

## Related Links

- Australian Greenhouse Office.  
[www.greenhouse.gov.au](http://www.greenhouse.gov.au)
- Carbon Dioxide Information Analysis Center.  
<http://cdiac.esd.ornl.gov>
- Centre for the Analysis and Dissemination of Demonstrated Energy Technologies.  
*Renewable Energy*: [www.caddet-re.org](http://www.caddet-re.org)  
*Energy Efficiency*: [www.caddet-ee.org](http://www.caddet-ee.org)
- Center for Renewable Energy and Sustainable Technology.  
<http://solstice.crest.org/index.shtml>
- Climate Ark.  
[www.climateark.org](http://www.climateark.org)
- Energy Information Administration.  
[www.eia.doe.gov](http://www.eia.doe.gov)
- Energy Information Administration, Greenhouse Gas Emissions and Climate Change Publications.  
[www.eia.doe.gov/env/ghg.html](http://www.eia.doe.gov/env/ghg.html)
- Environmental Defense Fund.  
[www.edf.org](http://www.edf.org)
- Global Change.  
[www.globalchange.org](http://www.globalchange.org)
- Global Change Data & Information System.  
<http://globalchange.gov>
- Global Environment Facility.  
[www.gefweb.org](http://www.gefweb.org)
- Global Climate Change from the Government of Canada.  
[www.climatechange.gc.ca](http://www.climatechange.gc.ca)
- Intergovernmental Panel on Climate Change.  
[www.ipcc.ch](http://www.ipcc.ch)
- International Energy Agency.  
[www.iea.org](http://www.iea.org)
- International Institute for Sustainable Development.  
[www.iisd.org](http://www.iisd.org)
- National Institute for Global Environment Change.  
<http://nigec.ucdavis.edu>
- Natural Resources Defense Council, Global Warming.  
[www.nrdc.org/globalWarming](http://www.nrdc.org/globalWarming)
- Organization for Economic Cooperation and Development.  
[www.oecd.org/env/](http://www.oecd.org/env/)
- Pew Center on Climate Change.  
[www.pewclimate.org](http://www.pewclimate.org)
- Resources for the Future.  
[www.rff.org](http://www.rff.org)
- Weathervane, Digital Forum on Global Climate Policy.  
[www.weathervane.rff.org](http://www.weathervane.rff.org)
- Union of Concerned Scientists.  
[www.ucsusa.org](http://www.ucsusa.org)
- United Nations Development Program.  
[www.undp.org](http://www.undp.org)
- United Nations Environment Programme.  
[www.unep.ch](http://www.unep.ch)
- United Nations Environment Programme, Ozone Secretariat (Montreal Protocol).  
[www.unep.ch/ozone/home.htm](http://www.unep.ch/ozone/home.htm)
- United Nations Food and Agriculture Program.  
[www.fao.org](http://www.fao.org)
- United Nations Framework Convention on Climate Change.  
[www.unfccc.de](http://www.unfccc.de)
- U.S. Agency for International Development.  
[www.usaid.gov](http://www.usaid.gov)
- U.S. Department of Agriculture, Global Change Program Office.  
[www.usda.gov/oce/gcpo/](http://www.usda.gov/oce/gcpo/)
- U.S. Department of Energy, Environmental Quality.  
[www.energy.gov/environ/](http://www.energy.gov/environ/)
- U.S. Department of Energy, Climate Challenge Program.  
[www.eren.doe.gov/climatechallenge/](http://www.eren.doe.gov/climatechallenge/)
- U.S. Department of State, Climate Change Homepage.  
<http://www.state.gov/g/oes/climate/>

## ***Related Links***

---

U.S. Environmental Protection Agency,  
Global Warming Homepage.  
[www.epa.gov/globalwarming/](http://www.epa.gov/globalwarming/)

U.S. Geological Survey, Global Change Research.  
<http://geochange.er.usgs.gov>

U.S. Global Change Research Office.  
<http://gcrio.gcrio.org>

U.S. Global Change Research Program.  
[www.usgcrp.gov](http://www.usgcrp.gov)

U.S. Initiative on Joint Implementation.  
[www.gcrio.org/usiji/](http://www.gcrio.org/usiji/)

U.S. National Aeronautics and Space Administration  
(NASA), Global Change Master Directory.  
<http://gcmd.gsfc.nasa.gov>

U.S. National Oceanographic and Atmospheric  
Administration (NOAA), Office of Global Programs.  
[www.ogp.noaa.gov](http://www.ogp.noaa.gov)

U.S. White House, Global Climate Change Policy Book.  
[www.whitehouse.gov/news/releases/2002/02/  
climatechange.html](http://www.whitehouse.gov/news/releases/2002/02/climatechange.html)

U.S. White House, Policies in Focus, Environment.  
[www.whitehouse.gov/infocus/environment/](http://www.whitehouse.gov/infocus/environment/)

World Bank Climate Change Web Site.  
[www.worldbank.org/climatechange](http://www.worldbank.org/climatechange)

World Health Organization, Protection of the Human  
Environment.  
[www.who.int/peh/](http://www.who.int/peh/)

World Meteorological Organization.  
[www.wmo.ch](http://www.wmo.ch)

World Resources Institute.  
[www.wri.org](http://www.wri.org)

Worldwatch Institute.  
[www.worldwatch.org](http://www.worldwatch.org)

World Wildlife Fund, Climate Change Campaign.  
[www.panda.org/climate/](http://www.panda.org/climate/)

## Glossary

**Acid stabilization:** A circumstance where the pH of the waste mixture in an animal manure management system is maintained near 7.0, optimal conditions for methane production.

**Aerobic bacteria:** Microorganisms living, active, or occurring only in the presence of oxygen.

**Aerobic decomposition:** The breakdown of a molecule into simpler molecules or atoms by microorganisms under favorable conditions of oxygenation.

**Aerosols:** Airborne particles.

**Afforestation:** Planting of new forests on lands that have not been recently forested.

**Agglomeration:** The clustering of disparate elements.

**Airshed:** An area or region defined by settlement patterns or geology that results in discrete atmospheric conditions.

**Albedo:** The fraction of incident light or electromagnetic radiation that is reflected by a surface or body. See *Planetary albedo*.

**Anaerobes:** Organisms that live and are active only in the absence of oxygen.

**Anaerobic bacteria:** Microorganisms living, active, or occurring only in the absence of oxygen.

**Anaerobic decomposition:** The breakdown of molecules into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

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

**Anode:** A positive electrode, as in a battery, radio tube, etc.

**Anthracite:** The highest rank of coal; used primarily for residential and commercial space heating. It is a hard, brittle, and black lustrous coal, often referred to as hard coal, containing a high percentage of fixed carbon and a low percentage of volatile matter. The moisture content of fresh-mined anthracite generally is less than 15

percent. The heat content of anthracite ranges from 22 to 28 million Btu per ton on a moist, mineral-matter-free basis. The heat content of anthracite coal consumed in the United States averages 25 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter). Note: Since the 1980's, anthracite refuse or mine waste has been used for steam electric power generation. This fuel typically has a heat content of 15 million Btu per ton or less.

**Anthropogenic:** Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation.

**API Gravity:** American Petroleum Institute measure of specific gravity of crude oil or condensate in degrees. An arbitrary scale expressing the gravity or density of liquid petroleum products. The measuring scale is calibrated in terms of degrees API; it is calculated as follows: Degrees API =  $(141.5 / \text{sp.gr.} \cdot 60 \text{ deg.F} / 60 \text{ deg.F}) - 131.5$ .

**Asphalt:** A dark brown-to-black cement-like material obtained by petroleum processing and containing bitumens as the predominant component; used primarily for road construction. It includes crude asphalt as well as the following finished products: cements, fluxes, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cut-back asphalts. Note: The conversion factor for asphalt is 5.5 barrels per short ton.

**Associated natural gas:** See *Associated-dissolved natural gas* and *Natural gas*.

**Associated-dissolved natural gas:** Natural gas that occurs in crude oil reservoirs either as free gas (associated) or as gas in solution with crude oil (dissolved gas). See *Natural gas*.

**Aviation gasoline (finished):** A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D 910 and Military Specification MIL-G-5572. Note: Data on blending components are not counted in data on finished aviation gasoline.

**Balancing item:** Represents differences between the sum of the components of natural gas supply and the sum of the components of natural gas disposition. These differences may be due to quantities lost or to the effects of data reporting problems. Reporting problems include differences due to the net result of conversions of flow data metered at varying temperature and pressure bases and converted to a standard temperature and pressure base; the effect of variations in company accounting and billing practices; differences between billing cycle and calendar period time frames; and imbalances resulting from the merger of data reporting systems that vary in scope, format, definitions, and type of respondents.

**Biofuels:** Liquid fuels and blending components produced from biomass (plant) feedstocks, used primarily for transportation.

**Biogas:** The gas produced from the anaerobic decomposition of organic material in a landfill.

**Biogenic:** Produced by the actions of living organisms.

**Biomass:** Organic nonfossil material of biological origin constituting a renewable energy source.

**Biosphere:** The portion of the Earth and its atmosphere that can support life. The part of the global carbon cycle that includes living organisms and biogenic organic matter.

**Bituminous coal:** A dense coal, usually black, sometimes dark brown, often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing and to make coke. Bituminous coal is the most abundant coal in active U.S. mining regions. Its moisture content usually is less than 20 percent. The heat content of bituminous coal ranges from 21 to 30 million Btu per ton on a moist, mineral-matter-free basis. The heat content of bituminous coal consumed in the United States averages 24 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

**BOD<sub>5</sub>:** The biochemical oxygen demand of wastewater during decomposition occurring over a 5-day period. A measure of the organic content of wastewater.

**Bromofluorocarbons (halons):** Inert, nontoxic chemicals that have at least one bromine atom in their chemical makeup. They evaporate without leaving a residue and are used in fire extinguishing systems, especially for large computer installations.

**Bunker fuel:** Fuel supplied to ships and aircraft, both domestic and foreign, consisting primarily of residual and distillate fuel oil for ships and kerosene-based jet

fuel for aircraft. The term “international bunker fuels” is used to denote the consumption of fuel for international transport activities. *Note:* For the purposes of greenhouse gas emissions inventories, data on emissions from combustion of international bunker fuels are subtracted from national emissions totals. Historically, bunker fuels have meant only ship fuel. See *Vessel bunkering*.

**Calcination:** A process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled.

**Calcium sulfate:** A white crystalline salt, insoluble in water. Used in Keene’s cement, in pigments, as a paper filler, and as a drying agent.

**Calcium sulfite:** A white powder, soluble in dilute sulfuric acid. Used in the sulfite process for the manufacture of wood pulp.

**Capital stock:** Property, plant and equipment used in the production, processing and distribution of energy resources.

**Carbon black:** An amorphous form of carbon, produced commercially by thermal or oxidative decomposition of hydrocarbons and used principally in rubber goods, pigments, and printer’s ink.

**Carbon budget:** Carbon budget: The balance of the exchanges (incomes and losses) of carbon between carbon sinks (e.g., atmosphere and biosphere) in the carbon cycle. See *Carbon cycle* and *Carbon sink*.

**Carbon cycle:** All carbon sinks and exchanges of carbon from one sink to another by various chemical, physical, geological, and biological processes. See *Carbon sink* and *Carbon budget*.

**Carbon dioxide (CO<sub>2</sub>):** A colorless, odorless, nonpoisonous gas that is a normal part of Earth’s atmosphere. Carbon dioxide is a product of fossil-fuel combustion as well as other processes. It is considered a greenhouse gas as it traps heat (infrared energy) radiated by the Earth into the atmosphere and thereby contributes to the potential for global warming. The global warming potential (GWP) of other greenhouse gases is measured in relation to that of carbon dioxide, which by international scientific convention is assigned a value of one (1). See *Global warming potential (GWP)* and *Greenhouse gases*.

**Carbon dioxide equivalent:** The amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas. Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured (for example, methane) by its

estimated global warming potential (which is 21 for methane). “Carbon equivalent units” are defined as carbon dioxide equivalents multiplied by the carbon content of carbon dioxide (i.e., 12/44).

**Carbon flux:** See *Carbon budget*.

**Carbon intensity:** The amount of carbon by weight emitted per unit of energy consumed. A common measure of carbon intensity is weight of carbon per British thermal unit (Btu) of energy. When there is only one fossil fuel under consideration, the carbon intensity and the emissions coefficient are identical. When there are several fuels, carbon intensity is based on their combined emissions coefficients weighted by their energy consumption levels. See *Emissions coefficient* and *Carbon output rate*.

**Carbon output rate:** The amount of carbon by weight per kilowatthour of electricity produced.

**Carbon sequestration:** The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes.

**Carbon sink:** A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. The four sinks, which are regions of the Earth within which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels).

**Catalytic converter:** A device containing a catalyst for converting automobile exhaust into mostly harmless products.

**Catalytic hydrocracking:** A refining process that uses hydrogen and catalysts with relatively low temperatures and high pressures for converting middle boiling or residual material to high octane gasoline, reformer charge stock, jet fuel, and/or high grade fuel oil. The process uses one or more catalysts, depending on product output, and can handle high sulfur feedstocks without prior desulfurization.

**Cesspool:** An underground reservoir for liquid waste, typically household sewage.

**Chlorofluorocarbon (CFC):** Any of various compounds consisting of carbon, hydrogen, chlorine, and fluorine used as refrigerants. CFCs are now thought to be harmful to the earth’s atmosphere.

**Clean Development Mechanism (CDM):** A Kyoto Protocol program that enables industrialized countries to finance emissions-avoiding projects in developing countries and receive credit for reductions achieved against

their own emissions limitation targets. See *Kyoto Protocol*.

**Climate:** The average course or condition of the weather over a period of years as exhibited by temperature, humidity, wind velocity, and precipitation.

**Climate change:** A term used to refer to all forms of climatic inconsistency, but especially to significant change from one prevailing climatic condition to another. In some cases, “climate change” has been used synonymously with the term “global warming”; scientists, however, tend to use the term in a wider sense inclusive of natural changes in climate, including climatic cooling.

**Clinker:** Powdered cement, produced by heating a properly proportioned mixture of finely ground raw materials (calcium carbonate, silica, alumina, and iron oxide) in a kiln to a temperature of about 2,700°F.

