 1780's to 1980's* (Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service, 1990).

[153]U.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.

[154]K. Bartlett and R.C. Harriss, "Review and Assessment of Methane Emissions from Wetlands," *Chemosphere*, Vol. 26, Nos. 1-4, pp. 272-276.

[155]See 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, p. 280.

[156]See A. Mosier et al., "Methane and Nitrous Oxide Fluxes in Native, Fertilized, and Cultivated Grasslands," *Nature*, Vol. 350, No. 6316 (March 28, 1991), pp. 330-332.

metric tons of methane per million acres per year.[157] Thus (assuming no methane uptake at all from previous use), adding 6 million acres of forestland during 1987 to 1992 should increase methane absorption by 221 to 3,746 metric tons per year. This figure can be compared with U.S. anthropogenic methane emissions as estimated in this report of about 29 million metric tons per year.

Another report in the scientific literature indicates that some sample plots of pastureland in the United States had methane uptake of 4.1 milligrams (measured in carbon units) per square meter per day (for fertilized pasture) and 6.3 milligrams per square meter per day (for unfertilized pasture), and uptake from fertilized wheat and maize fields ranged from 0.2 to 0.9 milligrams per square meter.[158]

This literature implies that an additional 0.6 to 6.1 milligrams per square meter per day of methane would be absorbed by the abandonment of farmland, equivalent to 118.1 to 1,201.1 grams per acre per year. Applying these figures to the 50 million acres of cropland taken out of production between 1982 and 1987, this implies an increase in methane uptake from 5,870 to 60,055 metric tons per year from this source.

If such estimates are to be applied to emissions inventories, the same problem of crediting such 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 meth-

ane 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.

Nitrous Oxide Emissions from Land Use Changes

The same research paper that described methane uptake in fertilized and unfertilized plots also described changes in nitrous oxide emissions from fertilized soils.[159] (The mechanism by which this occurs is discussed in Chapter 4.) This paper indicated that unfertilized soils had emissions of 0.25 to 0.35 milligrams (measured in nitrogen units) per square meter per day, while emissions from fertilized soils ranged from 0.6 to 1.65 milligrams per square meter per day. Thus, abandoning fertilization should reduce nitrous oxide emissions by 0.25 to 1.4 milligrams per square meter per day—the equivalent of 58 to 324 metric tons of nitrous oxide per million acres per year. Applying this figure to the 50 million acres of cropland taken out of production between 1982 and 1987 implies a reduction in nitrous oxide emissions ranging from 2,900 to 16,200 metric tons annually.

In principle, any reduction in emissions from this source should be captured by reduced application of nitrogen fertilizers; thus, reporting results from this method would result in double counting.

[157]P.A. Steudler et al., "Influence of Nitrogen Fertilization on Methane Uptake in Temperate Forest Soils," *Nature*, Vol. 341 (September 28, 1989), pp. 314-315.

[158]A. Mosier and D. Schimel, "Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide," *Chemistry & Industry*, Vol. 2 (December 1991), p. 875.

[159]A. Mosier and David Schimel, "Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide," *Chemistry & Industry*, Vol. 2 (December 1991), p. 875.

Appendix A
Uncertainty in Emissions Estimates

Overview

In general, emissions estimates in this report are computed by multiplying some activity, such as coal consumption, by an emissions coefficient to generate an estimate of emissions. The reliability of both the activity data and the emissions coefficients used in this report varies widely. This appendix discusses the uncertainties associated with the estimates presented in the report.

In general, estimates of carbon dioxide emissions are more reliable than estimates for other gases. While this report does not explicitly calculate uncertainty ranges, it is likely that the estimate is accurate to within 5 to 10 percent, or between 1.3 billion and 1.4 billion metric tons. To the extent that there is statistical bias in the point estimate, the actual (unobservable) figure is likely to be somewhat higher than the point estimate, because this report is unlikely to have captured all emissions sources.

The methane emissions estimates are much more uncertain. The level of precision is probably on the order of 30 to 50 percent. However, there are both missing sources and estimation procedures which may underestimate emissions. It is likely that actual methane emissions are therefore higher than those shown.

The nitrous oxide emissions estimates are less reliable than the methane emissions estimates. The largest source, nitrous oxide emissions from nitrogenous fertilizers, may be accurate to an order of magnitude or so. There are several known but missing sources.

Carbon Dioxide

Sources of Uncertainty

Most of the carbon dioxide emissions discussed in this report are caused by the combustion of fossil fuels. The uncertainties in 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 quality of fuel consumed. Fuel data are collected on a volume or weight basis, but the energy content of fuels must often be estimated. The energy content of natural gas is reliable to about 1 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, based on a laboratory analysis. However, the emissions coefficient for the sample fuel may not match the actual characteristics of fuels consumed. It is likely, however, that emissions coefficients for natural gas are accurate to 2 percent and those for other fuels to about 5 percent.

- Uncertainties of coverage, due to excluded or unknown sources of emissions.

Fuel Consumption Uncertainties

In general, EIA energy statistics are most accurate where the energy industry is highly concentrated and/or heavily regulated, and least accurate where activities are decentralized, with large numbers of producers or consumers. In the consumption chain for each fossil fuel, there is a point of maximum concentration, and hence maximum accuracy, for data collection.

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). Utility coal consumption accounts for about 77 percent of U.S. coal consumption. There are likely to be only minor errors (around 1 percent) in reported utility coal consumption. However, industrial, residential, and commercial coal consumption estimates are subject to potentially larger errors, especially in the counting of residential and commercial sector consumption.

The statistical discrepancy for coal production (the difference between reported consumption and reported production less exports, plus imports, plus stock

changes) was on the order of 4 million short tons, or about 0.4 percent of consumption in 1990. Reported consumption was higher than apparent consumption, although the coal statistical discrepancy occasionally changed sign.

Natural gas. Most gas is sold or transported by regulated local distribution companies. The statistical discrepancy for natural gas is 1 to 3 percent of consumption, with reported consumption always smaller than reported production. This may imply (as discussed in Chapter 2) some systematic source of underreporting of consumption.

Inaccuracies in natural gas volumetric data come from inherent limitations in the accuracy of natural gas metering, as well as the usual problems of misreporting and timing differences. For example, natural gas consumption by electric utilities, as reported by electric utilities, differed by about 1 percent from natural gas consumption as reported by natural gas sellers in 1990.[160]

Petroleum. U.S. petroleum consumption is estimated on the basis of "petroleum products supplied," which basically 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.

The EIA requires a detailed breakdown and accounting of petroleum products produced by refineries, including refinery fuel. There are several statistical anomalies in EIA petroleum data:

- Every year, more crude oil shows up at refineries than can be accounted for by oil production, imports, and stock changes. This "unaccounted for crude oil" typically amounts to 200,000 to 250,000 barrels per day, or about 2 percent of refinery runs or 1.5 percent of oil consumption.[161]

- Every year, 80,000 to 150,000 barrels per day more "unfinished oils" show up at refineries than can be accounted for by sales and imports of unfinished oils.[162] This is about 1.1 percent of refinery runs and 0.9 percent of oil consumption.

Since "unaccounted for" crude oil is, by definition, unaccounted for, the source of the discrepancy is unknown. It is likely due to imprecisions in recorded crude oil production, import, and stock change data. In the *State Energy Data Report*, which presents consumption estimates, unaccounted for crude oil is included in consumption.

The unfinished oil discrepancy is probably due to the asymmetric treatment of inter-refiner sales of unfinished oils. To the buyer, who knows the intended use of the product, it is an unfinished oil. To the seller, it is motor gasoline or distillate fuel. In the *State Energy Data Report*, the unfinished oil discrepancy is accounted for through an adjustment to "other oils." However, 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 or so.

Nonfuel use. Data for nonfuel use of petroleum products are much more uncertain than those for total usage 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 by determining consumption of these products by the chemical industry, and then using consumption surveys and trade association data to estimate the share of feedstock use of the various products within the chemical industry.

The largest uncertainties are therefore associated with petrochemical feedstocks (much of which may actually be combusted) and with nonfuel use of conventional fuels.

Uncertainties in 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 based on volu-

[160]Energy Information Administration, *Natural Gas Annual 1990*, DOE/EIA-0131(90)/1 (Washington, DC, December 1991), p. 232.
[161]Energy Information Administration, *Petroleum Supply Annual 1991*, DOE/EIA-0340(91)/1 (Washington, DC, October 1992), p. 33.
[162]Energy Information Administration, *Petroleum Supply Annual 1991*, DOE/EIA-0340(91)/1 (Washington, DC, October 1992), p. 33.

metric 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 estimates, which may not precisely match the actual composition of the fuel.

Coal. Coal data are collected by coal rank and by short ton. Electric utilities are asked to report both the coal rank and the energy content of the coal they burn. Since, in principle, utilities need to know the energy content of their fuels purchase with precision, the energy content data should be fairly accurate. On the other hand, there is no direct information about the energy content of coal distributed outside of the utility sector, which accounts for about 23 percent of coal consumption. The EIA's energy data assumes that the average energy content of coal by rank (except anthracite) in the utility and non-utility sectors is the same.

The quality of coal varies considerably, even within coal rank. Lignite, for example, is defined as containing 6,300 to 8,300 Btu per pound, a range of about 15 percent. Subbituminous coal, by definition has a range of 8,300 to 11,500 Btu per pound.[163] Thus, there may be errors of up to 15 percent in measuring the energy content of industrial and residential coal conversion factors. However, it is likely that the actual (but unobservable) imprecision is much smaller than 15 percent, because there is no reason to expect systematic differences in coal quality between utility and nonutility usage.

Natural Gas. The composition of natural gas also varies considerably. According to a recent survey of several thousand gas samples, taken from local distribution companies around the United States, the range of Btu content varied 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, implying a plausible range for a national average Btu content of about ±2 percent.

Local distribution companies monitor the energy content of natural gas to ensure adherence to contractual specifications and report on average energy content in their consumption forms to the EIA. Thus, the reported energy content of U.S. natural gas is probably accurate to the precision of the underlying energy data, that is, within 2 or 3 percent.

Petroleum. The energy content of petroleum products varies more by volume then by weight. The energy content of petroleum is directly measured by consumers in only a few cases. Electric utilities measure the energy content of the residual oil they burn and report it to the EIA. Liquid petroleum gases (propane, butane, and ethane) are pure compounds, and their energy content can be computed directly. However, liquid transportation fuels (jet kerosine, gasoline, and diesel fuel) are complex mixtures of many compounds, whose physical properties can vary considerably. Their energy content is not measured by consumers nor directly defined by product specifications. The EIA calculates the energy content of these fuels based on standard or "typical" values for each product.

The precision of these typical values can be determined by examining the range of allowable densities for each petroleum product, and converting the range of densities into heat content per barrel (Table A1). The maximum uncertainty range for these products is 3 to 5 percent. However, it is improbable that national average sales of particular products would fall close to the outside edge of the definition of the product, so that variations greater than 1 to 2 percent from the typical value are unlikely.