**Cloud condensation nuclei:** Aerosol particles that provide a platform for the condensation of water vapor, resulting in clouds with higher droplet concentrations and increased albedo.

**Coal coke:** See *Coke (coal)*.

**Coalbed methane:** Methane is generated during coal formation and is contained in the coal microstructure. Typical recovery entails pumping water out of the coal to allow the gas to escape. Methane is the principal component of natural gas. Coalbed methane can be added to natural gas pipelines without any special treatment.

**Coke (coal):** A solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal from which the volatile constituents are driven off by baking in an oven at temperatures as high as 2,000 degrees Fahrenheit so that the fixed carbon and residual ash are fused together. Coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. Coke from coal is grey, hard, and porous and has a heating value of 24.8 million Btu per ton.

**Coke (petroleum):** A residue high in carbon content and low in hydrogen that is the final product of thermal decomposition in the condensation process in cracking. This product is reported as marketable coke or catalyst coke. The conversion is 5 barrels (of 42 U.S. gallons each) per short ton. Coke from petroleum has a heating value of 6.024 million Btu per barrel.

**Combustion:** Chemical oxidation accompanied by the generation of light and heat.

**Combustion chamber:** An enclosed vessel in which chemical oxidation of fuel occurs.

**Conference of the Parties (COP):** The collection of nations that have ratified the Framework Convention on Climate Change (FCCC). The primary role of the COP is to keep implementation of the FCCC under review and make the decisions necessary for its effective implementation. See *Framework Convention on Climate Change (FCCC)*.

**Cracking:** The refining process of breaking down the larger, heavier, and more complex hydrocarbon molecules into simpler and lighter molecules.

**Criteria pollutant:** A pollutant determined to be hazardous to human health and regulated under EPA's National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act require EPA to describe the health and welfare impacts of a pollutant as the "criteria" for inclusion in the regulatory regime.

**Crop residue:** Organic residue remaining after the harvesting and processing of a crop.

**Cultivar:** A horticulturally or agriculturally derived variety of a plant.

**Deforestation:** The net removal of trees from forested land.

**Degasification system:** The methods employed for removing methane from a coal seam that could not otherwise be removed by standard ventilation fans and thus would pose a substantial hazard to coal miners. These systems may be used prior to mining or during mining activities.

**Degradable organic carbon:** The portion of organic carbon present in such solid waste as paper, food waste, and yard waste that is susceptible to biochemical decomposition.

**Desulfurization:** The removal of sulfur, as from molten metals, petroleum oil, or flue gases.

**Diffusive transport:** The process by which particles of liquids or gases move from an area of higher concentration to an area of lower concentration.

**Distillate fuel:** A general classification for one of the petroleum fractions produced in conventional distillation operations. It includes diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. Products known as No. 1, No. 2, and No. 4 fuel oils are used primarily for space heating and electric power generation.

**Efflux:** An outward flow.

**Electrical generating capacity:** The full-load continuous power rating of electrical generating facilities, generators, prime movers, or other electric equipment (individually or collectively).

**EMCON Methane Generation Model:** A model for estimating the production of methane from municipal solid waste landfills.

**Emissions:** Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).

**Emissions coefficient:** A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., pounds of carbon dioxide emitted per Btu of fossil fuel consumed).

**Enteric fermentation:** A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

**Eruption:** An act or instance of belching.

**ETBE (ethyl tertiary butyl ether):**  $(\text{CH}_3)_3\text{COC}_2\text{H}$ : An oxygenate blend stock formed by the catalytic etherification of isobutylene with ethanol.

**Ethylene:** An olefinic hydrocarbon recovered from refinery processes or petrochemical processes. Ethylene is used as a petrochemical feedstock for numerous chemical applications and the production of consumer goods.

**Ethylene dichloride:** A colorless, oily liquid used as a solvent and fumigant for organic synthesis, and for ore flotation.

**Facultative bacteria:** Bacteria that grow equally well under aerobic and anaerobic conditions.

**Flange:** A rib or a rim for strength, for guiding, or for attachment to another object (e.g., on a pipe).

**Flared:** Gas disposed of by burning in flares usually at the production sites or at gas processing plants.

**Flatus:** Gas generated in the intestines or the stomach of an animal.

**Flue gas desulfurization:** Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Also referred to as scrubbers. Chemicals such as lime are used as scrubbing media.

**Fluidized-bed combustion:** A method of burning particulate fuel, such as coal, in which the amount of air

required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of mineral ash in the proportions of 1 part fuel to 200 parts ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid.

**Flux material:** A substance used to promote fusion, e.g., of metals or minerals.

**Fodder:** Coarse food for domestic livestock.

**Forestomach:** See *Rumen*.

**Fossil fuel:** An energy source formed in the earth's crust from decayed organic material. The common fossil fuels are petroleum, coal, and natural gas.

**Framework Convention on Climate Change (FCCC):** An agreement opened for signature at the "Earth Summit" in Rio de Janeiro, Brazil, on June 4, 1992, which has the goal of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent significant anthropogenically forced climate change. See *Climate change*.

**Fuel cycle:** The entire set of sequential processes or stages involved in the utilization of fuel, including extraction, transformation, transportation, and combustion. Emissions generally occur at each stage of the fuel cycle.

**Fugitive emissions:** Unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels.

**Gasification:** A method for converting coal, petroleum, biomass, wastes, or other carbon-containing materials into a gas that can be burned to generate power or processed into chemicals and fuels.

**Gate station:** Location where the pressure of natural gas being transferred from the transmission system to the distribution system is lowered for transport through small diameter, low pressure pipelines.

**Geothermal:** Pertaining to heat within the Earth.

**Global climate change:** See *Climate change*.

**Global warming:** An increase in the near surface temperature of the Earth. Global warming has occurred in the distant past as the result of natural influences, but the term is today most often used to refer to the warming that some scientists predict will occur as a result of increased anthropogenic emissions of greenhouse gases. See *Climate change*.

**Global warming potential (GWP):** An index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric

concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time, such as 100 years.

**Greenhouse effect:** The result of water vapor, carbon dioxide, and other atmospheric gases trapping radiant (infrared) energy, thereby keeping the earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap this radiation, which would otherwise escape into space, and subsequent re-radiation of some of this energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent. See *Greenhouse gases*.

**Greenhouse gases:** Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving the Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

**Gross gas withdrawal:** The full-volume of compounds extracted at the wellhead, including nonhydrocarbon gases and natural gas plant liquids.

**Gypsum:** Calcium sulfate dihydrate ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), a sludge constituent from the conventional lime scrubber process, obtained as a byproduct of the dewatering operation and sold for commercial use.

**Halogenated substances:** A volatile compound containing halogens, such as chlorine, fluorine or bromine.

**Halons:** See *Bromofluorocarbons*.

**Heating degree-days (HDD):** A measure of how cold a location is over a period of time relative to a base temperature, most commonly specified as 65 degrees Fahrenheit. The measure is computed for each day by subtracting the average of the day's high and low temperatures from the base temperature (65 degrees), with negative values set equal to zero. Each day's heating degree-days are summed to create a heating degree-day measure for a specified reference period. Heating degree-days are used in energy analysis as an indicator of space heating energy requirements or use.

**Herbivore:** A plant-eating animal.

**Hydrocarbon:** An organic chemical compound of hydrogen and carbon in either gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simple (e.g., methane, a

constituent of natural gas) to the very heavy and very complex.

**Hydrochlorofluorocarbons (HCFCs):** Chemicals composed of one or more carbon atoms and varying numbers of hydrogen, chlorine, and fluorine atoms.

**Hydrofluorocarbons (HFCs):** A group of man-made chemicals composed of one or two carbon atoms and varying numbers of hydrogen and fluorine atoms. Most HFCs have 100-year Global Warming Potentials in the thousands.

**Hydroxyl radical (OH):** An important chemical scavenger of many trace gases in the atmosphere that are greenhouse gases. Atmospheric concentrations of OH affect the atmospheric lifetimes of greenhouse gases, their abundance, and, ultimately, the effect they have on climate.

**Intergovernmental Panel on Climate Change (IPCC):** A panel established jointly in 1988 by the World Meteorological Organization and the United Nations Environment Program to assess the scientific information relating to climate change and to formulate realistic response strategies.

**International bunker fuels:** See *Bunker fuels*.

**Jet fuel:** A refined petroleum product used in jet aircraft engines. It includes kerosene-type jet fuel and naphtha-type jet fuel.

**Joint Implementation (JI):** Agreements made between two or more nations under the auspices of the Framework Convention on Climate Change (FCCC) whereby a developed country can receive “emissions reduction units” when it helps to finance projects that reduce net emissions in another developed country (including countries with economies in transition).

**Kerosene:** A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps. Kerosene has a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point, a final boiling point of 572 degrees Fahrenheit, and a minimum flash point of 100 degrees Fahrenheit. Included are No. 1-K and No. 2-K, the two grades recognized by ASTM Specification D 3699 as well as all other grades of kerosene called range or stove oil, which have properties similar to those of No. 1 fuel oil. See *Kerosene-type jet fuel*.

**Kerosene-type jet fuel:** A kerosene-based product having a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point and a final maximum boiling point of 572 degrees Fahrenheit and meeting ASTM Specification D 1655 and Military

Specifications MIL-T-5624P and MIL-T-83133D (Grades JP-5 and JP-8). It is used for commercial and military turbojet and turboprop aircraft engines.

**Kyoto Protocol:** The result of negotiations at the third Conference of the Parties (COP-3) in Kyoto, Japan, in December of 1997. The Kyoto Protocol sets binding greenhouse gas emissions targets for countries that sign and ratify the agreement. The gases covered under the Protocol include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride.

**Ketone-alcohol (cyclohexanol):** An oily, colorless, hygroscopic liquid with a camphor-like odor. Used in soapmaking, dry cleaning, plasticizers, insecticides, and germicides.

**Leachate:** The liquid that has percolated through the soil or other medium.

**Lignite:** The lowest rank of coal, often referred to as brown coal, used almost exclusively as fuel for steam-electric power generation. It is brownish-black and has a high inherent moisture content, sometimes as high as 45 percent. The heat content of lignite ranges from 9 to 17 million Btu per ton on a moist, mineral-matter-free basis. The heat content of lignite consumed in the United States averages 13 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

**Liquefied petroleum gases:** A group of hydrocarbon-based gases derived from crude oil refining or natural gas fractionation. They include ethane, ethylene, propane, propylene, normal butane, butylene, isobutane, and isobutylene. For convenience of transportation, these gases are liquefied through pressurization.

**Lubricants:** Substances used to reduce friction between bearing surfaces, or incorporated into other materials used as processing aids in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases.

**Methane:** A colorless, flammable, odorless hydrocarbon gas (CH<sub>4</sub>) which is the major component of natural gas. It is also an important source of hydrogen in various industrial processes. Methane is a greenhouse gas. See also *Greenhouse gases*.

**Methanogens:** Bacteria that synthesize methane, requiring completely anaerobic conditions for growth.

**Methanol:** A light alcohol that can be used for gasoline blending. See oxygenate.

**Methanotrophs:** Bacteria that use methane as food and oxidize it into carbon dioxide.

**Methyl chloroform (trichloroethane):** An industrial chemical ( $\text{CH}_3\text{CCl}_3$ ) used as a solvent, aerosol propellant, and pesticide and for metal degreasing.

**Methyl tertiary butyl ether (MTBE):** A colorless, flammable, liquid oxygenated hydrocarbon containing 18.15 percent oxygen.

**Methylene chloride:** A colorless liquid, nonexplosive and practically nonflammable. Used as a refrigerant in centrifugal compressors, a solvent for organic materials, and a component in nonflammable paint removers.

**Mole:** The quantity of a compound or element that has a weight in grams numerically equal to its molecular weight. Also referred to as gram molecule or gram molecular weight.

**Montreal Protocol:** The Montreal Protocol on Substances that Deplete the Ozone Layer (1987). An international agreement, signed by most of the industrialized nations, to substantially reduce the use of chlorofluorocarbons (CFCs). Signed in January 1989, the original document called for a 50-percent reduction in CFC use by 1992 relative to 1986 levels. The subsequent London Agreement called for a complete elimination of CFC use by 2000. The Copenhagen Agreement, which called for a complete phaseout by January 1, 1996, was implemented by the U.S. Environmental Protection Agency.

**Motor gasoline (finished):** A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines. Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 to 158 degrees Fahrenheit at the 10 percent recovery point to 365 to 374 degrees Fahrenheit at the 90 percent recovery point. "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline, but excludes aviation gasoline. Note: Volumetric data on blending components, such as oxygenates, are not counted in data on finished motor gasoline until the blending components are blended into the gasoline.

**Multiple cropping:** A system of growing several crops on the same field in one year.

**Municipal solid waste:** Residential solid waste and some nonhazardous commercial, institutional, and industrial wastes.

**Naphtha less than 401 degrees Fahrenheit:** A naphtha with a boiling range of less than 401 degrees Fahrenheit that is intended for use as a petrochemical feedstock. Also see *Petrochemical feedstocks*.

**Naphtha-type jet fuel:** A fuel in the heavy naphtha boiling range having an average gravity of 52.8 degrees API, 20 to 90 percent distillation temperatures of 290 degrees to 470 degrees Fahrenheit, and meeting Military Specification MIL-T-5624L (Grade JP-4). It is used primarily for military turbojet and turboprop aircraft engines because it has a lower freeze point than other aviation fuels and meets engine requirements at high altitudes and speeds.

**Natural gas:** A mixture of hydrocarbons and small quantities of various nonhydrocarbons in the gaseous phase or in solution with crude oil in natural underground reservoirs.

**Natural gas liquids (NGLs):** Those hydrocarbons in natural gas that are separated as liquids from the gas. Includes natural gas plant liquids and lease condensate.

**Natural gas, pipeline quality:** A mixture of hydrocarbon compounds existing in the gaseous phase with sufficient energy content, generally above 900 Btu, and a small enough share of impurities for transport through commercial gas pipelines and sale to end-users.

**Nitrogen oxides ( $\text{NO}_x$ ):** Compounds of nitrogen and oxygen produced by the burning of fossil fuels.

**Nitrous oxide ( $\text{N}_2\text{O}$ ):** A colorless gas, naturally occurring in the atmosphere. Nitrous oxide has a 100-year Global Warming Potential of 310.

**Nonmethane volatile organic compounds (NMVOCs):** Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

**Octane:** A flammable liquid hydrocarbon found in petroleum. Used as a standard to measure the anti-knock properties of motor fuel.

**Oil reservoir:** An underground pool of liquid consisting of hydrocarbons, sulfur, oxygen, and nitrogen trapped within a geological formation and protected from evaporation by the overlying mineral strata.

**Organic content:** The share of a substance that is of animal or plant origin.

**Organic waste:** Waste material of animal or plant origin.

**Oxidize:** To chemically transform a substance by combining it with oxygen.

**Oxygenates:** Substances which, when added to gasoline, increase the amount of oxygen in that gasoline blend. Ethanol, Methyl Tertiary Butyl Ether (MTBE), Ethyl Tertiary Butyl Ether (ETBE), and methanol are common oxygenates.

**Ozone:** A molecule made up of three atoms of oxygen. Occurs naturally in the stratosphere and provides a

protective layer shielding the Earth from harmful ultraviolet radiation. In the troposphere, it is a chemical oxidant, a greenhouse gas, and a major component of photochemical smog.

**Ozone precursors:** Chemical compounds, such as carbon monoxide, methane, nonmethane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone.

**Paraffinic hydrocarbons:** Straight-chain hydrocarbon compounds with the general formula  $C_nH_{2n+2}$ .

**Perfluorocarbons (PFCs):** A group of man-made chemicals composed of one or two carbon atoms and four to six fluorine atoms, containing no chlorine. PFCs have no commercial uses and are emitted as a byproduct of aluminum smelting and semiconductor manufacturing. PFCs have very high 100-year Global Warming Potentials and are very long-lived in the atmosphere.

**Perfluoromethane:** A compound ( $CF_4$ ) emitted as a byproduct of aluminum smelting.

**Petrochemical feedstocks:** Chemical feedstocks derived from petroleum principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics.

**Petroleum:** A broadly defined class of liquid hydrocarbon mixtures. Included are crude oil, lease condensate, unfinished oils, refined products obtained from the processing of crude oil, and natural gas plant liquids. Note: Volumes of finished petroleum products include nonhydrocarbon compounds, such as additives and detergents, after they have been blended into the products.

**Petroleum coke:** See *Coke (petroleum)*.

**Photosynthesis:** The manufacture by plants of carbohydrates and oxygen from carbon dioxide and water in the presence of chlorophyll, with sunlight as the energy source. Carbon is sequestered and oxygen and water vapor are released in the process.

**Pig iron:** Crude, high-carbon iron produced by reduction of iron ore in a blast furnace.

**Pipeline, distribution:** A pipeline that conveys gas from a transmission pipeline to its ultimate consumer.

**Pipeline, gathering:** A pipeline that conveys gas from a production well/field to a gas processing plant or transmission pipeline for eventual delivery to end-use consumers.

**Pipeline, transmission:** A pipeline that conveys gas from a region where it is produced to a region where it is to be distributed.

**Planetary albedo:** The fraction of incident solar radiation that is reflected by the Earth-atmosphere system and returned to space, mostly by backscatter from clouds in the atmosphere.

**Pneumatic device:** A device moved or worked by air pressure.

**Polystyrene:** A polymer of styrene that is a rigid, transparent thermoplastic with good physical and electrical insulating properties, used in molded products, foams, and sheet materials.

**Polyvinyl chloride (PVC):** A polymer of vinyl chloride. Tasteless, odorless, insoluble in most organic solvents. A member of the family vinyl resin, used in soft flexible films for food packaging and in molded rigid products, such as pipes, fibers, upholstery, and bristles.

**Post-mining emissions:** Emissions of methane from coal occurring after the coal has been mined, during transport or pulverization.

**Radiative forcing:** A change in average net radiation at the top of the troposphere (known as the tropopause) because of a change in either incoming solar or exiting infrared radiation. A positive radiative forcing tends on average to warm the earth's surface; a negative radiative forcing on average tends to cool the earth's surface. Greenhouse gases, when emitted into the atmosphere, trap infrared energy radiated from the earth's surface and therefore tend to produce positive radiative forcing. See *Greenhouse gases*.

**Radiatively active gases:** Gases that absorb incoming solar radiation or outgoing infrared radiation, affecting the vertical temperature profile of the atmosphere. See *Radiative forcing*.

**Ratoon crop:** A crop cultivated from the shoots of a perennial plant.

**Redox potential:** A measurement of the state of oxidation of a system.

**Reflectivity:** The ratio of the energy carried by a wave after reflection from a surface to its energy before reflection.

**Reforestation:** Replanting of forests on lands that have recently been harvested or otherwise cleared of trees.

**Reformulated gasoline:** Finished motor gasoline formulated for use in motor vehicles, the composition and properties of which meet the requirements of the reformulated gasoline regulations promulgated by the U.S. Environmental Protection Agency under Section 211(k) of the Clean Air Act. Note: This category includes oxygenated fuels program reformulated gasoline (OPRG)

but excludes reformulated gasoline blendstock for oxygenate blending (RBOB).

**Renewable energy resources:** Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

**Residual fuel oil:** A general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. It conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore powerplants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

**Rumen:** The large first compartment of the stomach of certain animals in which cellulose is broken down by the action of bacteria.

**Sample:** A set of measurements or outcomes selected from a given population.

**Sequestration:** See *Carbon sequestration*.

**Septic tank:** A tank in which the solid matter of continuously flowing sewage is disintegrated by bacteria.

**Sinter:** A chemical sedimentary rock deposited by precipitation from mineral waters, especially siliceous sinter and calcareous sinter.

**Sodium silicate:** A grey-white powder soluble in alkali and water, insoluble in alcohol and acid. Used to fireproof textiles, in petroleum refining and corrugated paperboard manufacture, and as an egg preservative. Also referred to as liquid glass, silicate of soda, sodium metasilicate, soluble glass, and water glass.

**Sodium tripolyphosphate:** A white powder used for water softening and as a food additive and texturizer.

**Stabilization lagoon:** A shallow artificial pond used for the treatment of wastewater. Treatment includes removal of solid material through sedimentation, the decomposition of organic material by bacteria, and the removal of nutrients by algae.

**Still gas (refinery gas):** Any form or mixture of gases produced in refineries by distillation, cracking,

reforming, and other processes. The principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Still gas is used as a refinery fuel and a petrochemical feedstock. The conversion factor is 6 million Btu per fuel oil equivalent barrel.

**Stratosphere:** The region of the upper atmosphere extending from the tropopause (8 to 15 kilometers altitude) to about 50 kilometers. Its thermal structure, which is determined by its radiation balance, is generally very stable with low humidity.

**Stripper well:** An oil or gas well that produces at relatively low rates. For oil, stripper production is usually defined as production rates of between 5 and 15 barrels of oil per day. Stripper gas production would generally be anything less than 60 thousand cubic feet per day.

**Styrene:** A colorless, toxic liquid with a strong aromatic aroma. Insoluble in water, soluble in alcohol and ether; polymerizes rapidly; can become explosive. Used to make polymers and copolymers, polystyrene plastics, and rubber.

**Subbituminous coal:** A coal whose properties range from those of lignite to those of bituminous coal and used primarily as fuel for steam-electric power generation. It may be dull, dark brown to black, soft and crumbly, at the lower end of the range, to bright, jet black, hard, and relatively strong, at the upper end. Subbituminous coal contains 20 to 30 percent inherent moisture by weight. The heat content of subbituminous coal ranges from 17 to 24 million Btu per ton on a moist, mineral-matter-free basis. The heat content of subbituminous coal consumed in the United States averages 17 to 18 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

**Sulfur dioxide (SO<sub>2</sub>):** A toxic, irritating, colorless gas soluble in water, alcohol, and ether. Used as a chemical intermediate, in paper pulping and ore refining, and as a solvent.

**Sulfur hexafluoride (SF<sub>6</sub>):** A colorless gas soluble in alcohol and ether, and slightly less soluble in water. It is used as a dielectric in electronics. It possesses the highest 100-year Global Warming Potential of any gas (23,900).

**Sulfur oxides (SO<sub>x</sub>):** Compounds containing sulfur and oxygen, such as sulfur dioxide (SO<sub>2</sub>) and sulfur trioxide (SO<sub>3</sub>).

**Tertiary amyl methyl ether ((CH<sub>3</sub>)<sub>2</sub>(C<sub>2</sub>H<sub>5</sub>)COCH<sub>3</sub>):** An oxygenate blend stock formed by the catalytic etherification of isoamylene with methanol.

**Troposphere:** The inner layer of the atmosphere below about 15 kilometers, within which there is normally a steady decrease of temperature with increasing altitude.

Nearly all clouds form and weather conditions manifest themselves within this region. Its thermal structure is caused primarily by the heating of the earth's surface by solar radiation, followed by heat transfer through turbulent mixing and convection.

**Uncertainty:** A measure used to quantify the plausible maximum and minimum values for emissions from any source, given the biases inherent in the methods used to calculate a point estimate and known sources of error.

**Vapor displacement:** The release of vapors that had previously occupied space above liquid fuels stored in tanks. These releases occur when tanks are emptied and filled.

**Ventilation system:** A method for reducing methane concentrations in coal mines to non-explosive levels by blowing air across the mine face and using large exhaust fans to remove methane while mining operations proceed.

**Vessel bunkering:** Includes sales for the fueling of commercial or private boats, such as pleasure craft, fishing boats, tugboats, and ocean-going vessels, including vessels operated by oil companies. Excluded are volumes sold to the U.S. Armed Forces.

**Volatile organic compounds (VOCs):** Organic compounds that participate in atmospheric photochemical reactions.

**Volatile solids:** A solid material that is readily decomposable at relatively low temperatures.

**Waste flow:** Quantity of a waste stream generated by an activity.

**Wastewater:** Water that has been used and contains dissolved or suspended waste materials.

**Wastewater, domestic and commercial:** Wastewater (sewage) produced by domestic and commercial establishments.

**Wastewater, industrial:** Wastewater produced by industrial processes.

**Water vapor:** Water in a vaporous form, especially when below boiling temperature and diffused (e.g., in the atmosphere).

**Wax:** A solid or semi-solid material derived from petroleum distillates or residues by such treatments as chilling, precipitating with a solvent, or de-oiling. It is a light-colored, more-or-less translucent crystalline mass, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Includes all marketable wax, whether crude scale or fully refined. The three grades included are microcrystalline, crystalline-fully refined, and crystalline-other. The conversion factor is 280 pounds per 42 U.S. gallons per barrel.

**Weanling system:** A cattle management system that places calves on feed starting at 165 days of age and continues until the animals have reached slaughter weight.

**Wellhead:** The point at which the crude (and/or natural gas) exits the ground. Following historical precedent, the volume and price for crude oil production are labeled as "wellhead," even though the cost and volume are now generally measured at the lease boundary. In the context of domestic crude price data, the term "wellhead" is the generic term used to reference the production site or lease property.

**Wetlands:** Areas regularly saturated by surface or groundwater and subsequently characterized by a prevalence of vegetation adapted for life in saturated-soil conditions.

**Wood energy:** Wood and wood products used as fuel, including roundwood (cordwood), limbwood, wood chips, bark, sawdust, forest residues, charcoal, pulp waste, and spent pulping liquor..

**Yearling system:** A cattle management system that includes a stocker period from 165 days of age to 425 days of age followed by a 140-day feedlot period.

# Appendix A

## Estimation Methods

### Overview

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

### Carbon Dioxide

Most U.S. anthropogenic carbon dioxide emissions result from energy consumption. Energy production contributes a small amount from the flaring of natural gas at oil and gas wells and the scrubbing of carbon dioxide from natural gas, and a number of industrial processes also emit carbon dioxide through non-combustion processes. The largest single source of emissions from these processes is the calcination of limestone in cement production. Other sources include lime manufacture, limestone and dolomite consumption, soda ash manufacture and consumption, industrial carbon dioxide manufacture, and aluminum production. Lastly, some small adjustments are made to reach the total for national emissions as stipulated by the United Nations Framework Convention on Climate Change. This appendix describes each carbon dioxide emissions source, the estimation methods used, and the data sources.

Several emissions sources are excluded from the carbon dioxide emissions presented in this report, due either to the uncertainty of estimates or because they are based on biomass combustion (which is assumed to be consumed sustainably with a net flux of carbon dioxide to the atmosphere equal to zero). Should the energy use of biomass fuels result in a long-term decline in the total carbon embodied in standing biomass (e.g., forests), the net release of carbon would be treated as a land use issue (see Chapter 6).

### Energy Consumption

#### *Emissions Sources*

Most U.S. commercial energy is produced through the combustion of fossil fuels, such as coal, natural gas, and petroleum. Chemically, the main components of fossil fuels are hydrocarbons, made up of molecules containing hydrogen and carbon atoms. When these fuels are burned, atmospheric oxygen combines with the hydrogen atoms to create water vapor and with the carbon atoms to create carbon dioxide. In principle, if the amount of fuel burned and the amount of carbon in the fuel are known, the volume of carbon dioxide emitted into the atmosphere can be computed with a high degree of precision. In practice, however, a combination of real-world complexities can reduce the precision of the estimate. These complexities are discussed further in this appendix. Nonetheless, energy-related carbon dioxide emissions are known with greater reliability than are other greenhouse gas emissions sources, and the uncertainty of the estimate is probably in the 3 to 5 percent range. Appendix C, "Uncertainty in Emissions Estimates," contains an extended discussion of the nature and sources of uncertainty in the estimates.

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

#### *Estimation Methods*

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

## Consumption Data

The Energy Information Administration (EIA) collects a wide variety of information from primary suppliers on a frequent basis and from energy consumers less often, but still in a timely manner. Thus, levels of energy consumption in the United States are fairly well known by end-use sector and detailed fuel type.<sup>1</sup> To estimate carbon dioxide emissions, EIA uses annual data from the four end-use sectors (residential, commercial, industrial, and transportation) and for all the fossil fuels (coal, natural gas, and the full slate of petroleum products). The petroleum products include asphalt and road oil, aviation gasoline, distillate fuel, jet fuel, kerosene, liquefied petroleum gases (LPG), lubricants, motor gasoline, residential fuel, and other petroleum products. Definitions and heating values of the fossil fuels are documented in the appendixes of EIA's recurring reports: the *Annual Energy Review (AER)* and *State Energy Data Report (SEDR)*, as well as the *Petroleum Supply Annual*, *Coal Industry Annual*, and *Natural Gas Annual*. This approach to estimating emissions enables EIA to provide detailed information about trends in sources of emissions.