Uncertainty in Carbon Emissions Coefficients

Emissions factors are calculated by dividing the carbon content of a particular fuel (for example, 0.85 metric tons of carbon per ton of fuel) by the energy content of that fuel (say, 43 million Btu per metric ton), producing an emissions coefficient (in this example, 19.3 million metric tons of carbon per quadrillion Btu).

While both the energy content and the carbon content of the fuel are subject to a degree of uncertainty, the uncertainty about the carbon content is usually larger than the uncertainty about the Btu content. 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. Consequently, as in the case of heating values for petroleum products, carbon coefficients are often based on "typical" or "representative" values, which may or may not perfectly reflect the underlying composition of the fuel.

Coal. There are large variations in the carbon and energy content of coals in different parts of the United

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[163]Energy Information Administration, *Coal Production 1991*, DOE/EIA-0118(91) (Washington, DC, October 1992), pp. 109 and 111.

[164]W.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.

Table A1. Estimated Densities and Heat Contents of the Major Petroleum Products

Fuel	API Gravity Range	API Gravity "Norm"	EIA Estimated Btu per Barrel (Million Btu)	Btu per Barrel Range (Million Btu)	Uncertainty (Percent)
Motor Gasoline	47-72	60	5.253	4.99-5.54	5
Kerosine Jet Fuel	36-48	41	5.670	5.51-5.80	3
Middle Distillates	25-41	33	5.825	5.68-6.09	5
Residual Oil	11-24	17	6.287	6.12-6.44	3

Sources: "API Gravity Range" and "API Gravity Norm"—Federal Energy Administration, *Energy Interrelationships* (Washington, DC, June 1977). "Btu per Barrel Range"—U.S. Department of Commerce, Bureau of Standards, *Thermal Properties of Petroleum Products*, Miscellaneous Publication Number 97 (Washington, DC, 1933), Table 6, p. 17. "EIA Estimated Btu per Barrel"—Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(93/07) (Washington, DC, July 1993), Table A1, p. 141.

States. Lignite may have as little as 12.6 million Btu per ton and contain 36 percent carbon, while anthracite may have as much as 98 percent carbon and have an energy content as high as 27 million Btu per ton.[165]

The carbon and heating value of coal are, in general, controlled by two factors:

• The ratio of flammable materials (carbon, hydrogen, and sulfur) in coal to nonflammable impurities (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. In this report, the EIA relied on chemical analysis 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 million Btu) for each coal rank.

Natural Gas. Natural gas also varies in its composition, but the range of variation is much smaller than for coal. The emissions coefficient used in this report was based

on an analysis of U.S. natural gas consumption in 1976. The average energy content of U.S. natural gas has risen slightly in the intervening decade, which implies that the correct emissions coefficient might be slightly higher than the one used. However, based on observed variations in the Btu content of U.S. natural gas, it is unlikely that the actual (unobservable) carbon coefficient is more than 2 percent different from the coefficient used in this report.

Petroleum Products. Crude oil is refined into a wide range of petroleum products, each of which presents a different set of uncertainties in computing emissions coefficients. Emissions coefficients for liquid petroleum gases (propane, butane, and ethane) can be computed "perfectly" since these are pure compounds of known chemical composition, density, and energy content. The only residual uncertainty is the level of impurities in the product, which should be much less than 1 percent.

Heavier hydrocarbons present more difficulties. In general, the carbon content of petroleum products increases with increasing density. Uncertainties in emissions coefficients arise primarily from picking the wrong density for a fuel, or from mismatching the carbon and energy content of a particular fuel. For particular products, possible errors in emissions coefficients are similar to the uncertainty in the Btu content, that is, 2 to 5 percent.

Larger errors are possible, however, for some of the minor petroleum products, such as still gas, petrochemical feedstocks, and "other oils." In these cases, the actual density of the product, and hence its proper energy content and emissions coefficient, is not known with precision, and the potential exists for errors of 10

[165]Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(93/07) (Washington, DC, July 1993), pp. 143 and 149.

percent or greater. However, these products compose a relatively small portion of total petroleum products consumption.

Uncertainties in "Adjustments to Energy"

U.S. Territories. Energy data for U.S. territories presents certain problems. Published petroleum data for Puerto Rico and the Virgin Islands are considerably less detailed than 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 these emissions estimates is lower than for petroleum emissions estimates generally.

Unmetered Gas Consumption. Since the estimate for unmetered gas consumption is actually a balancing item, the uncertainty on this estimate is very large, on the order of 100 percent. Fortunately, this is only a small source of carbon emissions.

Other Sources of Carbon Emissions

The principal source of uncertainty in cement manufacture is the lime content of cement, which is estimated plus or minus about 3 percent. There may also be a degree of imprecision in the estimate of cement production, due to possible production in Puerto Rico (excluded in this report), exports of clinker (excluded in this report), and limitations on the inherent accuracy of the Interior Department data used to calculate the estimate.

A second source of uncertainty, common to all of the industrial estimates, is the use of stoichiometric computations to estimate emissions. This method calculates an emissions factor based on a chemical reaction known to have taken place. This method assumes, in effect, that the product produced (cement, lime, soda ash) is 100 percent pure, and that no raw materials were wasted in its production. In practice, impurities in the output would tend to reduce emissions below the stoichiometric estimate, while "wastage" of raw materials would tend to raise emissions above the estimate.

Excluded Sources

Appendix C lists several sources of emissions that are excluded, because of uncertainty. Sources excluded because of insufficient data include emissions from natural gas plants, limestone use in various aspects of the steel and glass industries, and limestone use in flue gas desulfurization.

Taking what is known about all excluded sources put together, 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 "unknown unknowns."

Uncertainties Associated with Methane Emissions

Overview

Estimates of methane emissions are, in general, highly uncertain. Because methane emissions are an unintended consequence of such other activities as coal mining and municipal solid waste disposal, they are infrequently the subject of systematic measurement. Also, because emissions are rarely at pressures or in volumes which make them commercially viable, there is little incentive for emitters to collect or even monitor emissions. Hence, estimates must rely on a limited sample of field experiments applied to a diverse set of producers. This may create estimates that overlook variations in crucial elements.

Coal Mining

Estimates of methane emissions from coal mining have a wide uncertainty range. Methane concentrations in coal mines have not been systematically measured except in cases where they posed a threat to miner safety or had the potential for collection and commercial sale. Thus, emissions estimates are based on data from the "gassiest" mines in the United States. These data consist of inspection reports prepared by the Mine Safety and Health Administration on methane concentrations in mine ventilation systems. In some of the "gassiest" mines, degasification systems supplement the normal ventilation systems. Measurements of the gas removed by these systems exist only for the few mines where it is collected for commercial sale. Further, because methane from surface mines does not threaten worker safety and cannot be collected for commercial sale, there is little hard data on its emissions.

Before it is combusted, coal is pulverized, releasing all of the methane contained in its pores. Consequently, the in situ methane content of the coal mined in the United States represents the minimum level of emissions. This minimum level was 2.05 million metric tons in 1990. The EPA/IPCC method discussed in Chapter 3 applies estimation techniques for emissions from

underground mines to surface mines with only minor modifications. However, emissions from surface mines should be far below those from underground mines. Hence, this methodology yields the high end of the estimation range, 9.5 million metric tons for 1990. This report's estimate of 4.9 million metric tons is near the midpoint of that range.

Oil and Gas Operations

Estimates of methane emissions from oil and gas operations have a wide uncertainty range, but the bounds of that range are difficult to quantify. It is likely that this report's emission estimate of 3.18 million metric tons for 1990 is at the low end of the range.

The underlying data for estimating emissions from field operations and transmission and distribution systems are drawn from a small sample of model facilities and pipelines where emissions were measured from various system components. These emissions are the product of routine maintenance of pressure valves, leaks from meters and flanges, and occasional accidents that result in large-scale emissions. The model facilities were chosen on the basis of their accessibility for data collection, location, and size. The conditions of these facilities were then generalized to a very diverse industry, whose plants and equipment may be older or not as well maintained as the sample used.

When oil is recovered it is generally mixed with natural gas. In large drilling operations this associated gas is usually captured and sold. However, at smaller "stripper" wells, which account for 14 percent of U.S. oil production, the volume of associated gas is too small to be marketed. It may be vented or merely evaporate from storage tanks, and it is unlikely that these emissions are reflected in any data series.

Combustion-Related Emissions

Methane emissions from combustion may be larger than the estimate offered in this report, but it unlikely that they are significantly smaller. Emissions factors for mobile transportation assume a well-maintained vehicle 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 may be described as well-maintained, there remains a portion which is old and/or poorly maintained that is not reflected in this report's estimates.

Methane emissions from stationary sources are estimated with a fair degree of certainty, with the exception of emissions from wood combustion. Data on residential wood consumption must be estimated from surveys of a sample of the population. More importantly, methane emissions factors for wood combustion are not well established. Using a different emissions factor, the U.S. Environmental Protection Agency provides estimates of methane emissions from wood combustion 28 times those of this report for 1990.[166]

Landfills

Estimates of methane emissions from landfills are highly uncertain. The production and release of methane to the atmosphere are functions of the amount of waste in a landfill, the composition of the waste, the age and depth of the waste, the temperature within the landfill, and the acidity of the moisture within the landfill. Data on landfills are, at best, sketchy. The total number of landfills is unknown. Age and depth of waste is known for only a few sites. The composition of the wastes can only be approximated.

This report adopts average degradable organic carbon (DOC) contents, and a constant for the portion of DOC converted to methane based on a landfill anaerobic zone temperature of 35 degrees Celsius. These figures may vary widely among landfills. Further, this report assumes that all methane is released in the year the waste is landfilled; yet it is known that methane is released gradually over many years, with emissions fluctuating with changing landfill conditions.

Enteric Fermentation in Domesticated Animals

The uncertainty of estimates of methane emissions from enteric fermentation in domesticated animals does not appear to be as large as that for other sources of methane emissions. However, the emissions factors for different animals are based on a small sample of experiments and may not be accurate when applied across a large population of animals. The vast majority of emissions are from cattle, whose food energy intake may vary across regions, management styles, and individual specimens. Emissions factors for goats, pigs, and horses were derived from experiments on animals in other countries, and their relationship to the larger and better fed animals in the United States is uncertain.

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[166]U.S. Environmental Protection Agency, *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990*, Review Draft (Washington, DC, June 21, 1993), p. 12.9.

Animal populations are monitored regularly by the U.S. Department of Agriculture and are likely to be accurate to within 5 percent.

Solid Waste of Domesticated Animals

The uncertainty of methane emissions estimates for the solid waste of domesticated animals is largely a function of the uncertainty in estimating methane conversion factors. As discussed above, animal population estimates are relatively reliable. Maximum methane-producing capacities of animal waste vary in experiments according to animal diet, but by no more than 50 percent from the values adopted for this report.

The low end of the possible range of emissions is likely to be somewhat below the 2.3 million metric tons this report estimates for 1990 using alternative methane conversion factors, because at lower temperatures methane emissions are reduced. It is difficult to determine the specific temperature at which waste is decomposing, as it varies according to time of day and location. The high end of the range of emissions is probably several times this report's estimate of 3.5 million metric tons for 1990. Methane production increases at higher temperatures and with increased levels of moisture. Waste in pasture, range, and drylots is assumed to be dry, but in areas of heavy rainfall emissions from these sources would increase. Further, methane conversion factors for liquid slurry and pit storage may be revised upward.