Information about consumption of "other petroleum" is derived from unpublished EIA data. In recent years, these products have included crude oil, naphtha with a boiling temperature <401°F, petrochemical feedstocks with a boiling temperature ≥401°F, motor gasoline blending components, miscellaneous products, petroleum coke, pentanes plus, still gas, special naphthas, waxes, and unfinished oils.

## Emission Coefficients

The amount of carbon released when a fossil fuel is burned depends on the density, carbon content, and gross heat of combustion of the fuel.<sup>2</sup> Most of the coefficients for major fuels are assumed to be constant over time. However, for motor gasoline, LPG, jet fuel, and crude oil, EIA developed annualized carbon emission coefficients to reflect changes in chemical composition or product mix over the years. Appendix B contains a more detailed discussion of the methods employed for developing the coefficients. Table B1 in Appendix B presents a full listing of emissions factors for crude oil, natural gas, and the complete slate of petroleum products.

## Data Series Revisions Underlying Changes in Electric Power Fuel Use Estimates

Chapter 2 provides information on resulting changes to the emissions estimates brought about by EIA revisions to key data series. Presented in table A1 below are the underlying changes to the fuel consumption values from one Annual Energy Review to the next.

Revisions resulting from changing the source of fuel consumption data for nonutilities and from EIA's data review affect data beyond the category of nonutilities. For example, the revised estimate of natural gas consumption for 2000 is 3 percent higher in the *Annual Energy Review 2001* than in *Annual Energy Review 2000* (Table A1).

---

<sup>1</sup>Although some of EIA's detailed sectoral surveys are conducted only every 4 years on a sample basis, EIA collects information about apparent consumption of petroleum products (taken as "petroleum product supplied") in mandatory monthly surveys of primary suppliers (e.g., refiners, pipeline operators, importers/exporters, and bulk terminal operators).

<sup>2</sup>Combustion of hydrocarbons results in the production of carbon dioxide, water vapor, and heat. In the United States, the heat resulting from combustion is generally measured as the heat associated with production of water vapor and carbon dioxide. This is commonly referred to as the "higher" or "gross" heating value and is used in EIA statistics on thermal energy. The estimates in this report consistently employ coefficients that reflect the higher heating value assumption. Internationally, however, the "lower" heating value is used. If the lower heating value were used, the Btu content of the fuel would be 5 to 10 percent lower, and the coefficients would be 5 to 10 percent larger, but the carbon emissions estimate would be unchanged. This is sometimes a source of discrepancy. See Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997). Web site [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm).

**Table A1. Revisions to Selected Estimates: AER 2001 and AER 2000 Electricity Net Generation: Total (All Sectors)**  
(Billion Kilowatthours)

Year	AER 2000	AER 2001	Percent Difference
1998	3,618	3,620	0.1
1999	3,706	3,695	-0.3
2000	3,792	3,802	0.3
<b>Total Natural Gas Consumption</b> (Trillion Cubic feet)			
Year	AER 2000	AER 2001	Percent Difference
1998	21.26	22.24	4.6
1999	21.70	22.40	3.2
2000	22.71	23.46	3.3
<b>Total Coal Consumption</b> (Million Short Tons)			
Year	AER 2000	AER 2001	Percent Difference
1998	1,038.3	1,037.1	-0.1
1999	1,045.3	1,038.6	-0.6
2000	1,079.7	1,084.1	0.4
Total Petroleum Consumption (Million Barrels Per Day)			
Year	AER 2000	AER 2001	Percent Difference
1998	18.92	18.92	0.0
1999	19.52	19.52	0.0
2000	19.48	19.70	1.1
<b>Total Renewable Energy Consumption</b> (Trillion Btu)			
Year	AER 2000	AER 2001	Percent Difference
1998	6,977	6,782	-2.8
1999	7,226	6,790	-6.0
2000	6,823	6,465	-5.2

Sources: Electricity Net Generation, Table 8.1 of *AER 2000* and *AER 2001*. Natural Gas, Consumption, Table 6.5 of *AER 2000* and *AER 2001*. Coal Consumption, Table 6.5 of *AER 2000* and *AER 2001*. Petroleum Consumption, Table 5.12 of *AER 2000* and *AER 2001*. Renewable Energy Consumption, Table 10.2b of *AER 2000* and *AER 2001*.

### Changes to Energy Consumption Data

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

- **Ethanol.** About 70 million barrels of ethanol are included in annual U.S. gasoline consumption after 1992. Because ethanol is a biofuel, the carbon it contains should not be counted as an emission. Hence, carbon from ethanol is deducted from transportation gasoline consumption. Ethanol consumption is reported in EIA's *Renewable Energy Annual* and the *Petroleum Supply Annual*.
- **Synthetic gas from coal.** Small amounts of "supplemental gas," particularly, gas from the Great Plains Coal Gasification Plant in North Dakota, are manufactured from coal. The coal is counted in industrial energy consumption, and the gas is shipped into the pipeline system. EIA deducts the carbon in synthetic gas (as reported in the *Natural Gas Annual*) from industrial coal emissions.
- **Still gas to pipelines.** Several refineries sell small volumes of "still gas" as supplemental gas to pipelines. EIA deducts the carbon in still gas sales to pipelines (as reported in the *Natural Gas Annual*) from industrial "other petroleum" consumption.
- **Biogas.** The *Natural Gas Annual* reports that small volumes of "supplemental gas" of biological origin (probably landfill gas) are incorporated in U.S. pipeline gas supplies. In keeping with the accounting rule of excluding carbon of biological origin, these supplies are deducted from U.S. natural gas consumption.

- **Carbon dioxide in geothermal steam.** Geothermal steam at The Geysers in Guerneville, California, where most U.S. geothermal electric power is generated, contains carbon dioxide dissolved in the steam, which is released into the atmosphere when the steam is brought to the Earth's surface for power production. EIA includes emissions from this source, at a rate of about 0.1 million metric tons of carbon per year.

### Carbon Sequestration: Nonfuel Use of Fossil Fuels

Gross emissions can be estimated by multiplying fossil fuel consumption by an emissions factor embodying the estimated carbon content of the fuel. However, portions of the fossil fuels consumed are not actually combusted but are used as chemical feedstocks, construction materials, lubricants, solvents, or reducing agents (Table A2). EIA estimates "nonfuel" use of fossil fuels annually in Table 1.15 of the *Annual Energy Review*.<sup>3</sup> For this report, EIA has estimated the fate of the carbon in fuels used for nonfuel purposes (see Table 5 in Chapter 2), based on the rates of sequestration shown in Table A3. Some but not all of the carbon is emitted to the atmosphere. The principal nonfuel uses of fossil fuels, the methods of estimating nonfuel consumption, and the fate of the carbon are listed below.

**Table A2 Fossil Fuel Consumption for Nonfuel Use, 1990-2001 (Quadrillion Btu)**

Year	Asphalt & Road Oil	LPG	Pentanes Plus	Lubricants	Petrochem Feedstocks	Petroleum Coke	Special Naphtha	Other Petroleum	Total Petroleum	Natural Gas	Coal	Total Energy
1990	1.17	1.20	0.08	0.36	1.12	0.18	0.11	0.23	4.45	0.59	0.02	5.06
1991	1.08	1.38	0.04	0.32	1.15	0.15	0.09	0.26	4.47	0.59	0.02	5.08
1992	1.10	1.39	0.06	0.33	1.20	0.23	0.10	0.20	4.63	0.61	0.04	5.28
1993	1.15	1.35	0.28	0.34	1.22	0.12	0.10	0.20	4.76	0.61	0.03	5.40
1994	1.17	1.55	0.26	0.35	1.26	0.14	0.08	0.20	5.01	0.69	0.03	5.73
1995	1.18	1.59	0.30	0.35	1.21	0.13	0.07	0.20	5.03	0.67	0.03	5.72
1996	1.18	1.65	0.32	0.34	1.21	0.15	0.07	0.20	5.11	0.68	0.03	5.82
1997	1.22	1.67	0.30	0.35	1.40	0.12	0.07	0.21	5.34	0.70	0.03	6.07
1998	1.26	1.60	0.27	0.37	1.40	0.21	0.11	0.23	5.45	0.79	0.03	6.27
1999	1.32	1.81	0.33	0.37	1.33	0.28	0.15	0.22	5.81	0.69	0.03	6.53
2000	1.28	1.86	0.31	0.37	1.35	0.14	0.10	0.22	5.62	0.71	0.03	6.35
2001	1.26	1.69	0.24	0.34	1.19	0.18	0.08	0.23	5.20	0.67	0.02	5.89

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001).

Source: Energy Information Administration, *Annual Energy Review 2001*, DOE/EIA-0384(2001) (Washington, DC, November 2002), Table 1.15, p. 33, and underlying estimates.

- **Natural Gas.** Nonfuel use of natural gas is based on periodic (1985, 1988, 1991, 1994 and 1998) reports in EIA's Manufacturing Energy Consumption Survey (MECS). Based on MECS, nonfuel use is divided into three categories: nitrogenous fertilizers, other chemical use, and all other nonfuel uses. Feedstock use of natural gas to make nitrogenous fertilizers is a nonsequestering use, because the underlying chemical in nitrogenous fertilizers is ammonia (NH<sub>3</sub>), which is manufactured by steam reforming of natural gas and reacting the synthesis gas with atmospheric nitrogen, leaving the carbon in the feedstock literally "up in the air." In many cases, the carbon dioxide is recovered to make urea or for industrial use. However, carbon in urea and industrial carbon dioxide are generally only temporarily delayed on their way to the atmosphere. EIA assumes that other nonfuel uses in the chemical industry result in 100-percent carbon sequestration. Natural gas is used as a feedstock for a range of chemical products other than ammonia, particularly methanol. Although the methanol used to make methyl tertiary butyl ether (MTBE) winds up in the gasoline pool and is combusted, EIA already counts the carbon in MTBE in gasoline emissions, and to count it again in the feedstock would be double counting. Future research on the fate of the carbon in feedstocks for other chemical industry uses will probably gradually reduce the 100-percent sequestration share currently assumed.

<sup>3</sup>Energy Information Administration, *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, August 2001), p. 33.

- **Liquefied Petroleum Gases.** Nonfuel use of LPG (ethane, propane, and butane) through 1996 is estimated on the basis of sales of these products to the chemical industry, as reported in the American Petroleum Institute (API) survey, *Sales of Natural Gas Liquids and Liquefied Refinery Gases*, from which EIA deducts chemical industry fuel use of LPG as reported periodically in the MECS. For 1997-2000 the sales to the chemical industry are estimated based on the 1996 ratio of the API's data to EIA's *Petroleum Supply Annual* (PSA) value for LPG, which is then multiplied by the PSA data for 1997-2000. Most of the ethane, propane, and butane used by the chemical industry is used to manufacture ethylene, propylene, and butadiene, respectively, all of which are intermediate products for plastics. Following the recommendation of the Intergovernmental Panel on Climate Change (IPCC), EIA assumes that 80 percent of nonfuel use is sequestered in plastics, synthetic rubber, and related products.<sup>4</sup>
- **Asphalt and Road Oil.** EIA assumes that asphalt and road oil use is nonfuel use by definition, and that all carbon in asphalt and road oil is sequestered.
- **Pentanes Plus.** "Pentanes plus" are hydrocarbons heavier than butane extracted from natural gas at gas processing plants. Their principal uses are as contributors to the gasoline pool and as petrochemical feedstocks. Nonfuel use of pentanes plus is estimated on the basis of the API's annual survey of natural gas liquids and refinery gases sold to the chemical industry. Following IPCC practice for LPG, EIA assumes that 80 percent of the carbon in pentanes plus used by the chemical industry is sequestered.
- **Petrochemical Feedstocks.** EIA's petroleum surveys recognize two categories of products called "petrochemical feedstocks." These are presumably naphtha and gas oils destined for ethylene crackers, and probably some mix of aromatic hydrocarbons (benzene, toluene, and xylene) and feedstocks used to make aromatic hydrocarbons. All petrochemical feedstock supplies are included in nonfuel use by definition, and, following the practice of the IPCC, EIA assumes that 75 percent of the carbon in synthetic feedstocks and 50 percent of the carbon in gas oil feedstock is sequestered in plastics, synthetic fibers, and related products.
- **Distillate and Residual Fuels.** The MECS reports small volumes (10 million barrels and 1 million barrels, respectively) of distillate and residual oils used for nonfuel purposes in the chemical industry. Following the practice for gas oil petrochemical feedstocks, EIA assumes 50-percent sequestration. Future research may shed more light on the industrial processes that use these fuels.
- **Petroleum Coke.** Petroleum coke is a coal-like solid, about 90 percent carbon by weight, created after intensive extraction of lighter hydrocarbons from petroleum feedstocks by oil refiners. Most petroleum coke is used in the refineries as fuel or as a catalyst. EIA estimates nonfuel use by taking the quantity of petroleum coke supplied and deducting all known fuel uses (refinery use from the *Petroleum Supply Annual*, electric utility use from the *Electric Power Annual*, and industrial use from the MECS). EIA assumes that 50 percent of the carbon in petroleum coke for nonfuel use is sequestered. It should be noted, however, that significant sequestering nonfuel uses of petroleum coke in the United States are difficult to identify. In conjunction with the Environmental Protection Agency this estimate is currently under evaluation and it may yield a downward estimation in the sequestering amounts allocated to petroleum coke. The principal identified nonfuel use is for sacrificial anodes in primary aluminum smelting, a nonsequestering use that EIA counts separately under process emissions (see the next section). It appears that petroleum coke is also used in small quantities by many different industries as a reducing agent (a source of carbon monoxide that, in turn, can be used to scour oxygen from products such as lead oxide (to produce lead) or iron oxide (to produce iron)). These are, however, nonsequestering uses.
- **Still Gas.** Still gas is the gas that floats to the top of distillation columns in oil refineries. Its chemical composition is a highly variable blend of free hydrogen, methane, carbon monoxide, and heavier hydrocarbons, depending on the refinery process, the feedstock, and process conditions. EIA estimates nonfuel use by deducting all known fuel uses (refinery fuel use from the *Petroleum Supply Annual* and pipeline gas supplies from the *Natural Gas Annual*). The remainder is assumed to be dispatched to chemical plants as a feedstock. Following the IPCC practice for LPG, EIA assumes that 80 percent of the carbon in still gas is sequestered.