Rice Fields

Methane emissions from rice fields are affected by numerous environmental factors such as soil type, temperature, redox potential, and acidity; the type, timing, and amount of fertilizer applied; water management practices; and rice cultivar type.[167] There is additional uncertainty regarding the area of rice fields in production, the length of the growing season, and whether the fields are flooded to a depth sufficient to promote methane production.

This report presents a high-end emissions estimate of 367,000 metric tons for 1990 and a low-end estimate of 105,000 metric tons. The midpoint estimate is 236,000 metric tons.

Uncertainties Associated with Nitrous Oxide Emissions

Nitrogenous Fertilizers

Nitrous oxide emissions from nitrogen fertilizers are highly uncertain. The production and evolution of natural and fertilizer-derived nitrous oxide from the soil surface are dependent on agricultural practices, biogenic processes, soil properties, and climate conditions.

The methodology used in this report is based on the amount of each type of nitrogen fertilizer consumed. The basis for this methodology is centered around a literature review and analysis by Eichner.[168] The emissions estimate derived for nitrous oxide for the fertilizer type ranged from 0.001 to 6.84. In a report by A. Moiser for the IPCC working group, the author stated that the data set used by Eichner for the analyses was small and that the studies were conducted only during the cropping season, or part of the cropping season.[169] Therefore, little is known about nitrogen emissions following crop harvest and before planting in the spring, and the emissions range could be highly skewed, with a confidence interval that could be plus or minus an order of magnitude.

Stationary Sources

Estimates of nitrous oxide emissions from stationary sources are highly uncertain. Until recently, flask samples taken from combustion experiments led researchers to believe that combustion activities represented a major anthropogenic source of nitrous oxide emissions. However, later studies revealed that the samples taken from the flasks did not have the same levels as the initial samples. Further research indicated that most of the nitrous oxide was not emitted during fossil fuel burning, but was actually generated in the flasks between the time the samples were taken and the time the flasks were analyzed. Therefore, this report contains no estimate for emissions from several stationary sources that may, in fact, produce emissions.

Adipic Acid

Emissions estimates for adipic acid are uncertain because of limited data available about the exact amount

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[167]OECD, *Estimation of Greenhouse Gas Emissions and Sinks* (Final Report) (Paris, France, August 1991), pp. 5-28 - 5-34.

[168]M. Eichner, "Nitrous Oxide Emissions from Fertilized Soils: Summary of Available Data," *Journal of Environmental Quality*, Vol 19 (1990), pp. 272-280.

[169]A.R. Mosier, *Nitrous Oxide Emissions from Agricultural Soils* (mimeo, February 1993).

of adipic acid produced, and the extent to which control technologies have been implemented.

In common with several other estimates in this report, the adipic acid estimate is based on stoichiometric computations, which assume, in effect, that the industrial process is perfectly efficient in converting nitric acid into adipic acid. The actual conversion efficiency is unknown.

Nitric Acid

Nitric acid emissions estimates are exceptionally uncertain because of insufficient information about industrial processes and possible control technologies. The DuPont Company has estimated nitrous oxide emissions from this source by using a ratio based on tons of nitric acid produced per year from the company and total U.S. production, and multiplying the production number by the emissions in the facility.[170]

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[170]W.R. Stevens, III, The DuPont Company, personal communication (Wilmington, DE, August 19, 1993).

Appendix B
Detailed Emissions Estimates and Activity Data

Table B1. U.S. Carbon Dioxide Emissions from Energy Use in the Residential Sector, 1980-1991
(Million Metric Tons Carbon)

Fuel	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Petroleum												
LPG	5.6	5.3	5.1	6.0	4.9	5.6	5.5	6.1	6.1	6.9	6.2	6.7
Distillate Fuel	26.0	22.7	20.8	18.3	19.0	19.7	20.0	20.4	21.0	20.6	16.6	16.4
Kerosene	2.1	1.6	1.8	1.6	1.7	3.1	2.3	2.3	2.8	2.3	1.2	1.4
Total	33.6	29.6	27.7	25.9	25.6	28.4	27.9	28.8	29.9	29.7	24.0	24.5
Coal	1.6	1.8	2.0	2.0	2.1	1.8	1.8	1.7	1.7	1.5	1.6	1.5
Natural Gas	69.9	67.0	68.4	65.0	67.4	65.7	63.8	63.8	68.5	70.9	65.0	67.4
Electricity	143.5	141.6	139.6	143.3	146.0	150.0	150.7	156.7	164.9	165.5	162.4	163.8
Total	248.6	240.1	237.6	236.2	241.2	245.9	244.1	251.1	265.0	267.6	253.1	257.2

Note: Totals may not equal sum of components due to independent rounding.
Source: Energy Information Administration estimates, based on energy data from *State Energy Data Report 1991*, DOE/EIA-0214(91) (Washington, DC, May 1993), and emissions coefficients shown in Table 11 of this report.

Table B2. U.S. Carbon Dioxide Emissions from Energy Use in the Commercial Sector, 1980-1991
(Million Metric Tons Carbon)

Fuel	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Petroleum												
Motor Gasoline	2.1	1.8	1.7	2.0	2.1	1.8	2.0	2.1	2.1	2.0	2.1	1.6
LPG	1.0	0.9	0.9	1.1	0.9	1.0	1.0	1.1	1.1	1.2	1.1	1.2
Distillate Fuel	10.2	9.0	8.7	12.9	13.5	12.4	11.8	11.7	11.3	10.6	9.6	9.5
Residual Fuel	12.1	8.9	8.5	4.5	5.7	4.9	6.2	5.6	5.7	4.9	5.0	4.6
Kerosene	0.8	1.3	0.6	2.1	1.8	0.6	1.0	0.9	0.5	0.5	0.2	0.2
Total	26.2	22.0	20.4	22.5	23.9	20.7	22.0	21.5	20.7	19.2	18.1	17.1
Coal	2.3	2.5	2.9	3.0	3.2	2.8	2.7	2.5	2.6	2.2	2.3	2.1
Natural Gas	38.4	37.1	38.4	36.1	37.3	36.0	34.3	36.0	39.5	40.3	38.8	40.4
Electricity	111.7	116.9	116.5	118.5	124.4	130.3	131.6	137.3	144.9	148.3	147.4	146.8
Total	178.5	178.5	178.3	180.1	188.8	189.7	190.5	197.2	207.7	210.1	206.7	206.4

Note: Totals may not equal sum of components due to independent rounding.
Source: Energy Information Administration estimates, based on energy data from *State Energy Data Report 1991*, DOE/EIA-0214(91) (Washington, DC, May 1993), and emissions coefficients shown in Table 11 of this report.

Table B3. U.S. Carbon Dioxide Emissions from Energy Use in the Industrial Sector, 1980-1991

(Million Metric Tons Carbon)

Fuel	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Petroleum												
Motor Gasoline	3.0	3.1	2.7	2.2	3.1	4.2	4.0	3.9	3.7	3.8	3.5	3.7
LPG	15.7	15.4	15.0	13.6	16.7	17.1	16.2	13.9	13.7	13.5	9.6	9.4
Distillate Fuel	26.2	27.5	26.0	22.6	23.6	23.5	23.7	24.3	24.1	22.7	23.4	22.5
Residual Fuel	28.9	23.2	22.4	17.0	19.1	16.0	15.8	12.5	11.7	8.9	8.9	7.2
Lubricants	1.9	1.8	1.7	1.7	1.9	1.7	1.7	1.9	1.9	1.9	2.0	1.8
Kerosene	3.5	2.1	2.7	1.3	1.1	0.9	0.6	0.5	0.6	0.6	0.2	0.2
Other	40.6	24.2	23.8	30.3	33.9	31.1	31.0	33.0	38.1	37.0	44.3	35.4
Total	119.9	97.2	94.2	88.6	99.3	94.5	93.0	90.1	93.9	88.3	91.9	80.2
Coal	74.7	75.4	61.0	59.8	69.2	67.3	64.0	65.6	70.6	68.8	67.7	64.0
Natural Gas	118.2	116.5	100.5	96.0	104.8	99.6	94.4	103.4	108.6	114.6	119.6	121.7
Electricity	163.0	161.9	142.6	148.1	156.8	158.1	152.8	158.1	165.6	169.2	166.2	162.3
Total	475.8	451.1	398.3	392.5	430.1	419.5	404.2	417.1	438.6	440.9	445.4	428.3

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

Source: Energy Information Administration estimates, based on energy data from State Energy Data Report 1991, DOE/EIA-0214(91) (Washington, DC, May 1993), and emissions coefficients shown in Table 11 of this report.

Table B4. U.S. Carbon Dioxide Emissions from Energy Use in the Transportation Sector, 1980-1991

(Million Metric Tons Carbon)

Fuel	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Petroleum												
Motor Gasoline	238.1	238.1	236.8	240.0	242.3	245.8	253.3	259.6	265.4	264.4	261.1	259.7
LPG	0.3	0.6	0.5	0.7	0.7	0.5	0.4	0.4	0.4	0.4	0.4	0.3
Jet Fuel	42.0	39.7	39.9	41.3	46.5	48.1	51.7	54.8	57.5	59.0	60.3	58.3
Distillate Fuel	55.3	57.4	55.2	57.4	62.2	63.3	65.3	67.0	72.9	75.9	75.7	72.7
Residual Fuel	30.0	26.1	21.9	17.6	17.3	16.8	18.7	19.3	19.7	21.0	22.1	22.1
Lubricants	1.8	1.7	1.6	1.7	1.8	1.6	1.6	1.8	1.8	1.8	1.8	1.7
Aviation Gas	1.2	1.1	0.9	0.9	0.8	1.0	1.1	0.9	0.9	0.9	0.9	0.8
Total	368.7	364.6	356.7	359.6	371.6	377.2	392.2	403.7	418.6	423.4	422.3	415.6
Natural Gas	9.4	9.5	8.8	7.3	7.8	7.5	7.2	7.7	9.1	9.4	9.8	8.9
Electricity	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Total	378.7	374.7	366.1	367.5	380.1	385.4	400.1	412.2	428.4	433.4	432.9	425.2

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

Source: Energy Information Administration estimates, based on energy data from State Energy Data Report 1991, DOE/EIA-0214(91) (Washington, DC, May 1993), and emissions coefficients shown in Table 11 of this report.

Table B5. U.S. Carbon Dioxide Emissions from Electric Utilities, 1980-1991

(Million Metric Tons Carbon)

Fuel	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Petroleum	56.2	47.0	33.5	33.0	27.5	23.3	31.0	26.9	33.4	36.0	26.8	25.2
Heavy Fuel Oil	52.7	44.5	31.6	30.9	25.5	21.4	29.1	24.8	30.9	32.6	24.4	23.1
Light Fuel Oil	3.3	2.5	1.8	1.9	1.7	1.7	1.6	1.8	2.2	2.9	1.7	1.6
Petroleum Coke	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.7	0.6
Coal	307.9	319.9	317.9	334.5	354.1	370.3	366.0	383.7	403.8	406.5	408.8	407.3
Anthracite	0.5	0.4	0.4	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.3	0.3
Bituminous	230.3	230.2	226.1	232.7	247.5	249.1	249.4	263.1	272.6	275.7	280.2	271.5
Subbituminous	63.2	73.4	75.7	83.5	87.9	99.9	94.7	98.0	105.0	104.9	103.3	109.0
Lignite	13.9	15.9	15.7	18.1	18.4	21.0	21.7	22.3	25.9	25.7	25.0	26.5
Natural Gas	54.7	54.1	48.0	43.1	46.3	45.4	38.7	42.2	39.0	41.2	41.2	41.1
Total	418.9	421.1	399.4	410.5	427.9	439.1	435.7	452.8	476.2	483.7	476.7	473.6

Note: Electric utilities include Independent Power Producers but exclude cogeneration facilities.

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

Source: Energy Information Administration estimates, based on energy data from State Energy Data Report 1991, DOE/EIA-0214(91) (Washington, DC, May 1993), and emissions coefficients shown in Table 11 of this report.

Table B6. Production Data for Industrial Sources of Carbon Dioxide, 1980-1991
(Thousand Short Tons)

Item	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Cement Produced	75,224	71,710	63,355	70,420	77,700	77,895	78,786	78,198	76,867	77,189	77,111	71,127
Limestone Consumed in Steelmaking	1,023	1,047	578	730	920	760	809	878	955	1,167	752	814
Limestone Consumed in Iron Smelting	12,522	12,319	6,718	7,487	7,803	NA	NA	NA	NA	NA	NA	NA
Lime Produced	19,010	18,856	14,075	14,867	15,922	15,690	14,474	15,733	17,052	17,152	17,452	16,800
Industrial Carbon Dioxide Produced	NA	NA	6,807	7,280	7,944	8,458	8,389	NA	NA	NA	18,262	18,468
Soda Ash Production	7,507	7,513	7,093	7,681	7,721	7,721	7,655	8,066	8,738	8,995	9,156	9,005
Soda Ash Consumed in Glass Production	3,494	3,357	3,176	3,130	3,085	3,084	3,152	3,343	3,390	3,294	3,177	2,997
Aluminum Production	5,130	4,948	3,609	3,696	3,718	3,175	2,755	3,032	3,577	3,655	3,672	ᵃ3,719

ᵃEstimate.
NA = not available.
Sources: Cement Production from U.S. Department of the Interior, Bureau of Mines, *Cement Annual Report*, *Mineral Industry Surveys*, and *Minerals Yearbook* (Washington, DC, various years). Limestone used in steelmaking and iron smelting from American Iron and Steel Institute, "Consumption of Fluxes," *Annual Statistical Report* (Washington, DC, various years). Lime production, Soda ash production and consumption, and aluminum production from U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook* (Washington, DC, various years).

Table B7. Activity Data for Methane Emissions from Oil Production, Processing, and Distribution, 1980-1991

Item	Unitsᵃ	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Natural Gas Wellheads	Thousand Wells	182	199	211	222	234	242	242	249	257	263	270	277
Producing Oil Wells	Thousand Wells	548	557	580	603	621	647	629	620	627	607	602	610
Gathering Pipelines	Thousand Wells	84	86	91	92	94	94	94	94	92	91	90	86
Total Gas Throughput	Tcf	NA	15	14	13	14	13	13	13	13	13	15	16
Total Gas Withdrawals	Tcf	22	22	20	19	20	20	19	20	21	21	22	22
Transmission System Pipelines	Thousand Miles	267	270	272	274	272	271	271	274	275	276	280	282
Distribution Pipeline													
Main Pipeline	Thousand Miles	NA	NA	NA	NA	NA	753	769	784	800	818	837	857
Plastic	Thousand Miles	NA	NA	NA	NA	NA	126	138	152	166	183	202	221
Nonplastic	Thousand Miles	NA	NA	NA	NA	NA	628	631	632	634	635	635	636
Service Pipeline	Thousand Miles	NA	NA	NA	NA	NA	389	400	411	449	461	474	494
Plastic	Thousand Miles	NA	NA	NA	NA	NA	140	151	163	201	213	226	246
Nonplastic	Thousand Miles	NA	NA	NA	NA	NA	248	248	248	248	248	248	248
Total Distribution Pipeline	Thousand Miles	NA	NA	NA	NA	NA	1,142	1,169	1,195	1,250	1,279	1,311	1,352
Marine Transport													
Net Crude Imports	Kbd	5,300	4,400	3,500	3,300	3,400	3,200	4,200	4,700	5,100	5,800	5,900	5,800
Net Crude Exports	Kbd	300	200	200	200	200	200	200	200	200	100	100	100
Alaskan Crude Production	Kbd	NA	1,600	1,700	1,700	1,700	1,800	1,900	2,000	2,000	1,900	1,800	1,800
Total Marine Transport	Kbd	NA	6,200	5,400	5,200	5,300	5,200	6,200	6,800	7,300	7,900	7,800	7,700
Refinery Crude Input	Mbd	14	13	12	12	12	12	13	13	13	13	13	13

ᵃUnits: Tcf = trillion cubic feet; Kbd = thousand barrels per day; Mbd = million barrels per day.
NA = not available.
Sources: Natural Gas Wellheads, Total Gas Throughput, and Total Gas Withdrawals—Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (various years). Producing Oil Wells—*World Oil*, February issue (various years). Gathering Pipelines, Transmission Pipelines, and Distribution Pipelines—American Gas Association, *Gas Facts* (various years). Net Crude Imports, Net Crude Exports, and Refinery Crude Input—Energy Information Administration, *Annual Energy Review 1992*, DOE/EIA-0384(92) (Washington, DC, June 1993). Alaskan Crude Production—Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (various years).

Table B8. Coal Production from Underground Mining, 1981-1991
(Million Short Tons)

Coal Basin	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Northern Appalachia											
Pennsylvania	34.59	35.50	34.50	36.90	35.86	36.76	37.78	38.77	39.07	40.08	40.60
Northern West Virginia	36.12	44.12	41.10	47.84	42.26	40.92	45.31	46.15	48.29	50.10	47.54
Maryland	1.72	1.90	1.65	2.21	1.79	2.45	2.40	2.02	1.83	1.99	2.63
Ohio	10.65	12.22	10.82	14.11	13.65	14.35	12.61	11.26	10.82	12.92	12.23
Total	**83.08**	**93.74**	**88.06**	**101.06**	**93.56**	**94.48**	**98.10**	**98.21**	**100.01**	**105.09**	**103.00**
Central Appalachia											
Virginia	32.29	30.99	26.78	32.90	33.55	33.80	36.73	37.58	35.92	39.07	34.03
Southern West Virginia	53.00	59.41	50.82	58.37	61.49	62.21	61.86	63.62	64.72	73.01	72.12
Eastern Kentucky	59.62	57.07	49.01	61.82	63.32	65.01	66.26	68.29	75.27	80.42	73.04
Tennessee	5.06	4.52	4.36	5.26	5.20	5.23	4.81	4.61	4.60	4.45	3.01
Total	**149.97**	**151.99**	**130.97**	**158.35**	**163.57**	**166.25**	**169.66**	**174.10**	**180.51**	**196.95**	**182.20**
Warrior											
Alabama	8.62	11.29	10.86	13.18	14.44	13.27	14.33	14.83	16.31	17.53	17.06
Piceance											
Colorado	6.57	6.61	5.58	6.41	6.38	5.46	5.64	6.85	8.50	10.62	9.60
San Juan											
New Mexico	0.82	0.71	0.10	0.55	0.80	0.75	0.62	0.22	0.05	0.08	0.03
Illinois											
Illinois	29.19	34.66	31.84	38.50	37.34	39.72	37.52	38.52	39.33	41.67	43.13
Indiana	0.56	1.57	1.78	2.25	2.05	1.86	2.45	2.41	2.52	3.04	2.83
Western Kentucky	17.58	17.72	15.82	17.32	17.91	22.20	25.89	25.79	23.32	24.46	23.98
Iowa	0.06	0.00	0.00	0.17	0.17	0.13	0.06	0.00	0.00	0.00	0.00
Total	**47.40**	**53.95**	**49.44**	**58.24**	**57.48**	**63.90**	**65.92**	**66.72**	**65.17**	**69.17**	**69.95**
Uinta											
Utah	13.71	17.03	11.76	12.32	12.78	14.27	14.51	18.16	20.10	22.06	21.95
Green River											
Wyoming	1.31	1.28	1.25	1.35	1.06	0.16	0.11	1.14	1.65	1.72	2.42
Pennsylvania Anthracite											
Pennsylvania	NA	0.36	0.30	0.58	0.73	0.41	0.39	0.35	0.26	0.24	0.13
Total Underground Production ..	**NA**	**336.95**	**298.32**	**352.04**	**350.79**	**358.95**	**369.26**	**380.58**	**392.54**	**423.45**	**406.32**

NA = not available.
Source: Energy Information Administration, *Coal Production*, DOE/EIA-01· ʳs.

Table B9. Methane Emissions from Underground Coal Mining, 1981-1991
(Million Metric Tons)

Coal Basin	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Northern Appalachia	0.55	0.62	0.58	0.67	0.62	0.63	0.65	0.65	0.66	0.70	0.68
Central Appalachia	1.91	1.94	1.67	2.02	2.08	2.12	2.17	2.22	2.30	2.51	2.33
Warrior	0.32	0.42	0.40	0.49	0.53	0.49	0.53	0.55	0.60	0.65	0.63
Piceance	0.06	0.06	0.05	0.06	0.06	0.06	0.06	0.07	0.08	0.10	0.09
San Juan	0.01	0.01	--	--	0.01	0.01	0.01	--	--	--	--
Illinois	0.10	0.12	0.11	0.13	0.13	0.14	0.15	0.15	0.14	0.15	0.15
Uinta	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.04
Green River	--	--	--	--	--	--	--	--	--	--	--
Pennsylvania Anthracite	N/A	--	--	--	--	--	--	--	--	--	--
Total	**2.98**	**3.20**	**2.84**	**3.40**	**3.46**	**3.46**	**3.58**	**3.67**	**3.83**	**4.15**	**3.93**

-- = Less than 0.05 million metric tons.
NA = not available.
Note: Totals may not equal sum of components due to independent rounding.
Source: EIA estimates, based on *Coal Production*, DOE/EIA-0118, various years, and methods described in Chapter 3.