<sup>4</sup>Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.28, web site [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm).

**Table A3. Rates of Sequestration for U.S. Fossil Fuel Consumption**

Fuel Type	Fraction of Fuel Combusted	Fraction of Nonfuel Use of Energy Sequestered
<b>Petroleum</b>		
Motor Gasoline	0.99	--
LPG	0.995	0.8
Jet Fuel	0.99	--
Distillate Fuel	0.99	0.5
Residual Fuel	0.99	0.5
Asphalt and Road Oil	0.99	1
Lubricants	0.99	0.5
Petrochemical Feed	0.99	0.75
Aviation Gas	0.99	--
Kerosene	0.99	--
Petroleum Coke	0.99	0.5
Special Naphtha	0.99	0
<b>Other</b>		
Aviation Gas		
Blending Components	0.99	--
Crude Oil	0.99	--
Naphtha <401oF	0.99	0.75
Other Oil 401oF	0.99	0.5
Petrochemical Feed		
Still Gas	0.99	0.8
Motor Gasoline		
Blending Components	0.99	--
Miscellaneous	0.99	1
Natural Gasoline	0.99	--
Plant Condensate	0.99	--
Pentanes Plus	0.99	0.8
Still Gas	0.995	--
Special Naphthas	0.99	0
Unfinished Oils	0.99	--
Unfractionated Stream	0.99	--
Waxes	0.99	1
<b>Coal</b>		
Residential and Commercial	0.99	--
Industrial Coking	0.99	0.75
Industrial Other	0.99	--
Electric Utility	0.99	--
<b>Natural Gas</b>		
Flare Gas	1	--
Natural Gas	0.995	0.29-0.52
<b>Crude Oil</b>		
	0.99	--

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

- **Special Naphtha.** “Special naphtha” is a catch-all for an array of hydrocarbon-based solvents, such as hexane and the volatile oils used in petroleum-based paint. In general, solvents evaporate into the atmosphere as “nonmethane volatile organic compounds” after use and swiftly weather into atmospheric carbon dioxide. EIA assumes that all special naphthas are for nonfuel use and that no carbon in special naphtha is sequestered.
- **Lubricants.** The most common petroleum-based lubricant is motor oil, but the category also includes numerous other products, such as industrial greases. Following the IPCC, EIA assumes that 50 percent of the carbon in lubricants is sequestered. The ultimate fate of lubricants is not easy to determine. For example, it is often the case that “recycling” motor oil means burning it as boiler fuel.

- **Waxes and Polishes.** The principal use of waxes is to make wax paper and food packaging materials, which usually end up in landfills. Following the IPCC, EIA assumes 100-percent nonfuel use and 100-percent carbon sequestration for these materials.
- **Miscellaneous.** EIA assumes 100-percent nonfuel use and 100-percent carbon sequestration for this category.
- **Coal.** The manufacture of coke is the largest nonfuel use of coal. By convention, however, coke manufacture is treated as a fuel use. This is not unreasonable, because coke is almost always ultimately combusted. Coke is manufactured by “cooking” high-grade coal in huge ovens in the absence of oxygen. Volatile materials, moisture, and certain categories of impurities are driven off, leaving behind a high-carbon material suitable for metallurgical use. Among the byproducts of the process are “coal tars” or “coal liquids,” which typically are rich in aromatic hydrocarbons, such as benzene. Coal tars generally are used as feedstocks in the chemical industry. “Nonfuel use” of coal, as defined for this report, consists of the coal tars driven off during the manufacture of coke. Coal tar production was obtained, for years prior to 1995, from the International Trade Commission’s *Synthetic Organic Chemicals*. Since 1995, production has been estimated on the basis of the ratio of 1994 coke production to coal tar production. Following the IPCC guidelines, EIA assumes that 75 percent of the carbon in coal tars is sequestered.

### Carbon Sequestration: Fraction Combusted

A small amount of carbon sequestration is associated with the combustion of fossil fuels. Using IPCC assumptions, EIA assumes that oxidation of liquid and solid fuels during combustion is 99 percent complete, and that 1 percent of the carbon remains sequestered. Oxidation of gaseous fuels (LPG and natural gas) is assumed to be 99.5 percent complete.<sup>5</sup> Conceptually, fuel may be “lost” before combustion due to evaporation, leaks, or spills; it may be subject to incomplete combustion and vented to the atmosphere in the form of volatile organic compounds or particulates; or it may remain at the site of combustion in the form of carbon-containing ash or soot.

### Data Sources

Fossil Fuel Consumption: (1990-1997), Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(97) (Washington, DC, September 1999). (1998-2001), Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384(2001) (Washington, DC, November 2002); *Petroleum Supply Annual 2001*, DOE/EIA-0340(2001)/1 (Washington, DC, June 2002); *Natural Gas Annual 2000*, DOE/EIA-0131(2000) (Washington, DC, October 2001); and *Renewable Energy Annual 2001*, DOE/EIA-0603(2001) (Washington, DC, December 2001).

Nonfuel Use of Energy and Biofuels Consumption: Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384(2001) (Washington, DC, November 2002); ; Energy Information Administration, *Manufacturing Consumption of Energy*, DOE/EIA-0512(various years) (Washington, DC); American Petroleum Institute, *Sales of Natural Gas Liquids and Liquefied Refinery Gas* (various years); U.S. International Trade Commission, *Synthetic Organic Chemicals*, USITC Publication 2933 (various years through 1994); and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.28, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

### Adjustments to U.S. Energy Consumption

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

<sup>5</sup>Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.29, web site [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm).

## U.S. Territories

### Emissions Sources

EIA's energy data for the United States cover only the 50 States and the District of Columbia. In contrast, energy data produced by the International Energy Agency for the United States cover the 50 States plus U.S. territories, including Puerto Rico, the U.S. Virgin Islands, and Guam. Annual energy consumption in the U.S. territories is only about 0.5 quadrillion Btu (Table A4). For the territories as a group, oil consumption ranges between 220,000 and 325,000 barrels per day, and coal consumption averages 315,000 to 425,000 short tons per year, in the U.S. Virgin Islands and Puerto Rico.

### Estimation Methods

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

### Data Sources

1990-2000: Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (various years), and unpublished data included in "Other" countries in the Asia/Pacific region. Data are shown in tables of "Apparent Consumption of Petroleum Products." Data for 2001 based on unpublished preliminary information.

**Table A4. U.S. Territories Primary Energy Consumption (Btu), 1990, 1992-2001  
(Quadrillion Btu)**

Territory	1990	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
Puerto Rico	0.30	0.33	0.35	0.35	0.35	0.33	0.33	0.34	0.33	0.35	0.38
Virgin Islands, U.S.	0.12	0.12	0.12	0.12	0.19	0.16	0.20	0.26	0.31	0.31	0.32
American Samoa	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Guam	0.03	0.04	0.05	0.07	0.05	0.04	0.05	0.04	0.05	0.05	0.05
Hawaiian Trade Zone	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
U.S. Pacific Islands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.004
Wake Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
<b>Total</b>	<b>0.47</b>	<b>0.52</b>	<b>0.54</b>	<b>0.57</b>	<b>0.62</b>	<b>0.57</b>	<b>0.61</b>	<b>0.68</b>	<b>0.71</b>	<b>0.75</b>	<b>0.78</b>

\*Less than 5 trillion Btu.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001).

Sources: Energy Information Administration, *International Energy Annual*, DOE/EIA-0219 (various years), and unpublished data included in "Other" countries in the Asia/Pacific region. Data are shown in tables of "Apparent Consumption of Petroleum Products." Data for 2001 based on unpublished preliminary information.

## International Bunker Fuels

### Emissions Sources

The term "international bunker fuels" refers to fuels sold to and consumed by air or marine vessels engaging in international transport activities. By convention, trade statistics treat the sale of bunker fuels as a form of export by the selling country, because the purchaser promptly hauls the fuel outside national boundaries. This convention is followed by organizations that prepare international energy statistics, such as the United Nations and the International Energy Agency.

Bunker fuels, however, are an export without a corresponding import, because the purchasing vessel generally combusts the fuel during transport. EIA energy statistics, which are based on domestic sales of products, treat bunker fuels sales in the same manner as the sale of other fuels, i.e. as domestic energy consumption. Therefore, carbon emissions from bunker fuels are already incorporated in the domestic energy consumption statistics of the

United States, primarily as transportation-related consumption of residual and distillate fuel oil by cargo and passenger vessels and kerosene-based jet fuel by commercial aircraft. Table A5 shows U.S. international bunker fuel usage. Beginning with the 1999 data year, we have included estimates for military bunker fuels that make up about 10 percent of the total category.

## Estimation Methods

Carbon coefficients are applied to annual consumption estimates for each of the relevant international bunker fuels, namely residual and distillate fuel oil to account for international marine bunkers, and kerosene-based jet fuel for international aviation bunkers. It is assumed that 99 percent of the fuel is combusted. Consumption estimates for distillate and residual fuel oil are each taken as the sum of oil laden on American and foreign ocean-going vessels in the United States. Since the data available for jet fuel consumption by U.S. air carriers reflects total fuel consumed on international routes, EIA estimates assume that domestic fuel purchases for outgoing international flights are 50 percent of this total. Jet fuel consumption by foreign air carriers fueled in the United States are based on the share of total expenses by these air carriers in U.S. ports that account for fuel and oil purchases, multiplied by the average annual price of jet fuel in U.S. ports. The estimate of military bunker fuels is obtained from the EPA inventory of the previous year. The 1999 estimate is used as a proxy for 2000 emissions.

## Data Sources

**1990-2001:** U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division, "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries" (unpublished, various years); EIA estimate. (1988-2001): U.S. Department of Commerce, Bureau of Economic Analysis, unpublished BE-36 survey data (various years); Air Transportation Association, *Monthly Fuel Cost and Consumption* (various years), web site [www.air-transport.org/public/industry/16.asp](http://www.air-transport.org/public/industry/16.asp). Military Bunker Fuels: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*(Washington, DC 20460) April 2002.

**Table A5. Consumption and Carbon emissions from International Bunker Fuels Supplied in the United States, 1990,1992-2001**

Item	1990	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
Carbon Emissions (MMTCE)											
Marine Bunkers											
Distillate	1.7	1.5	1.7	1.4	1.6	1.2	1.2	1.7	0.8	0.8	0.6
Residual	15.2	14.3	11.4	11.2	11.1	11.4	12.2	12.7	10.4	9.4	9.1
<i>Total Marine</i>	<i>16.9</i>	<i>15.8</i>	<i>13.0</i>	<i>12.6</i>	<i>12.7</i>	<i>12.7</i>	<i>13.4</i>	<i>14.4</i>	<i>11.3</i>	<i>10.2</i>	<i>9.7</i>
Aviation Bunkers											
US Carriers	5.0	5.3	5.3	5.5	5.7	6.0	6.3	6.6	6.8	7.1	6.8
Foreign Carriers	5.3	5.6	5.8	6.0	6.6	6.8	7.6	7.6	8.5	7.8	7.9
<i>Total Aviation</i>	<i>10.4</i>	<i>11.0</i>	<i>11.1</i>	<i>11.5</i>	<i>12.4</i>	<i>12.8</i>	<i>13.9</i>	<i>14.2</i>	<i>15.3</i>	<i>14.9</i>	<i>14.6</i>
Total	27.3	26.7	24.2	24.1	25.1	25.4	27.3	28.6	26.6	25.1	24.2
Internat'l Bunker Fuels Consumed (Quadrillion Btu)											
Marine	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.7	0.5	0.5	0.5
Aviation	0.5	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8
<b>Total</b>	<b>1.3</b>	<b>1.3</b>	<b>1.2</b>	<b>1.2</b>	<b>1.2</b>	<b>1.3</b>	<b>1.4</b>	<b>1.4</b>	<b>1.3</b>	<b>1.3</b>	<b>1.2</b>

P = preliminary data.

Source: Distillate and Residual Fuels (1980-1987): Energy Information Administration, International Energy Annual, DOE/EIA-0219 (Washington, DC). (1988-2000); U.S. Department of Commerce, Bureau of the Census, Foreign Trade Division, "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries", (Unpublished). Jet Fuels (1980-1987): Oak Ridge National Laboratory, Transportation Energy Data Book (Oak Ridge, TN, various years). (1988-2000): U.S. Department of Commerce, Bureau of Economic Analysis, Unpublished BE-36 survey data (various years). Air Transportation Association, Monthly Fuel Cost and Consumption (various years), see web site <http://www.air-transport.org/public/industry/31.asp>

## Other Carbon Dioxide Emissions

Other carbon dioxide emissions include emissions from energy production and industrial emissions that are not caused by the combustion or feedstock use of commercial fossil fuels. These emissions typically are created either

by the combustion of waste products containing fossil carbon (natural gas flaring) or by chemical reactions with carbon-containing minerals (for example, calcining sodium carbonate [limestone] to make lime or cement).

## Energy Production

### Emissions Sources

U.S. energy production also generates small volumes of carbon dioxide emissions. The two principal sources are the flaring of natural gas and the venting of carbon dioxide produced in conjunction with natural gas.<sup>6</sup> When a field is developed for petroleum extraction, any natural gas associated with that field may be flared if its use is not economically justifiable. This is typically the case for remote sites or when the gas is of poor quality or minimal volume. During natural gas production, flaring may be used for disposal of waste products (e.g., hydrogen sulfide), capacity testing, or as a result of process upsets.

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

### Estimation Methods

The method for estimating emissions from natural gas flaring is based on the volume of vented and flared gas reported to EIA (assuming that all gas is flared). To calculate carbon emissions, the figures are aggregated, converted into Btu, and then multiplied by an emissions coefficient of 14.92 million metric tons of carbon per quadrillion Btu.