Table B10. Coal Production from Surface Mining, 1981-1991
(Million Short Tons)

Coal Basin or State	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Appalachian											
Pennsylvania	48.40	42.42	34.06	40.01	34.82	33.40	31.28	30.49	30.22	29.28	23.75
Ohio	25.05	24.12	22.76	25.15	21.96	21.86	22.94	22.58	22.70	22.16	18.23
Virginia	8.28	8.08	7.74	7.47	7.39	6.97	7.45	7.97	6.85	7.68	7.78
West Virginia	23.09	24.37	22.37	24.79	24.01	26.14	28.76	34.61	40.14	45.61	47.28
Eastern Kentucky	55.79	51.96	44.19	55.46	49.93	46.19	52.23	48.07	49.63	47.24	43.57
Tennessee	4.65	2.77	2.21	2.05	2.24	1.52	1.54	1.80	1.77	1.65	1.20
Alabama	15.74	14.94	12.77	13.91	13.36	12.42	11.13	11.60	11.58	11.41	10.10
Maryland	2.52	1.87	1.48	1.90	1.20	1.42	1.53	1.20	1.51	1.48	1.11
Total	183.53	170.51	147.58	170.74	154.90	149.90	156.86	158.31	164.39	166.52	153.01
Illinois Basin											
Indiana	28.57	30.15	30.01	35.31	31.26	30.95	31.73	28.82	31.11	32.85	28.62
Illinois	22.66	25.60	25.01	25.27	21.86	22.15	21.63	20.07	19.92	18.72	17.12
Iowa	0.65	0.56	0.37	0.36	0.42	0.35	0.41	0.33	0.39	0.38	0.34
Missouri	4.88	5.34	4.98	6.72	5.57	4.68	4.28	4.17	3.38	2.65	2.30
Total	56.76	61.65	60.36	67.66	59.11	58.13	58.04	53.39	54.80	54.60	48.39
Powder River											
Montana	33.55	27.88	28.92	33.00	33.29	33.98	34.40	38.88	37.74	37.62	38.23
Wyoming	101.66	107.08	110.96	129.57	139.66	136.66	146.74	162.88	169.91	182.53	191.44
Total	135.21	134.97	139.89	162.57	172.95	170.63	181.14	201.76	207.66	220.14	229.66
Arkoma											
Oklahoma	5.77	4.71	3.66	4.64	3.33	3.04	2.86	2.13	1.69	1.58	1.82
San Juan											
New Mexico	17.87	19.23	20.31	20.73	21.40	20.74	18.51	21.58	23.66	24.22	21.49
Colorado	13.30	11.69	11.13	11.56	10.87	9.76	8.77	9.04	8.61	8.28	8.23
Total	31.16	30.93	31.44	32.28	32.26	30.50	27.29	30.62	32.27	32.50	29.73
Alaska	0.81	0.83	0.79	0.86	1.43	1.57	1.49	1.75	1.58	1.71	1.44
Arizona	11.61	12.36	11.40	11.52	9.63	11.56	11.38	12.40	11.94	11.30	13.20
Arkansas	0.22	0.14	0.06	0.08	0.08	0.15	0.07	0.26	0.04	0.04	0.03
California	0.00	0.00	0.00	0.00	0.07	0.00	0.05	0.05	0.04	0.06	0.06
Louisiana	0.00	0.00	0.00	0.00	0.21	2.25	2.75	2.89	2.98	3.19	3.15
North Dakota	18.12	17.85	19.18	22.11	26.87	25.64	25.14	29.72	29.56	29.21	29.53
Texas	32.81	34.82	38.95	41.15	45.46	48.59	50.53	52.28	53.85	55.76	53.83
Washington	4.64	4.16	3.88	3.87	4.44	4.59	4.45	5.17	5.04	5.00	5.14
Total Surface Production	480.63	472.93	457.19	517.48	510.73	506.56	522.03	550.72	565.82	581.60	568.99

Source: Energy Information Administration, *Coal Production*, DOE/EIA-0118, various years.

Table B11. Methane Emissions from Surface Coal Mining, 1981-1991
(Million Metric Tons)

Coal Basin or State	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Appalachia	0.22	0.20	0.18	0.20	0.18	0.18	0.19	0.19	0.20	0.20	0.18
Illinois Basin	0.05	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Powder River	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Arkoma	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	--	--	--
San Juan	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Alaska	--	--	--	--	--	--	--	--	--	--	--
Arizona	--	--	--	--	--	--	--	--	--	--	--
Arkansas	--	--	--	--	--	--	--	--	--	--	--
California	0.00	0.00	0.00	0.00	--	0.00	--	--	--	--	--
Louisiana	0.00	0.00	0.00	0.00	--	--	--	--	--	--	--
North Dakota	--	--	--	--	--	--	--	--	--	--	--
Texas	--	--	--	--	--	--	--	--	--	--	--
Washington	--	--	--	--	--	--	--	--	--	--	--
Total	0.32	0.30	0.27	0.31	0.28	0.28	0.28	0.28	0.29	0.29	0.27

-- = Less than 0.05 million metric tons.
Note: Totals may not equal sum of components due to independent rounding.
Source: EIA estimates, based on *Coal Production*, DOE/EIA-0118, various years, and methods described in Chapter 3.

Table B12. Methane Emissions Factors for Oil Production, Processing, and Distribution

Emissions Source	Coefficient	Unit	Reference
Oil and Gas Production			
Natural Gas Wellheads	0.870	Metric tons per well	EIA Estimate[a]
Oil Wells	0.072	Metric tons per well	EIA Estimate[a]
Gathering Pipelines	3.590	Metric tons per mile	EIA Estimate[a]
Gas Processing Plants	6.160	Metric tons per billion cubic feet of throughput	EIA Estimate[a]
Heaters, Separators, Dehydrators	21.870	Metric tons per billion cubic feet of gross withdrawals	EIA Estimate[a]
Transmission Pipeline	3.713	Metric tons per mile	EIA Estimate[a]
Plastic Distribution Pipeline	0.020	Metric tons per mile	EPA, 1993[b]
Nonplastic Distribution Pipeline	0.180	Metric tons per mile	EPA, 1993[b]
Gate Stations	0.092	Metric tons per mile of distribution pipeline	EIA Estimate[a]
System Upsets	0.031	Metric tons per mile of distribution pipeline	EPA, 1993[b]
Oil Refineries			
Fugitive Emissions	1.635×10^{-5}	Short tons per barrel of refinery capacity	Radian, 1992[c]
Tank Farms	4.37×10^{-7}	Short tons per barrel of throughput	Radian, 1992[c]
Flaring	4.00×10^{-7}	Short tons per barrel of refinery capacity	Radian, 1992[c]
Crude Transportation (Marine)	2.55×10^{-6}	Short tons per barrel loaded	Radian, 1992[c]

[a]EIA estimate based on scaling of factors published in U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States—Estimates for 1990*, Report to Congress (Washington, DC, April 1993).

[b]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).

[c]Radian Corporation, *Global Emissions of Methane from Petroleum Sources*, Final Report Prepared for the American Petroleum Institute (Research Triangle Park, NC, February 1992).

Table B13. U.S. Annual Consumption of Nitrogen Fertilizer (Year Ending June 30), 1985-1991
(Thousand Short Tons)

Fertilizer Type	1985	1986	1987	1988	1989	1990	1991
Anhydrous Ammonia	5,388	4,572	4,528	4,599	4,624	4,634	5,130
Aqua Ammonia	629	515	438	469	494	407	340
Nitrogen Solution	8,256	7,030	6,824	7,272	7,057	7,745	7,705
Ammonium Nitrate	2,195	1,735	1,643	1,769	1,899	1,778	1,850
Ammonium Sulfate	778	666	633	752	818	875	824
Urea	2,680	3,436	3,326	3,331	3,382	3,739	3,439
Sodium Nitrate	52	61	34	34	40	NA	NA
Ammonium Nitrate Limestone	NA	NA	NA	NA	NA	NA	NA
Total	19,978	18,015	17,426	18,226	18,313	19,178	19,288

NA = not available.

Sources: U.S. Department of Agriculture, Crop Reporting Board, Statistical Reporting Service, *Commercial Fertilizers*, SpCr 7 (Washington, DC, November, 1981-1985). Tennessee Valley Authority, National Fertilizer and Environmental Research Center, *Commercial Fertilizers (Including Fertilizer Use by Class)* (Muscle Shoals, AL, 1986-1992).

Table B14. Nitrous Oxide Emissions from Nitrogen Fertilizers, 1985-1991
(Metric Tons of Nitrous Oxide)

Fertilizer Type	1985	1986	1987	1988	1989	1990	1991
Median Emissions							
Anhydrous Ammonia	101,934	88,031	87,392	87,641	8,823	88,239	96,471
Aqua Ammonia	2,849	2,341	2,160	2,226	2,322	1,910	1,588
Nitrogen Solution	10,705	9,071	8,798	9,306	9,204	10,170	10,077
Ammonium Nitrate	2,780	2,136	2,109	2,190	2,402	2,234	2,319
Ammonium Sulfate	275	235	229	266	295	314	294
Urea	1,913	2,450	2,407	2,367	2,437	2,687	2,440
Sodium Nitrate	4	0	0	0	0	0	0
Ammonium Nitrate Limestone	1	0	0	0	0	0	0
Other Nitrogen Fertilizer	3,843	3,482	3,364	3,610	3,538	3,800	3,858
Total	**124,303**	**107,748**	**106,459**	**107,605**	**108,437**	**109,354**	**117,047**
Minimum Emissions							
Anhydrous Ammonia	53,781	46,446	46,109	46,240	46,555	46,556	50,899
Aqua Ammonia	1,503	1,235	1,140	1,174	1,225	1,008	838
Nitrogen Solution	2,549	2,160	2,095	2,216	2,192	2,421	2,399
Ammonium Nitrate	428	329	324	337	370	344	357
Ammonium Sulfate	46	39	38	44	49	52	49
Urea	1,217	1,559	1,531	1,506	1,551	1,710	1,553
Sodium Nitrate	0	0	0	0	0	0	0
Ammonium Nitrate Limestone	0	0	0	0	0	0	0
Other Nitrogen Fertilizer	35	32	31	33	32	35	35
Total	**59,559**	**51,800**	**51,268**	**51,550**	**51,974**	**52,125**	**56,130**
Maximum Emissions							
Anhydrous Ammonia	427,747	369,408	366,727	367,768	370,277	370,279	404,824
Aqua Ammonia	11,954	9,826	9,064	9,339	9,744	8,016	6,6635
Nitrogen Solution	83,603	70,843	68,706	72,676	71,882	79,425	78,697
Ammonium Nitrate	18,286	14,045	13,872	14,404	15,801	14,695	15,249
Ammonium Sulfate	3,431	2,943	2,859	3,331	3,685	3,923	3,675
Urea	26,088	33,413	32,817	32,274	33,233	36,638	33,279
Sodium Nitrate	59	0	0	0	0	0	0
Ammonium Nitrate Limestone	82	0	0	0	0	0	0
Other Nitrogen Fertilizer	238,936	216,524	209,186	224,460	219,985	236,274	239,886
Total	**810,187**	**717,002**	**703,230**	**724,253**	**724,607**	**749,249**	**782,273**

Sources: U.S. Department of Agriculture, Crop Reporting Board, Statistical Reporting Service, *Commercial Fertilizers*, SpCr 7 (Washington, DC, November, 1981-1985). Tennessee Valley Authority, National Fertilizer and Environmental Research Center, *Commercial Fertilizers (Including Fertilizer Use by Class)* (Muscle Shoals, AL, 1986-1992).

Appendix C
Carbon Sources Excluded

In general, this report attempts to include all known significant anthropogenic sources of gases studied. However, there are a number of potential carbon emissions sources that have been excluded due to lack of data, or because they have been defined as nonanthropogenic.

Combustion of Biofuels

As the product of atmospheric uptake by organic matter, the carbon present in biofuels is, arguably, a component of the terrestrial carbon cycle. Thus, no net additions to the global carbon budget result from their combustion. Carbon emissions from biofuels consumption are, therefore, excluded from the emissions estimates in this report. However, had they been included, it would have raised the estimate by about 70 million metric tons of carbon.

While emissions from the combustion of municipal solid waste have grown almost threefold between 1985 and 1990 and emissions from the consumption of

alcohol fuel have almost doubled, these increases have been more than offset by a large drop in emissions from wood combustion, the largest portion of biofuel consumption. Table C1 illustrates these trends.

Estimates of emissions from the combustion of municipal waste were calculated using an emissions coefficient of 24.7 million metric tons of carbon per quadrillion Btu.[171] Quantities of municipal solid waste burned were provided by Franklin Associates of Prairie Village, Kansas.

Emissions from the consumption of alcohol fuels were calculated using an emissions coefficient of 19.67 million metric tons of carbon per quadrillion Btu, based on the carbon content by weight of the ethanol molecule.[172] Ethanol is 52.2 percent carbon by weight, and it was assumed that 99 percent of carbon was oxidized when ethanol was consumed.

Emissions from the use of wood fuels were calculated using an emissions coefficient of 27.43 million metric

Table C1. Carbon Dioxide Emissions from Biofuels, 1985-1990
(Million Metric Tons of Carbon)

Fuel	1985	1986	1987	1988	1989	1990
Municipal Solid Waste	2.89	3.29	4.85	6.89	7.12	7.87
Alcohol Fuel	1.02	1.20	1.36	1.38	1.40	1.99
Wood and Wood Waste	70.50	68.71	66.85	69.12	71.43	62.18
Total	74.41	73.20	73.06	77.39	79.95	72.04

Note: Values for wood and alcohol consumption in 1985, 1986, and 1988 are estimated.
Sources: Underlying energy data from Energy Information Administration, *Annual Energy Review 1992*, DOE/EIA-0384(92) (Washington, DC, 1992), Table 10.2. Emissions coefficients from Energy Information Administration, *Electric Power Annual 1991*, DOE/EIA-0348(91) (Washington, DC, 1992), Table C-2. Volume of municipal solid waste combusted provided by Franklin Associates, Prairie Village, Kansas.

[171] Emissions coefficient based on Energy Information Administration, *Electric Power Annual 1991*, DOE/EIA-0348(91), Table C-2. Thermal content of 5,000 Btu per pound of waste based on Oak Ridge National Laboratory, *Data and Sources Biomass Supply*, draft report prepared for the Energy Information Administration (June 27, 1993). Carbon dioxide converted to carbon by multiplying by 12/44. Pounds of carbon converted to metric tons by dividing by 2,204.7.

[172] Consumption of alcohol fuels from Energy Information Administration, *Annual Energy Review 1992*, DOE/EIA-03894(92) (Washington, DC, 1992), Table 10.2. Consumption was converted from trillion Btu to pounds using a ratio of 11,920 Btu per pound, based on H. Douglas, *Handbook of Mineral Economics* (San Francisco, CA: Hugh Douglas and Company, 1983), p. 46. Carbon dioxide converted to carbon by multiplying by 12/44. Pounds converted to metric tons by dividing by 2,204.7.

tons of carbon per quadrillion Btu.[173] Data for alcohol fuel and wood fuel consumption were unavailable for the years 1985, 1986, and 1988. Consumption was interpolated using data from the surrounding years.

Burning Agricultural Wastes

The volume of crop residues and agricultural waste burned in the United States is very large. One estimate, drawn from the scientific literature, put the amount at about 300 million metric tons in the mid-1970s.[174] The authors suggested that about 10 percent of the material was left unburned, and that the carbon content of agricultural waste was about 45 percent by weight, implying annual carbon emissions from this source of about 120 million metric tons, equal to 8 to 9 percent of emissions from fossil fuels. However, as in the case of biofuels, the carbon emitted from this source would, in principle, be reabsorbed by the growth of crops during the next crop cycle, and hence not constitute a net source of emissions.

Burning Coal Wastes

An EPA report indicates that coal mine operators burn coal waste (mined material with an energy content too low to qualify as a commercial product) to dispose of it.[175] However, available information dates from the early 1970s, and the EPA report indicated that "the number of coal refuse piles had decreased to negligible by 1975." There are no data, and we have found no recent evidence to indicate that this activity continues to take place on any significant scale.

Forest Fires

Forest fires are a large source of both carbon dioxide and methane emissions. However, they are both a temporary source of carbon dioxide and usually a biogenic one.

Fermentation

Fermentation is a chemical process in which complex organic compounds, such as sugar, are broken down into simpler substances, namely alcohol and carbon dioxide. The carbon emitted during this process does not represent a net source of emissions, however, since the agricultural materials used during fermentation are renewable.

Oil Consumption by the U.S. Military Abroad

Table C2 reports estimated oil consumption by U.S. military forces. Energy consumption by the U.S. military is something of an anomaly in energy statistics. Domestic military energy consumption is included in domestic energy consumption statistics. U.S. military energy consumption of nonpetroleum fuels and some petroleum sources is generally included in the national energy statistics of the countries (such as Britain, Germany, Japan, and Korea) where the U.S. military operates. However, a substantial portion of U.S. military oil consumption is treated as an export in national energy statistics, but without any corresponding record of imports or consumption, since the fuel is loaded on tankers (recorded as an export) and then transferred directly to U.S. warships and military facilities without ever reappearing in the energy statistics of any country.

The amount of oil involved is problematic, because the Defense Department does not keep its books for the purpose of clarifying ambiguities in international energy statistics. Total oil consumption by U.S. military

Table C2. Carbon Emissions from U.S. Military Operations Abroad, 1985-1991
(Million Metric Tons of Carbon)

Item	1985	1986	1987	1988	1989	1990	1991
Energy Consumption (Quadrillion Btu)	0.30	0.27	0.29	0.31	0.26	0.25	0.30
Carbon Emissions	5.90	5.30	5.70	6.00	5.00	4.90	5.90

Sources: Energy consumption from Defense Fuel 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 chapter.

[173]Emissions coefficient based on Energy Information Administration, *Electric Power Annual 1991*, DOE/EIA-0348(91), Table C2. Carbon dioxide converted to carbon by multiplying by 12/44. Pounds of carbon converted to metric tons by dividing by 2,204.7. Consumption of wood from Energy Information Administration, *Annual Energy Review 1992*, DOE/EIA-0384(92) (Washington, DC, 1992), Table 10.2.

[174]W. Seiler and P. Crutzen, "Estimates of Gross and Net Fluxes of Carbon Between the Biosphere and the Atmosphere from Biomass Burning," *Climatic Change*, Vol. 2 (1980), pp. 231-232.

[175]U.S. Environmental Protection Agency, *National Air Pollutant Emissions Estimates 1940-1990*, EPA-450/4-91-026 (Washington, DC, November 1991), pp. 33-34.

forces amounts to about 500,000 barrels per day, according to records of fuel sales by the Defense Department's Defense Fuel Supply Center. The Defense Department does not maintain central records of the location of fuel sales, but reports that 65 to 75 percent of this amount (approximately 350,000 barrels per day) is acquired domestically, and hence is presumably counted in U.S. domestic oil consumption. The accuracy of these calculations may be impaired by the fact that estimates of the percentage acquired domestically is based on bulk fuel purchases, while consumption estimates are based on sales figures. Motor gasoline is presumably acquired almost entirely for motor vehicles, and is largely counted in national energy statistics, whether domestic or foreign. However, most of the oil consumption by the U.S. military consists of jet fuel and "middle distillates" used both to power ships and diesel vehicles.

A reasonable "order of magnitude" estimate for U.S. military oil consumption, not reported elsewhere, might be 25 percent of total military oil consumption of jet fuel, middle distillates, and residual oil. Table C2 illustrates carbon emissions associated with this estimate: approximately 5 million metric tons of carbon per year. The range of uncertainty associated with this estimate is on the order of 20 percent, i.e., between 20 and 30 percent of total military oil consumption.

Carbon Dioxide Coproduction with Natural Gas

Natural gas, as found in nature, usually consists predominantly of methane (CH_4) but is actually a mixture of several different hydrocarbon and nonhydrocarbon gases in varying proportions. A typical blend of raw gas might be 85 percent methane, 14 percent other hydrocarbons (particularly propane, butane, and ethane), and 1 percent carbon dioxide. The precise proportions of the blend are unique to each of the tens of thousands of natural gas reservoirs in the United States. Natural gas as shipped by pipeline, however, must be a standard product of fairly precise quality and must consist largely of methane.

If the quality of raw natural gas varies appreciably from pipeline quality, it must be treated in a gas processing plant. In the plant, valuable heavier hydrocarbons are stripped out for separate sale as "natural gas liquids." Hydrogen sulfide gas, a common contaminant, is always removed and the sulfur frequently recovered for separate sale. Excess carbon dioxide (if

any) is also removed and recovered for industrial use or vented to the atmosphere. In natural gas statistics, these removals account for most of the difference between raw or "wet" gas production and marketed "dry" gas production.

In 1990 some 289 billion cubic feet of nonhydrocarbon gases were removed from natural gas production in 25 States.[176] Eight gas-producing States (including Louisiana, a major producer) do not report on nonhydrocarbon removals. While no State reports on the breakdown among nonhydrocarbon gases, Texas reports on commercial carbon dioxide recovery from gas plants. In the early 1980s, commercial recovery was less than 10 percent of total nonhydrocarbon gas removals. Since 1988, the value has ranged from 75 percent to 95 percent of removals and has totaled 1.3 million to 2.1 million metric tons of carbon per year.[177]

It is possible to make crude estimates of carbon dioxide removals from rich gas for other states based on the Texas data. Table C3 illustrates an attempt to do this. In Texas, nonhydrocarbon gas extraction accounts for about 2 percent of gross natural gas production. In Table C3, nonhydrocarbon gas extraction is assumed to be 2 percent of gross production for the eight nonreporting States. This produces a 33-State estimate of nonhydrocarbon gas extraction. In Texas, commercial production of carbon dioxide from gas plants is as much as 95 percent of nonhydrocarbon gas extraction in 1988-1992. If we assume that other States have a similar ratio (90 percent), then national carbon dioxide extraction would be on the order of 400 billion cubic feet per year. From this amount, we deduct commercial carbon dioxide recovery from Texas (to avoid double counting with industrial carbon dioxide production). Commercial carbon dioxide recovery from gas plants in other States (if any) is double counting, although no data in this area have yet been found.