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

The carbon dioxide produced in conjunction with natural gas is estimated by multiplying regional natural gas production data by regional carbon dioxide contents from a Gas Research Institute (GRI) study. The estimates of carbon dioxide emitted during transmission and distribution are derived by multiplying pipeline and end-use consumption data by the carbon dioxide content of natural gas delivered to consumers from a second GRI study. Emissions associated with production activities are calculated by subtracting consumption-related emissions from the total carbon dioxide initially produced. For 1999 through 2001 the 1998 value was moved by production of dry gas in quadrillion Btu as it appears in Table 1.3 of the *Monthly Energy Review July 2002*.

### Data Sources

Flaring (1980-2000): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). (2001): *Natural Gas Monthly*, DOE/EIA-0130(2002/08) (Washington, DC, August 2002). Carbon Dioxide Produced with Natural Gas: Composition (1980-1998): Gas Research Institute, *Chemical Composition of Discovered and Undiscovered Natural Gas in the United States: 1993 Update*, GRI-93/0456.1; Gas Research Institute, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*, GRI-92/0123. Production (1980-1996): Dwight's Energy Data Lease/Well Production File. (1997-1998): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, 1999). (1999, 2000) Energy Information Administration, *Monthly Energy Review*, DOE/EIA-035(2001/07) (Washington, DC, July 2001). Transmission and End-Use Consumption (1980-1998): Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (Washington, DC, various years). (1999): Energy Information Administration, *Natural Gas Monthly*, DOE/EIA-0130(2000/06) (Washington, DC, June 2000).

---

<sup>6</sup>See discussion of carbon dioxide manufacture for the treatment of vented carbon dioxide.

## Industrial Processes

In addition to energy-related emissions, carbon dioxide is also produced during certain industrial processes. The primary source of industrial emissions is the calcination of limestone ( $\text{CaCO}_3$ ) to create lime ( $\text{CaO}$ ). These two compounds are basic materials in a variety of manufacturing processes, particularly cement, iron and steel, and glass. Other sources of industrial emissions include the production and use of soda ash ( $\text{Na}_2\text{CO}_3$ ), the manufacture of carbon dioxide, and aluminum production.

For this source category, emissions estimates are based on the compound used in the industrial process. Table A6 shows activity data for industrial processes. By multiplying the amount of production or consumption of the compound by a carbon coefficient (the relative amount of carbon in that compound), a process-specific estimate is derived. During the period 1990 through 2000, carbon dioxide emissions from industrial sources have ranged from 16 to 19 million metric tons of carbon annually. Each industrial process, emissions source, and estimation method is discussed below.

### Cement Manufacture

More than half (60 percent) of the carbon dioxide emissions from industrial sources originate from cement manufacturing (see Chapter 2).

**Emissions Sources.** Four basic materials are required to make cement: calcium, silicon, aluminum, and iron. Substrates of these materials are ground into a powder and heated in a kiln. While in the kiln, limestone (the predominant source of calcium) is broken down into carbon dioxide and lime. The carbon dioxide is driven off into the atmosphere. After the kilning process has been completed, cement clinker is left.

**Estimation Methods.** One mole of calcined limestone produces one mole of carbon dioxide and one mole of lime. Since virtually all of the lime produced is absorbed into the clinker, the lime content of clinker is assumed to be representative of the amount of carbon dioxide emitted. In order to estimate emissions from cement manufacture, a carbon coefficient must be calculated. EIA has adopted the IPCC recommendation that 64.6 percent of cement clinker is lime.<sup>7</sup> Multiplying this lime content factor by the ratio of carbon produced to lime produced yields the coefficient for cement clinker. A separate coefficient is necessary for estimating emissions from the additional lime used to produce masonry cement. In this case, the amount of lime not accounted for as clinker is assumed to be 3 percent.<sup>8</sup> This factor is then multiplied by the same production ratio of carbon to lime, generating the carbon coefficient for masonry cement. It should also be noted that during clinker production, some of the clinker materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The carbon dioxide emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker production emission factor. In keeping with the IPCC/OECD/IEA 1999 draft meeting report on emissions from industrial processes and the new gases (appearing in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*), EIA estimates that an additional increment of carbon dioxide emissions from clinker production equal to 2-percent of direct emissions from clinker production are attributable to cement kiln dust.

---

<sup>7</sup>Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.6, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

<sup>8</sup>U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999* (Washington, DC, April 2001), p. 3-5.

**Table A6. Production and Consumption Data for U.S. Carbon Dioxide Emissions from Industrial Processes, 1990-2001.**

(Thousand Metric Tons)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
Cement Clinker Production	63,326	61,608	62,184	65,745	69,787	69,983	70,361	72,686	74,523	76,003	78,138	78,900
Masonry Cement Production	2,911	2,592	2,806	2,962	3,613	3,603	3,469	3,634	3,989	4,000	5,000	4,000
Lime Production	15,832	15,667	16,199	16,700	17,400	18,500	19,200	19,700	20,100	19,700	19,600	18,700
Limestone Consumed in Iron Smelting	3,955	3,635	3,098	2,561	2,538	2,615	2,538	2,549	2,477	2,379	2,461	2,271
Limestone Consumed in Steelmaking	682	738	612	1,087	1,225	1,126	949	750	798	612	1,029	1,416
Limestone Consumed in Glass Manufacture	272	269	354	439	680	754	450	203	443	443	443	443
Limestone Consumed in FGD Units	4,369	4,552	4,479	4,274	4,621	5,815	6,125	6,595	6,322	6,835	7,607	7,607
Limestone Consumed in Dolomite Manufacture	986	732	641	549	526	428	691	673	654	295	658	658
Soda Ash Production (from Trona)	8,147	8,152	8,269	8,056	8,111	9,167	9,056	9,500	9,167	8,833	8,722	8,556
Soda Ash Consumed in Glass Manufacture	3,177	2,997	3,082	3,095	3,150	3,130	3,040	3,130	3,220	3,270	3,170	3,170
Soda Ash Consumed in FGD Units	179	155	156	146	191	211	206	295	296	210	235	235
Sodium Silicate Production	740	789	827	913	914	1,091	1,002	1,101	1,096	992	1,034	1,036
Sodium Tripolyphosphate Production	451	419	419	419	419	419	419	419	205	181	181	181
Aluminum Manufacture	4,048	4,121	4,042	3,695	3,299	3,375	3,577	3,603	3,713	3,779	3,668	2,600
Copper Primary Smelting	1,577	1,580	1,710	1,790	1,840	1,930	2,010	2,070	2,140	1,890	1,590	1,600

P = preliminary data.

Sources: U.S. Department of the Interior, United States Geological Survey, *Mineral Commodity Summaries* (Washington, DC, various years). *Cement Annual Report* (Washington, DC, various years). *Soda Ash Annual Report* (Washington, DC, various years) (soda ash production calculated from quantity of trona ore production). *Crushed Stone Annual Report* (Washington, DC, various years). *Iron and Steel Annual Report* (Washington, DC, various years). *Copper Annual Report* (Washington, DC, various years). *Aluminum Annual Report* (Washington, DC, various years). Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook 1999* (Washington, DC, August 1999). Energy Information Administration unpublished survey data, *Steam Electric Plant Operation and Design Report, Form EIA-767* (Washington, DC, various years). Freedomia Group, Inc., *Carbon Dioxide*, Business Research Report B286 (Cleveland, OH, November 1991), and *Carbon Dioxide*, Industry Study 564 (Cleveland, OH, February 1994). American Iron and Steel Institute, *Annual Statistical Report* (Washington, DC, various years).

## Lime Manufacture

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

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

**Estimation Methods.** Based on the ratio of the molecular weight of carbon dioxide to the weight of calcium carbonate, EIA assumes that 785 metric tons of carbon dioxide, or 214 metric tons of carbon, are released for every 1,000 metric tons of lime produced. This factor is applied to annual levels of lime manufacture to estimate potential emissions. EIA does not account for the instances in which the carbon dioxide is recovered or reabsorbed. Representatives of the National Lime Association believe that 10 to 20 percent of the carbon dioxide emitted in lime manufacture is recovered for industrial use or reabsorbed from the atmosphere by chemical reactions induced by the use of lime.

## Limestone Consumption

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

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

**Estimation Methods.** Assuming that limestone has a carbon content of 12 percent and dolomite 13.2 percent, EIA applies the appropriate factor to the annual level of consumption in the iron smelting, steelmaking, and glass manufacture industries, and in flue gas desulfurization systems that use this sorbent. This amounts to 120 metric tons of carbon for every 1,000 metric tons of limestone consumed, or 132 metric tons of carbon for every 1,000 tons of dolomite consumed (when dolomite is distinguished in the data). In the case of limestone (including dolomite) used in flue gas desulfurization units, the estimate of carbon emitted was adjusted based on the application of a capacity utilization rate from the calcination process of sorbents used, typically limestone (including dolomite). According to information obtained in May 1999 from the U.S. Geological Survey regarding the characterization of limestone consumed in fluidized-bed combustion systems and flue gas desulfurization units, the utilization rate of calcium obtained from the calcination process, ranges from approximately 30 to 40 percent.

## Soda Ash Manufacture and Consumption

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

**Emissions Sources.** Two methods are used to manufacture natural soda ash in the United States. The majority of production comes from Wyoming, where soda ash is manufactured by calcination of trona ore in the form of naturally occurring sodium sesquicarbonate. For every mole of soda ash created in this reaction, one mole of carbon dioxide is also produced and vented to the atmosphere. The other process used to manufacture soda ash is carbonation of brines; however, the carbon dioxide driven off in this process is captured and reused.

Once manufactured, most soda ash is consumed in glass and chemical production. Other uses include water treatment, flue gas desulfurization, soap and detergent production, and pulp and paper production. As soda ash is processed for these purposes, additional carbon dioxide may be emitted if the carbon is oxidized. Because of the limited availability of specific information about such emissions, only certain uses of soda ash are considered in this report. Sodium silicate and sodium tripolyphosphate are included as chemicals manufactured from soda ash and components of detergents.

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

## Carbon Dioxide Manufacture

**Emissions Source.** Carbon dioxide is produced from a small number of natural wells and as a byproduct of chemical (i.e., ammonia) manufacturing. The Freedonia Group has determined that, in the United States, there is an 80 percent to 20 percent split between carbon dioxide produced as a byproduct and carbon dioxide produced from wells.<sup>9</sup> Emissions of byproduct carbon dioxide are incorporated into the natural gas energy consumption estimates as nonfuel, nonsequestered carbon and therefore are not included here to avoid double counting. Most carbon dioxide produced from wells is injected back into the ground for enhanced oil recovery. This process sequesters the carbon dioxide, at least in the short run. Conceptually, only carbon dioxide produced from wells and diverted to industrial use is emitted to the atmosphere.

**Estimation Methods.** The Freedonia Group estimates that non-sequestering industrial use of carbon dioxide resulted in emissions of 1.3 million metric tons of carbon in 1993.<sup>10</sup> If 20 percent of this industrial use is supplied by wells, emissions can be estimated at 0.26 million metric tons of carbon. Based on the Freedonia report, the 2000 estimate is calculated by assuming an annual 4.2-percent increase, implying emissions of 0.35 million metric tons of carbon.

<sup>9</sup>The Freedonia Group, Inc., *Carbon Dioxide, Business Research Report B286* (Cleveland, OH, November 1991), p. 46.

<sup>10</sup>The Freedonia Group, Inc., *Carbon Dioxide, Industry Study 564* (Cleveland, OH, February 1994), p. 37.

## Aluminum Manufacture

Aluminum is an element used in alloys. Because it is light in weight, malleable, and not readily corroded or tarnished, it is used as a principal material for kitchen utensils, aircraft, some automobiles, bicycles, and other manufactured products. The United States is a major producer of aluminum and also an importer, depending on market conditions.

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

**Estimation Methods.** The 1994 MECS indicated that nonfuel use of fuels by aluminum smelters (SIC 3334) totaled 40 trillion Btu in 1994.<sup>11</sup> The composition of nonfuel use by fuel type has been withheld for confidentiality purposes, but it is probable that most of the 40 trillion Btu consists of petroleum coke, which would imply an emissions factor of about 0.338 metric tons of carbon per metric ton of aluminum smelted (0.04 quadrillion Btu of coke  $\times$  27.85 million metric tons of carbon per quadrillion Btu / 3.295 million metric tons of aluminum smelted in 1994). EIA now uses an emissions factor of 0.4 metric tons carbon per metric ton of aluminum smelted, which is at the low end of Abrahamson’s range and also equals the mass balance for a “typical” aluminum smelter from another source.<sup>12</sup>

## Municipal Solid Waste

A portion of the municipal solid waste (MSW) that is burned contains plastics. The carbon that goes into plastics is subtracted from the inventory. Therefore, when those plastics are burned they must be accounted for as additions to the atmosphere of carbon. The U.S. EPA accounted for MSW for the first time in the 1998 official inventory. This document uses the EPA estimate for 1990 through 2000 and uses the 2000 estimate for 2001. This number is currently reported under “waste” as it includes for example emissions from the burning of toxic wastes in addition to the MSW, much of which is burned in the generation of electrical energy.

## Data Sources for Industrial Processes

The U.S. Geological Survey reports listed below can be found on the Internet at <http://minerals.usgs.gov/minerals/pubs/mcs/>.

**Cement and Clinker Production (1980-2000):** U.S. Department of the Interior, U.S. Geological Survey, *Cement Annual Report* (Washington, DC, various years). **(2001):** U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries* (Washington, DC, 2002).

**Lime Manufacture: (1980-2001):** U.S. Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries* (Washington, DC, various years).

**Limestone Consumption in Iron Smelting, Steelmaking, and Glass Manufacture: (1980-2000):** U.S. Department of the Interior, U.S. Geological Survey, *Crushed Stone Report* (Washington, DC, various years). **(2001):** EIA estimate. **Limestone Consumption in Flue Gas Desulfurization: (1980-2000):** Energy Information Administration, unpublished survey data, Form EIA-767, “Steam Electric Plant Operation and Design Report” (Washington, DC, various years). **(2001):** EIA estimate.

**Soda Ash Manufacture and Soda Ash Consumption in Glass Making (1980-2001):** U.S. Department of the Interior, U.S. Geological Survey, *Soda Ash Report* (Washington, DC, various years). **Soda Ash Consumption in Flue Gas Desulfurization (1980-2000):** Energy Information Administration, unpublished survey data, Form EIA-767, “Steam Electric Plant Operation and Design Report” (Washington, DC, various years). **(2001):** EIA estimate. **Sodium Silicate and Sodium Tripolyphosphate: (1980-1996):** Chemical Manufacturers Association, *U.S.*

<sup>11</sup> Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), Table A3, p. 49.