This very speculative estimation procedure produces net carbon dioxide emissions of 6 million metric tons in 1985, declining to 4 million metric tons by 1991. The main source of the decline is increasing commercial use of carbon dioxide in Texas. Some of this gas was vented to the atmosphere, some was used for industrial purposes, resulting in its being vented to the atmosphere, and an indeterminate (but probably large) volume was captured for reinjection into oil reservoirs.

This estimate has not been included in the main report because of its excessive uncertainty. The entire estimate

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[176]Energy Information Administration, *Natural Gas Annual 1991*, (DOE/EIA-0131(91)) (Washington, DC, October 1992), p. 14. This data item is collected by only 25 of the 33 gas-producing States. The excluded States account for about a third of U.S. gas production.

[177]Railroad Commission of Texas, *Annual Summary of Texas Natural Gas 1991* (mimeo, not dated) and prior years back to 1980.

Table C3. Estimated Carbon Dioxide Emissions from Natural Gas Plants, 1985-1991
(Billion Cubic Feet, Unless Otherwise Noted)

Item	1985	1986	1987	1988	1989	1990	1991
Total Gross Withdrawals	19,534.5	19,062.9	20,055.8	20,880.2	20,998.8	21,490.5	21,740.2
States Reporting NHCGR[a]	4,326.6	4,075.4	10,037.8	4,953.7	5,082.5	5,341.0	5,862.1
Texas	6,576.9	6,656.3	6,687.7	6,918.6	6,881.0	6,907.1	6,898.9
All Other States	8,630.9	8,331.2	3,330.3	9,007.8	9,035.3	9,242.4	8,979.2
Estimated NHCGR	499.1	503.5	442.6	640.0	543.2	474.2	455.4
States Reporting NHCGR	204.5	222.5	250.2	315.7	203.3	133.7	102.4
Texas	122.0	114.3	125.8	144.1	159.1	155.6	173.4
All Other States[b]	172.6	166.6	66.6	180.2	180.7	184.8	179.6
Estimated CO_2 Removed[c]	449.2	453.1	398.3	576.0	488.8	426.8	409.9
Estimated CO_2 Recovered	27.8	33.6	69.1	109.2	135.5	148.9	133.5
States Reporting NHCGR	--	--	--	--	--	--	--
Texas	27.8	33.6	69.1	109.2	135.5	148.9	133.5
All Other States	--	--	--	--	--	--	--
Estimated CO_2 Emissions							
Billion Cubic Feet	421.4	419.5	329.3	466.8	353.3	277.9	276.4
Million Metric Tons CO_2	22.2	22.1	17.3	24.6	18.6	14.6	14.5
Million Metric Tons Carbon	6.1	6.0	4.7	6.7	5.1	4.0	4.0

[a]Nonhydrocarbon gases removed.
[b]Assumes that 2 percent of All Other States' gas withdrawals are nonhydrocarbon gases.
[c]Assumes that 90 percent of the total nonhydrocarbon gas removed is carbon dioxide.
Note: Totals may not equal sum of components due to independent rounding.
Sources: Railroad Commission of Texas, *Annual Summaries of Texas Natural Gas* (various years), and Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (various years).

is really based on a single ratio: the ratio of commercial carbon dioxide recovery to nonhydrocarbon gases removed in Texas. There is no real basis for assuming that the nonhydrocarbon gas share of nonreporting States is equal to the share of those that do report, nor any real basis for assuming that the carbon dioxide share of nonhydrocarbon gases outside of Texas equals that within Texas. Finally, there is no basis for determining how much carbon dioxide is recovered for commercial use or in enhanced oil recovery outside of Texas. There are, however, some emissions from this source, and this estimate provides a first approximation of what their magnitude might be.

Sulfur Scrubbing in Power Generation

Calcination of limestone used for the scrubbing of sulfur oxides from the emissions of coal-fired power plants is another potential source of carbon emissions. In this process, each sulfur atom in sulfur dioxide (SO_2) is exchanged for a carbon atom donated by limestone ($CaCO_3$), so that carbon dioxide goes up the stack instead of sulfur dioxide, and elemental sulfur is left

behind as calcium sulfate. It is not clear, however, that all scrubber processes produce this result, since limestone is not universally used. Even assuming the universal use of limestone, however, the likely number is less than 1 million metric tons of carbon per year.

It is also worth noting that most proposed "Clean Coal" power generation technologies, including integrated gasification combined cycle (IGCC) and fluidized bed combustion, also use limestone as a sulfur sorbent, and consequently emit 1 mole of carbon dioxide for each mole of sulfur scrubbed, over and above carbon emissions from the combustion of the coal.

Iron Smelting

Prior to 1985, limestone consumption in iron smelting was reported by the American Iron and Steel Institute. In 1984, some 7 million metric tons of limestone were used during this process. This item would have accounted for about 0.8 million metric tons of carbon emissions annually.[178] No recent data have been found on this item.

[178]American Iron and Steel Institute, *Iron and Steel Annual Statistical Report* (various dates).

Lead Smelting

EPA reports that limestone is also calcined as part of the lead smelting process.[179] No data on the amount of limestone involved have yet been found, though the volume is likely to be very small, since less than 400,000 tons of lead is smelted annually.

Limestone in Glass

Limestone is also used in the manufacture of soda-lime glass, which accounts for some 75 percent of the glass manufactured in the United States. No data have yet been found on the volume of limestone used.

Other Industrial Sources

In addition to those specifically noted above, there may be other industrial sources of carbon emissions of which the authors are unaware. EPA reports that 4.69 million metric tons of carbon monoxide, or 2.1 million metric tons of carbon, were emitted from industrial processes in 1991. It is likely that most of this carbon is included in emissions from known industrial sources or from the direct or indirect combustion of fossil fuels. However, other sources may be identified in the future.

[179]U.S. Environmental Protection Agency, *Air Pollutant Emission Factors*, AP-42 (Research Triangle Park, NC, 1985).

Appendix D
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 (CH_4-C) = 1.333 pounds methane, measured at full molecular weight (CH_4)

1 pound carbon dioxide, measured in carbon units (CO_2-C) = 3.6667 pounds carbon dioxide, measured at full molecular weight (CO_2)

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 (N_2O-N) = 1.571 pounds nitrous oxide, measured at full molecular weight (N_2O)

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 m^2

1 hectare (ha) = 10,000 m^2 = 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
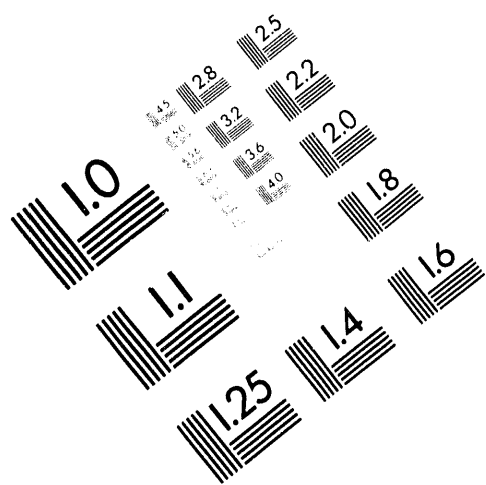
1 quadrillion Btu = 1.0551 exajoule

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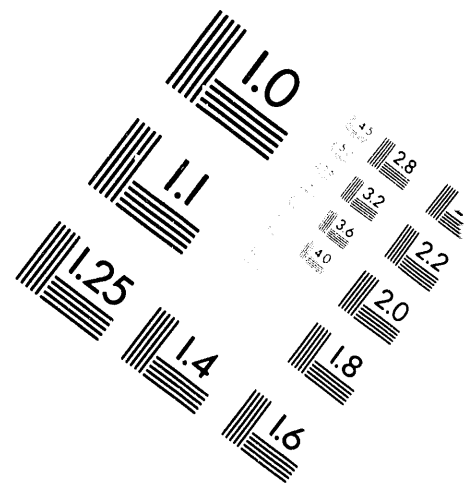
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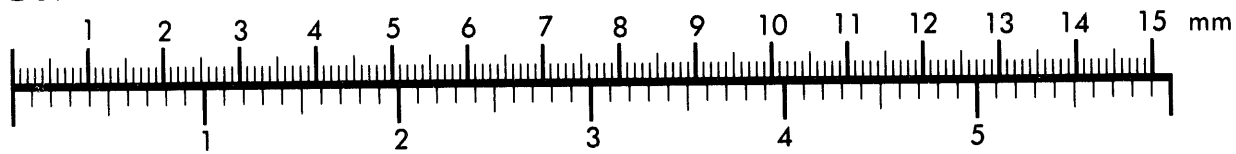
Centimeter

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Inches

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	5.0 3.2	2.2
	3.6	
1.1	4.0	2.0
		1.8
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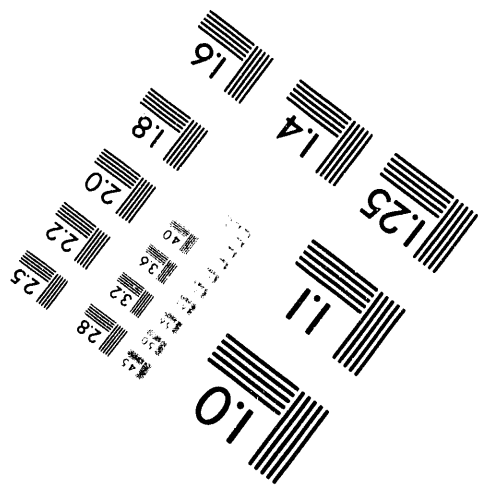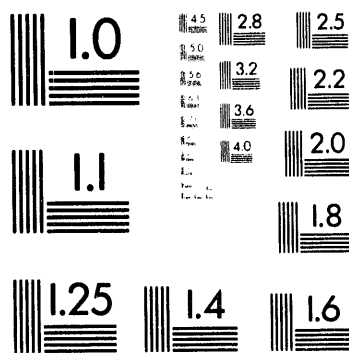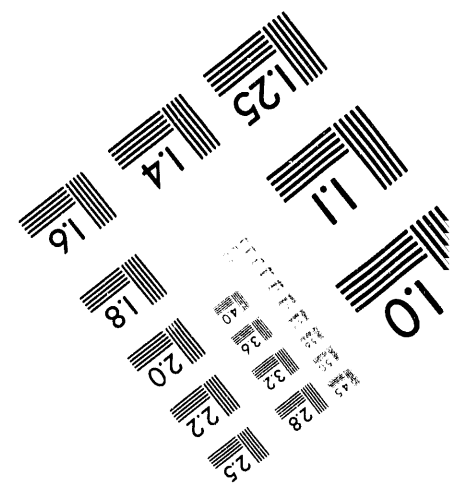
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Glossary

Aerobic decomposition: The breakdown of a molecule into simpler molecules or atoms by microorganisms under favorable conditions of oxygenation.

Airshed: An area or region defined by settlement patterns or geology which result in discrete atmospheric conditions.

Anaerobic decomposition: The breakdown of a molecule into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

Anode: A positive electrode, as in a battery, radio tube, etc.

Anthracite: A hard, black lustrous coal containing a high percentage of fixed carbon and a low percentage of volatile matter. Often referred to as hard coal.