<sup>12</sup> Drexel University Project Team, *Energy Analysis of 108 Industrial Processes* (Lilburn, GA: The Fairmont Press, 1996), p. 282.

*Chemical Industry Statistical Handbook 1998* (Washington, DC, September 1998), pp. 37-38. **(1997-2001):** data published by the U.S. Department of Commerce, Bureau of the Census, in its annual and quarterly *Current Industrial Reports* on inorganic materials.

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

**Aluminum (1980-2001):** U.S. Department of the Interior, U.S. Geological Survey, *Aluminum Report* (Washington, DC, various years).

**Municipal Solid Waste (1990-2000, 2001 estimate):** U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000* (Washington, DC, April 2002).

## Methane

### Energy Sources

#### Coal Mining

#### Emissions Sources

As coal is formed from organic material by natural chemical and physical processes, methane is also produced. The methane is stored in the pores (open spaces) of the coal itself and in cracks and fractures within the coalbed. As coal is mined, the pressure surrounding the stored methane decreases, allowing much of it to be released into the operating coal mine (in the case of an underground mine) or into the atmosphere (in the case of a surface mine). The methane remaining in the coal pores is emitted when the coal is transported and pulverized for combustion. There are five avenues for methane emissions from coal mines:

- **Ventilation Systems in Underground Mines.** Methane in concentrations over 5 percent is explosive and presents a mortal danger to coal miners. To meet safety standards set by the Mine Safety and Health Administration (MSHA) requiring levels of methane concentration to be maintained well below the 5-percent threshold, mine operators use large fans to provide a steady airflow across the mine face and ventilate the mine shaft. Typically, these ventilation systems release substantial quantities of methane in the fan exhaust.
- **Degasification Systems in Underground Mines.** When the volume of gas in underground mines is too high to be practically reduced to safe levels by standard ventilation techniques, degasification systems are employed. Degasification may take place before mining or may take the form of gob-wells or in-mine horizontal boreholes. Methane captured by degasification systems may be vented, flared, or recovered for energy.
- **Surface Mines.** Because coal mined from the surface has formed at lower temperature and pressure than coal from underground mines, its methane content is lower. Further, because the coal is located near the surface, methane has had ample opportunity to migrate to the atmosphere before mining. Thus, while methane emissions from surface mines are heterogeneous in nature, they are systematically smaller than emissions from underground mines.
- **Post-Mining Emissions.** Methane that remains in coal pores after either underground or surface mining will desorb slowly as the coal is transported (typically by train) to the end user. Because coal that is consumed in large industrial or utility boilers is pulverized before combustion, methane remaining in the coal pores after transport will be released prior to combustion.
- **Methane Recovery for Energy.** In some cases (for example, in some mining degasification systems), methane is emitted from coal mines in sufficiently high volumes and concentrations to permit commercial recovery of the gas as either pipeline gas, power generation fuel, or for mine site uses. Because coal mine methane recovered commercially is combusted, the quantities recovered are subtracted from estimates of total coal mine methane emissions.

## Estimation Methods

**Ventilation Systems in Underground Mines.** Emissions from this source are segregated into two classes: emissions from “gassy” mines and emissions from “nongassy” mines.<sup>13</sup> Because methane concentrations and airflows in gassy mines are carefully monitored by the MSHA, a fairly reliable set of data can be derived for emissions from ventilation systems in gassy mines. Prior to 1993, MSHA data are available for only a subsample of years (1980, 1985, 1988, 1990, 1993). Thus, EIA developed a methodology that uses available MSHA data in conjunction with coal production data to develop emissions factors per ton of coal mined on a basin-by-basin level.<sup>14</sup> Emissions factors for nonsample years are interpolated. MSHA data are available for all years after 1993 and estimates of emissions from ventilation systems are based on a compilation of MSHA data by the U.S. EPA Office of Air and Radiation.

Emissions from nongassy mines make up less than 2 percent of all emissions from underground mines.<sup>15</sup> Basin-level emissions factors for nongassy mines were established by dividing 2 percent of each basin’s estimated emissions from nongassy mines for 1988 by that year’s production levels. The resulting emissions factors are applied to annual production data for the period through 1998. For 1999 through 2001, emissions from nongassy mines are based on calculations from the U.S. EPA Office of Air and Radiation.

**Degasification Systems in Underground Mines.** Degasification emissions are not monitored by any regulatory agency. Where degasification does occur, the method of disposition may not be tabulated. Estimated emissions from degasification systems during the period 1993 through 2001 are based on data collected by the EPA’s Office of Air and Radiation, Coalbed Methane Outreach Program. For years prior to 1993, emissions from degasification systems are estimated by multiplying annual production in mines known to have degasification systems in place by a per-ton emissions factor.

**Surface Mines.** Emissions from U.S. surface mines have not been systematically measured. However, studies on surface coal mines in the United States, England, France, and Canada suggest a range of 0.3 to 2.0 cubic meters per metric ton of coal mined.<sup>16</sup> This report adopts the central value of that range and multiplies it by U.S. surface coal production.

**Post-Mining Emissions.** Like emissions from surface mines, post-mining emissions are not measured systematically. Thus, global average emissions factors must be applied. Post-mining emissions for coal mined from the surface are estimated to be very low, between 0.0 and 0.2 cubic meters per metric ton of coal mined. In contrast, post-mining emissions from underground coal are estimated to be more significant, between 0.9 and 4.0 cubic meters of methane per metric ton of coal mined.<sup>17</sup> The central values of these ranges are adopted and multiplied by annual production data for this report.

**Methane Recovery for Energy.** Methane recovery for energy is restricted to a small sample of mines that typically meter their gas sales. Thus, total methane recovery can be estimated from the volume and heat content of sales. The EIA adopts a time series of methane recovery prepared by the EPA Coalbed Methane Outreach Program for all years through 2001.

## Data Sources

**Ventilation Systems in Underground Mines.** Coal mine ventilation data for the gassiest U.S. mines were drawn from a database prepared by the Department of Interior’s Bureau of Mines for the years 1980, 1985, 1988, 1990, and 1993. Ventilation data for 1994-2001 were obtained from the EPA, Climate Protection Partnerships Division, Coalbed Methane Outreach Program. Coal production data for years prior to 1998 are reported to EIA on Form EIA-

<sup>13</sup> Gassy mines are defined as those underground coal mines with measured emissions from ventilation exhaust in excess of 100,000 cubic feet of methane per day.

<sup>14</sup> For purposes of this analysis, the U.S. has five distinct coal basins: Northern Appalachia includes Pennsylvania, Northern West Virginia, Maryland, and Ohio; Central Appalachia includes Eastern Kentucky, Virginia, Southern West Virginia, and Tennessee; the Warrior basin includes Alabama; the Illinois basin includes Illinois, Indiana, Western Kentucky, Iowa, and Oklahoma; and the Western basin includes Colorado, New Mexico, Utah, and Wyoming.

<sup>15</sup> M.A. Trebits, G.L. Finfinger, and J.C. LaScola, “Evaluation of U.S. Coal Mine Emissions,” in Society for Mining, Metallurgy and Exploration, *Proceedings of the Fifth U.S. Mine Ventilation Symposium* (Littlejohn Co., 1991), p. 2.

<sup>16</sup> Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.98-1.112, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

<sup>17</sup> Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.98-1.112, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

7A, "Coal Production Report." Coal production data for 1998 based on Form 7000-2, "Quartely Mine Employment and Coal Report," collected by the Mine Safety and Health Administration. Basin-level emissions for non-gassy mines in 1988 were calculated by the EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-19–3-24.

**Degasification Systems in Underground Mines.** Data on drainage from degasification systems from 1993 through 2001 are from the EPA's Office of Air and Radiation, Climate Protection Partnerships Division, Coalbed Methane Outreach Program. Emissions factors for this source are derived from estimates of 1988 emissions from degasification systems prepared by the EPA's Office of Air and Radiation, in *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), pp. 3-19B–3-24. Annual production figures for years prior to 1998 are reported to EIA on Form EIA-7A, "Coal Production Report." Coal production data for 1998 based on Form 7000-2, "Quartely Mine Employment and Coal Report," collected by the Mine Safety and Health Administration.

**Surface Mines.** Emissions factors for surface mines are found in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm) Coal production data for years prior to 1998 are reported to EIA on Form EIA-7A, "Coal Production Report." Coal production data for 1998 based on Form 7000-2, "Quartely Mine Employment and Coal Report," collected by the Mine Safety and Health Administration.

**Post-Mining Emissions.** Emissions factors for post-mining emissions are found in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm) Coal production data for years prior to 1998 are reported to EIA on Form EIA-7A, "Coal Production Report." Coal production data for 1998 based on Form 7000-2, "Quartely Mine Employment and Coal Report," collected by the Mine Safety and Health Administration.

**Methane Recovery for Energy.** Methane recovery estimates the EPA's Office of Air and Radiation, Climate Protection Division, Coalbed Methane Outreach Program.

## **Natural Gas Production, Processing, and Distribution**

### **Emissions Sources**

Because methane is the principal constituent of natural gas (representing about 95 percent of the mixture), releases of natural gas result in methane emissions. Methane emissions can be grouped into three categories: (1) fugitive or unintentional leaks emitted from sealed surfaces such as pipelines, gaskets, and flanges; (2) vented or intentional releases from process vents, maintenance blowdowns, and pneumatic devices; and (3) releases from incomplete combustion in compressor engines, burners, and flares.<sup>18</sup> The natural gas industry can be divided into four source segments:

- **Gas Production.** This segment consists of gas and oil wells, surface equipment to produce gas, and gathering pipeline. Leakage occurs from valves, meters, and flanges. Pneumatic valves release gas when they are reset. Gathering pipeline may be emptied for maintenance or may have fugitive emissions.
- **Gas Processing.** When gas is processed, liquefied petroleum gases and natural gasoline are removed for sale or further refining. Water is also removed, and gas is conformed to commercial pipeline quality and heat content. Methane is released during maintenance, via leaks, and during system upsets when sudden increases in pressure require a gas release or result in a system rupture.
- **Transmission and Storage.** High-pressure transmission pipelines transport natural gas from production fields and gas processing facilities to distribution pipelines. Natural gas may escape through leaky pipes and valves. Methane may be emitted as part of compressor exhaust. Gas is often stored near consumption centers to meet peak demand during periods of high consumption. These storage facilities emit methane in compressor exhaust and from dehydrators.

<sup>18</sup> National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996), p. 19.

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

## Estimation Methods

Estimates of emissions from the natural gas system are scaled to commonly available activity data such as number of wells in operation, miles of gathering pipeline, gas throughput, gas volumes processed, miles of transmission pipeline and miles of distribution pipeline. The activity data are multiplied by emissions factors derived from point-in-time emissions estimates for 1992 developed in a study sponsored jointly by the U.S. Environmental Protection Agency (EPA) and the Gas Research Institute (EPA/GRI).<sup>19</sup> The EPA/GRI study provides activity data and disaggregated emissions factors for 86 separate gas industry process components. In an effort to take advantage of this level of detail, this report estimates the number of each process component for the years 1990-2001. Each process component is scaled to a widely available metric, such as gas withdrawals or pipeline miles most related to the process activity. The derived activity data are then applied to the component emissions factor from the EPA/GRI report.

## Data Sources

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

## Petroleum Systems

### Emissions Sources

The vast preponderance of emissions from petroleum systems occur during crude oil exploration and production. Much smaller emissions occur during crude transportation and crude refining. Emissions from petroleum systems can be divided into four types: 1) vented emissions; 2) fugitive emissions; 3) combustion emissions and 4) upset emissions.

- vented emissions are intentional releases to the atmosphere by facility design or operational practice.
- fugitive emissions are accidental and often ongoing releases associated with a leak source within the system
- combustion emissions are the result of fuel use to drive compressors or flares
- upset emissions are typically the result of safety measures such as emergency pressure releases or oil platform shutdowns<sup>20</sup>

The largest single emissions source is the venting at crude oil storage tanks.

## Estimation Methods

Estimates of emissions from petroleum systems are derived by multiplying emission factors for approximately 90 separate components of the petroleum system by an estimate of the total number of components on the national system. To produce a time-series of estimates, the number of components for 1990 - 2001 are scaled to readily available industry activity data such as number of oil wells, refinery input, and crude transported by pipeline, marine vessel or truck.

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

<sup>20</sup>U.S. Environmental Protection Agency, Office of Air and Radiation, *Estimates of Methane Emissions from the U.S. Oil Industry*, (Draft Report, Washington, D.C.)

## Data Sources

Emission factors are from the U.S. Environmental Protection Agency, Office of Air and Radiation, Draft Report, *Estimates of Methane Emissions from the U.S. Oil Industry*. Activity data are from EIA's *Monthly Energy Review* (July, various years), EIA's *Petroleum Supply Annual* (various years), Oil and Gas Journal's *Worldwide Refining Issue and Pipeline Economics Issue*.

## Stationary Combustion

### Emissions Sources

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

### Estimation Methods

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

## Data Sources

Emissions coefficients for stationary fuel were obtained from the EPA's Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm). Fuel consumption data were drawn from the Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(99) (Washington, DC, September 1999) for 1980-1997; and *Monthly Energy Review*, DOE/EIA-0035(02/07)(Washington, DC, July 2002) for 1998-2001. Residential woodfuel consumption data were derived from EIA's *Annual Energy Review 2001*, DOE/EIA-0384(01) (Washington, DC, November 2002).

## Mobile Combustion

### Emissions Sources

Methane emissions from mobile combustion are, like those from stationary combustion, the result of incomplete fuel combustion. In automobiles, methane emissions result when oxygen levels in the combustion chamber drop below levels sufficient for complete combustion. The effects of incomplete combustion in automobiles may be moderated somewhat by post-combustion emissions controls, such as catalytic converters. Methane emissions are also generated by fuel combustion in other modes of transport. Other sources include aircraft, ships and locomotives, in addition to methane emissions from farm and construction equipment. There is, however, some evidence that jet airplane engines may consume ambient methane during flight, thereby reducing their net emissions.