Anthropogenic: Man made. Usually used in the context of emissions that are produced as the result of human activities.

Asphalt: A dark-brown to black cement-like material containing bitumens as the predominant constituents obtained by petroleum processing. The definition includes crude asphalt as well as the following finished products: cements, fluxed, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cutback asphalts.

Atmosphere: The envelope of air surrounding the Earth and bound to it by the Earth's gravitational attraction.

Aviation gasoline: All special grades of gasoline for use in aviation reciprocating engines. Excludes blending components which will be used in blending or compounding into finished aviation gasoline.

Balancing item: A measurement of the difference between the reported amount of natural gas produced and the amount consumed.

Biofuels: Wood, waste, and alcohol fuels.

Biogas: The gas produced from the anaerobic decomposition of organic material in a landfill.

Biogenic: Produced by the actions of living organisms.

Biomass: The total dry organic matter or stored energy content of living organisms that is present at a specific time in a defined unity of the Earth's surface.

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 life-derived organic matter.

Bituminous coal: Bituminous coal, or soft coal, is the most common coal. It is dense, black, often with well-defined bands of bright and dull material. Its moisture content usually is less than 20 percent. It is used for generating electricity, making coke, and space heating.

Bunker fuels: Fuel supplied to ships and aircraft in international transportation, irrespective of the flag of the carrier, consisting primarily of residual fuel oil for ships and distillate and jet fuel oils for aircraft.

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.

Carbon budget: The balance of the exchanges (incomes and losses) of carbon between the carbon reservoirs or between one specific loop (e.g. atmosphere - biosphere) of the carbon cycle.

Carbon cycle: All reservoirs and fluxes of carbon; usually thought of as a series of the four main reservoirs of carbon interconnected by pathways of exchange. The four reservoirs, regions of the Earth in which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually includes freshwater systems), oceans, and sediments (includes fossil fuels). Each of these global reservoirs may be subdivided into smaller pools ranging in size from individual communities or ecosystems to the total of all

living organisms (biota). Carbon exchanges from reservoir to reservoir by various chemical, physical, geological, and biological processes.

Carbon sink: A pool (reservoir) that absorbs or takes up released carbon from another part of the carbon cycle.

Chlorofluorocarbons (CFCs): A family of inert, non-toxic, and easily liquified chemicals used in refrigeration, air conditioning, packaging, and insulation, or as solvents or aerosol propellants. Because they are not destroyed in the lower atmosphere, they drift into the upper atmosphere where their chlorine components destroy ozone.

Clinker: Powdered cement—produced by heating a properly proportioned mixture of finely ground raw materials containing calcium carbonate, silica, alumina, and iron oxide in a kiln to a temperature of about 2,700 degrees Fahrenheit at which partial fusion occurs.

Cloud condensation nuclei: Aerosol particles which provide a platform for the condensation of water vapor, resulting in clouds with higher droplet concentrations and increased albedo.

Coal coke: A hard porous product made from baking bituminous coal in ovens at temperatures as high as 2,000 degrees. It is used both as a fuel and as a reducing agent in smelting iron ore in a blast furnace. The term "coal coke" is used instead of "coke" to distinguish it from petroleum coke.

Coalbed methane: Methane that is produced from coalbeds in the same manner as natural gas produced from other strata. Methane is the principal component of natural gas.

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.

Cultivar: A horticulturally or agriculturally derived variety of a plant.

Deforestation: The removal of forest stands by cutting and burning to provide land for agricultural purposes, residential or industrial building sites, roads, etc. or by harvesting the tress for building materials or fuel.

Degradable organic carbon: The portion of organic carbon from such solid waste as paper, food waste and yard waste which is susceptible to biochemical decomposition.

Desulfurization: The removal of sulfur from molten metals or petroleum oil.

Distillate fuel: A general classification for one of the petroleum fractions produced in conventional distillation operations. Included are products known as No. 1, No. 2, and No. 4 fuel oils and No. 1, No. 2, and No. 4 diesel fuels. It is used primarily for space heating, on- and off-highway diesel engine fuel (including railroad engine fuel and fuel for agricultural machinery), and electric power generation.

Enteric fermentation: A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream.

Facultative bacteria: Bacteria that grow equally well under aerobic and anaerobic conditions.

Flared natural gas: Natural gas burned in flares on the base site or at gas processing plants.

Flatus: Gas generated in the intestines or the stomach.

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.

Fossil fuel: Any naturally occurring organic fuel formed in the earth's crust, such as petroleum, coal, and natural gas.

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 which can be burned to generate power or processed into chemicals and fuels.

Global Warming Potential (GWP): The instantaneous radiative forcing due to the addition of 1 kilogram of a trace gas to the atmosphere relative to that of 1 kilo-

gram of carbon dioxide. The concentration of that gas in the atmosphere at any point on the time horizon relative to that of carbon dioxide can be used to calculate GWP for that time frame.

Greenhouse effect: A popular term used to describe the roles of water vapor, carbon dioxide, ant other trace gases in keeping the Earth's surface warmer than it would be otherwise. These radiatively active gases are relatively transparent to incoming shortwave radiation, but are relatively opaque to outgoing longwave radiation. The latter radiation, which would otherwise escape to space, is trapped by these gases within the lower levels of the atmosphere. The subsequent reradiation of some of the energy back to the Earth maintains surface temperatures higher than they would be if the gases were absent. There is concern that increasing concentrations of greenhouse gases, including carbon dioxide, methane and manmade chlorofluorocarbons, may enhance the greenhouse effect and cause global warming.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, tropospheric ozone, nitrous oxide, and methane, that are transparent to solar radiation but opaque to longwave radiation. Their action is similar to that of glass in a greenhouse.

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 simples (e.g., methane, a constituent of natural gas) to the very heavy and very complex.

Hydroxyl radical: The hydroxyl radical, OH, is an important chemical scavenger of many trace gases in the atmosphere that are greenhouse gases. The atmospheric concentrations of OH affect the atmospheric lifetime of these gases and thus affect their abundances and ultimately the effect they have on climate.

Jet fuel: The term includes kerosene-type jet fuel and naphtha-type jet fuel. Kerosene-type jet fuel is a kerosene quality product used primarily for commercial turbojet and turboprop aircraft engines. Naphtha-type jet fuel is a fuel in the heavy naphthas range used primarily for military turbojet and turboprop aircraft engines.

Kerosene: A petroleum distillate that has a maximum distillation temperature of 401 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. Kerosene is used in space heaters,

cook stoves, and water heaters; it is suitable for use as an illuminant when burned in wick lamps.

Leachate: A liquid that results from water collecting contaminants as it percolates through wastes.

Lignite: A brownish-black coal of low rank with high inherent moisture and volatile matter. It is also referred to as brown coal. It is used almost exclusively for electric power generation.

Liquified 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.

Lubricants: A substance used to reduce friction between bearing surfaces or as a process material either incorporated into other materials used as processing aids in the manufacturing of other products 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 certain required properties. Does not include byproducts of lubricating oil from solvent extraction or tars derived from deasphalting. Lubricants includes all grades of lubricating oils from spindle oil to cylinder oil and those used in greases. Lubricants categories are parafinnic and napthenic.

Methanogenic bacteria: Bacteria which synthesize methane, requiring completely anaerobic conditions for growth.

Methanotropic bacteria: Bacteria that derive energy from the oxidation of methane.

Mole: A specified number of molecules (6.28 × 10^{23}).

Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer 1987 is 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 fifty 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 yet to be ratified Copenhagen agreement calls for a complete phaseout by January 1, 1996.

Motor gasoline: A complex mixture of relatively volatile hydrocarbons, with or without small quantities of additives, obtained by blending appropriate refinery

streams to form a fuel suitable for use in spark-ignition engines. Motor gasoline includes both leaded and unleaded grades of finished motor gasoline, blending components, and gasohol.

Multiple cropping: A system of growing several crops on the same field in one year.

Naphtha: A generic term applied to a petroleum fraction with an approximate boiling range between 122 and 400 degrees Fahrenheit.

Natural gas: A mixture of hydrocarbons and small quantities of various nonhydrocarbons existing in the gaseous phase or in solution with crude oil in natural underground reservoirs at reservoir conditions.

Nitrogen oxides (NO$_x$): Compounds of nitrogen and oxygen which may be produced by the burning of fossil fuels.

Ozone: A molecule made up of three atoms of oxygen. In the stratosphere, it occurs naturally and provides a protective layer shielding the Earth from harmful ultraviolet radiation. In the troposphere, it is a chemical oxidant and major component of photochemical smog.

Ozone precursor: A chemical compound such as carbon monoxide, methane, nonmethane hydrocarbons and nitrogen oxides which in the presence of solar radiation reacts with other chemical compounds to form ozone.

Petrochemical feedstock: Chemical feedstocks derived from petroleum principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics. The categories reported are naphthas less than 401 degrees Fahrenheit an other oils equal to or greater than 401 degrees Fahrenheit endpoint.

Petroleum: Hydrocarbon mixtures broadly defined to include crude oil, lease condensate, natural gas, products of natural gas processing plants (plant products), refined products, and semifurnished products and blending materials.

Petroleum coke: A residue, the final product of the condensation process in cracking.

Photolysis: The use of radiant energy to produce chemical changes.

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. Oxygen and water vapor are released in the process.

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.

Radiatively active gases: Gases that absorb incoming solar radiation or outgoing infrared radiation, thus affecting the vertical temperature profile of the atmosphere.

Redox potential: A measurement of the state of oxidation of a system.

Reflectivity: The ratio of the energy carried by a wave that is reflected from a surface to the energy of a wave incident to the surface.

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 that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations and that conform to ASTM Specifications D396 and 975. Included are No. 5, a residual fuel oil of medium viscosity; Navy Special, for use in steam-powered vessels in government service and in shore power plants; and No. 6, which includes Bunker C fuel oil and is used for commercial and industrial heating, electricity generation, and to power ships. Imports of residual fuel oil include imported crude oil burned as fuel.

Stratosphere: The region of the upper atmosphere extending from the tropopause (8 to 15 km altitude) to about 50 km. The thermal structure is determined by its radiation balance and is generally very stable with low humidity.

Stripper wells: A well that produces 60 Mcf per day or less of gas-well gas for a period of three consecutive months while producing at its maximum rate flow. In determining abandonments, a stripper well is one that produced less than 22,500 Mcf in its last 12 months of production.

Subbituminous coal: A dull, black coal of rank intermediate between lignite and bituminous coal.

Trace gas: A minor constituent of the atmosphere.

Troposphere: The inner layer of the atmosphere below about 15 km, 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 by turbulent mixing and convection.

Vented natural gas: Gas released into the air on the base site or at processing plants.

Volatile organic compound: Organic compounds which participate in atmospheric photochemical reactions.

Waxes: Solid or semisolid materials derived from petroleum distillates or residues. Waxes are light-colored, more or lest 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. Waxes are used primarily as industrial coating for surface protection.

Wetlands: An area regularly saturated by surface or groundwater and subsequently is characterized by a prevalence of vegetation that is 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, charcoal, pulp waste, and spent pulping liquor.

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