### Estimation Methods

Methane emissions from highway vehicles are estimated by applying emissions factors (per vehicle mile traveled) to vehicle use data. Research indicates that emissions rates differ among motor vehicles by vehicle type and by type of catalytic converter (associated with the vintage of the motor vehicle) for light duty vehicles. Consequently, EIA partitions vehicle use data by vehicle type (i.e. by passenger cars, light-duty trucks, buses, motorcycles, and heavy-duty trucks), as well as by motor vehicle vintage (model year) for passenger cars and light duty trucks. Due to improvements in technology and increasing stringency of environmental regulations, motor vehicle methane emissions have generally declined over time. For non-highway sources, emissions coefficients are applied directly to annual fuel consumption data.

## Data Sources

Emissions factors for all vehicles are provided in Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm). EIA collected data on miles traveled in personal transportation vehicles (cars and light-duty trucks) as part of its triennial Residential Transportation Energy Consumption Survey (RTECS): Energy Information Administration, *Household Vehicles Energy Consumption 1994*, DOE/EIA-0464 (Washington, DC, July 1996, and previous years). This survey contains data for the years 1983, 1985, 1988, 1991, and 1994. Vehicle miles traveled for other years are estimated using weighted averages from survey data in conjunction with statistics on the U.S. fleet of cars and trucks by model year, provided by provided by the American Automobile Manufacturers Association, *AAMA Vehicle Facts and Figures* (Detroit, MI, various years) and by Ward's Communications Inc., *Ward's Automotive Yearbook* (Southfield, MI, 1999) and Ward's Automotive Report (Southfield, MI, various years). Vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks were obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics* (Washington, DC, various years), web site [www.fhwa.dot.gov/ohim/ohimstat.htm](http://www.fhwa.dot.gov/ohim/ohimstat.htm).

Fuel consumption for ships, locomotives, farm and construction equipment is based on data from EIA's *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, various years). Jet and piston-powered aircraft fuel consumption data are contained in the Energy Information Administration's *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years). Data on fuel consumption by recreational boats are taken from Oak Ridge National Laboratory, Center for Transportation Analysis, *Transportation Energy Data Book* (Oak Ridge, TN, various years), web site [www-cta.ornl.gov/publications/tedb.html](http://www-cta.ornl.gov/publications/tedb.html).

## Landfill Methane Emissions

### Emissions Sources

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

The biogas produced in a landfill is typically between 50 and 60 percent methane. When emitted, biogas mixing with air can result in methane concentrations within the explosive range of 5 to 15 percent. Often, landfill operators put methane control systems in place to prevent migration of high concentrations to buildings. Methane captured by control systems may be vented to the atmosphere or flared, but it is also a potentially valuable energy resource. Where landfills produce steady, large volumes of methane and landfill gas-to-energy prices are competitive with other energy alternatives, recovered gas may be used as an energy resource. In most cases, the gas is converted to electricity and used for on-site energy needs or sold to local utilities. In some cases, the gas is transported via pipeline to a local end user.

### Estimation Methods

Data on methane emissions from landfills are limited to those landfills with methane recovery systems in place. For more than 100 U.S. landfills with gas recovery systems in place, Thorneloe et al. measured or estimated methane emissions at 2.1 million metric tons for 1992.<sup>21</sup> Methane emissions from landfills without gas recovery systems have not been measured, and even the number of landfills is subject to considerable uncertainty. Emissions from a given landfill are largely the product of the composition of the waste it contains and an array of site-specific factors. Waste composition data on a landfill-specific basis are nonexistent; however, national-level waste flow and waste composition data are available, and their reliability has improved over time. Thus, for this report, all waste not disposed of in a landfill with measured emissions is treated as if it has flowed to one very large national landfill.

<sup>21</sup> S.A. Thorneloe, M.R.J. Doorn, L.A. Stefanski, M.A. Barlaz, R.L. Peer, and D.L. Epperson, "Estimate of Methane Emissions From U.S. Landfills," Prepared for U.S. Environmental Protection Agency, Office of Research and Development (April 1994), p. 1087.

To estimate methane emissions from all waste not disposed of in a landfill with measured emissions, waste volumes are subjected to a slightly modified version of the EMCON Methane Generation Model.<sup>22</sup> This model divides the waste into three categories: readily decomposable, moderately decomposable, and slowly decomposable, each with its own set of emissions characteristics. The EMCON model provides both a high methane yield scenario and a low methane yield scenario. For each category of decomposable waste, a time lag until methane generation begins is estimated, as well as a time constant during which the methane yield of the waste is realized. The methane yield represents the total amount of methane that a given amount of waste will produce over its lifetime. For example, under a low methane yield scenario, slowly decomposing waste will begin producing methane after a 5-year lag and will continue emitting over a 40-year period. Table A7 shows the EMCON methane generation model parameters.

Waste flows were estimated from 1940 through 2001. Waste in place in the Nation's landfills was assumed to represent the waste stream for all previous years plus the current year's additions. The landfills examined by Thorne et al. contained 9.2 percent of the waste estimated to be in place in the Nation's landfills during 1992. This report assumes that the share of waste in these landfills and the share in all other landfills remained constant over time. Thus, the EMCON model was applied to 90.8 percent of the waste generated each year.

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

**Table A7. EMCON Methane Generation Model Parameters**

Waste Category	Decomposable Portion (Percent by Dry Weight)	Methane Yield (Cubic Feet per Pound)	Lag Time (Years)	Time Constant
High Yield (Default)				
Readily Decomposable	4.0	4.5	0.2	3
Moderately Decomposable	45.0	3.6	1.5	10
Slowly Decomposable	5.2	0.5	5.0	20
Low Yield (Default)				
Readily Decomposable	4.0	2.8	0.3	4
Moderately Decomposable	45.0	2.0	2.0	20
Slowly Decomposable	5.2	0.3	5.0	40
High Yield (Modified)				
Readily Decomposable	4.0	8.8	0.0	3
Moderately Decomposable	45.0	7.0	2.0	10
Slowly Decomposable	5.2	1.0	5.0	20
Low Yield (Modified)				
Readily Decomposable	4.0	5.4	0.0	4
Moderately Decomposable	45.0	3.8	2.0	20
Slowly Decomposable	5.2	0.6	5.0	40

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

## Data Sources

Data on waste generated and landfilled for the period 1988 through 2000 (Table A8) were drawn from "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-2001). These data were not collected by *Biocycle* before 1988. Waste generated and landfilled for the period 1960 through 1987 was estimated from data produced by Franklin Associates. On behalf of the EPA's Office of Solid Waste and Emergency Response, Franklin Associates have estimated municipal solid waste (MSW) generated and landfilled for the years 1960 through 1997. See 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) and U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1998 Update*, EPA-530-S-99-021 (Washington DC, July 1999). In contrast to the *Biocycle* data, which include all waste going to landfills, including construction and

<sup>22</sup>D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environment Change* (December 1992), pp. 311-328.

demolition (C&D) waste and sludge, the Franklin data include only MSW going to landfills. For 2001, waste generation data were not yet available so 2000 estimates were scaled up by GDP growth of 0.3 percent to provide an estimate of waste generation in 2001. The volume of waste recycled or combusted rather than landfilled was assumed to have remained stable at 40% in 2000.

**Table A8. U.S. Solid Waste Generated and Landfilled, 1990-2001**  
(Million Metric Tons)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Waste Generated	266.4	254.6	264.7	278.4	292.9	296.4	297.1	308.9	339.9	353.7	371.1	372.2
Waste Landfilled	205.2	193.6	190.6	197.7	196.3	186.8	184.2	188.5	207.4	215.8	222.7	223.3
Waste In Place	6868.7	7062.3	7252.9	7450.6	7646.9	7833.7	8017.9	8206.4	8413.7	8629.6	8852.3	9075.7

Source: "Nationwide Survey: The State of Garbage in America," *Biocycle* (1988-2001).

In order to account for categories of waste other than MSW going to landfills between 1960 and 1987, an average ratio of waste generation estimated by *Biocycle* and waste generation estimated by Franklin Associates for 1988 through 1997 was calculated. The annual average ratio during this period was 1.47 to 1. Thus, all Franklin estimates for 1960 through 1987 were multiplied by 1.47 to estimate overall waste generation and landfilling for those years. To further extend waste generation estimates back to 1940, a regression equation relating waste generation to GNP and population was developed. Annual methane recovery data are from the U.S. Environmental Protection Agency's Landfill Methane Outreach Program database.<sup>23</sup>

## Domestic and Commercial Wastewater Treatment

### Emissions Sources

Emissions of methane from the treatment of wastewater occur when liquid waste streams containing high concentrations of organic materials are treated anaerobically (in the absence of oxygen). Treatment processes used in the United States are anaerobic digestion, aerobic, and facultative (combining aerobic and anaerobic processes) stabilization lagoons, septic tanks, and cesspools.<sup>24</sup> Treatment of wastewater solids using anaerobic digestion is the most obvious potential source of methane emissions; however, emission of significant quantities of methane from this process requires that the digester gas be vented rather than recovered or flared. Anaerobic and facultative lagoons involve retention of wastewater in impoundments, where the organic materials in the wastewater undergo bacterial decomposition. The growth of algae, which absorb carbon dioxide and release oxygen as a result of photosynthesis, sustains aerobic conditions at least near the surface of the lagoon. Bacteria deplete oxygen at the bottom of the lagoon, producing conditions suitable for methanogenic bacteria. The extent of the resulting anaerobic zone and the associated methane generation depend on such factors as organic loadings and lagoon depth. In facultative lagoons, unlike anaerobic lagoons, a significant aerobic zone persists.

Nearly 75 percent of U.S. households are served by sewers that deliver domestic wastewater to central treatment plants. Septic tanks or cesspools treat domestic wastewater from most of the remaining households.<sup>25</sup> Anaerobic digestion is frequently used to treat sludge solids at U.S. municipal wastewater treatment plants; however, anecdotal evidence suggests that neither recovery nor flaring of digester gas is common in the United States and that equipment for recovery and flaring of digester gas is poorly designed or maintained, allowing most of the methane produced to be released to the atmosphere.<sup>26</sup>

### Estimation Methods

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

<sup>23</sup> See web site [www.epa.gov/lmop](http://www.epa.gov/lmop).

<sup>24</sup> U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *International Anthropogenic Methane Emissions: Estimates for 1990*, EPA-230-R-93-010 (Washington, DC, January 1994), p. 10-9.

<sup>25</sup> U.S. Census, 1980, 1990, 2000.

<sup>26</sup> William Hahn, Science Applications International Corporation, personal communication, May 23, 1996.

Therefore, EIA bases its current estimate of methane emissions from wastewater treatment on the highly simplified approach recommended by the IPCC,<sup>27</sup> which assumes that each person in a developed nation contributes 0.05 kilogram of BOD<sub>5</sub> to domestic wastewater annually, and 15 percent of this wastewater is treated anaerobically, yielding 0.22 kilogram of methane per kilogram of BOD<sub>5</sub> in the wastewater.<sup>28</sup> The EIA assumes that recovery of methane at municipal wastewater treatment facilities is negligible.

## Data Sources

Estimates of the U.S. resident population on July 1 of each year were obtained from the U.S. Census Bureau.

## Agricultural Sources

### *Enteric Fermentation in Domesticated Animals*

#### Emission Sources

The breakdown of carbohydrates in the digestive track of herbivores (including insects and humans) results in the production of methane.<sup>29</sup> The volume of methane produced from this process (enteric fermentation) is largest in those animals that possess a rumen, or forestomach, such as cattle, sheep, and goats. The forestomach allows these animals to digest large quantities of cellulose found in coarse plant material. This digestion is accomplished by microorganisms in the rumen, some of which are methanogenic bacteria. These bacteria produce methane while removing hydrogen from the rumen. The majority (about 90 percent) of the methane produced by the methanogenic bacteria is released through normal animal respiration and eructation (belching). The remainder is released as flatus.

#### Estimation Method

The level of methane emissions from enteric fermentation in domesticated animals is a function of several variables, including quantity and quality of feed intake, the growth rate of the animal, its productivity (reproduction and/or lactation), and its mobility. To estimate emissions from enteric fermentation, the animals are divided into distinct, relatively homogeneous groups. For a representative animal in each group, feed intake, growth rate, activity levels, and productivity are estimated. An emissions factor per animal is developed based on these variables. The factor is then multiplied by population data for that animal group to calculate an overall emissions estimate. Because emissions from cattle represent about 95 percent of U.S. emissions from enteric fermentation, the estimation method for cattle is more complex and detailed.

**Cattle.** The U.S. cattle population is separated into dairy and beef cattle. Dairy cattle are then divided into replacement heifers 0-12 months old, replacement heifers 12-24 months old, and mature cows. Dairy cattle are further subdivided into regional populations in an effort to capture variations in diet and feed quality. Beef cattle are divided into six classes: replacements 0-12 months old, replacements 12-24 months old, mature cows, bulls, steers and heifers raised for slaughter under the weanling system, and steers and heifers raised for slaughter under the yearling system. These populations are then multiplied by emissions factors developed for each category of cattle based on their energy intake requirements.<sup>30</sup> Because characteristics critical in determining energy intake, and thus emissions rates, for cattle—such as growth rates and milk production—change annually, an effort to scale emission factors to these changes is made. For dairy cattle, emission factors are scaled to average milk production per cow on a regional basis. For beef cattle, emissions rates were pegged to average pre-slaughter live weights for the calves and adult cattle, respectively (Table A9).

<sup>27</sup> Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 6.23, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

<sup>28</sup> Biological oxygen demand (BOD) represents the oxygen consumed by bacteria to decompose organic matter contained in a wastewater stream. It provides a measure of the organic loading of wastewater, which is the primary determinant of its potential to produce methane. BOD<sub>5</sub> is a standardized measurement of BOD that measures the oxygen consumed over a 5-day period.

<sup>29</sup> P.J. Crutzen, I. Aseilmann, and W.S. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," *Tellus*, Vol. 38B (1986), p. 272.

<sup>30</sup> U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993), p. 5-3; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997*, EPA-236-R-99-003 (Washington, DC, April 1999), p. G-2, web site [www.epa.gov/globalwarming/publications/emissions/us2000](http://www.epa.gov/globalwarming/publications/emissions/us2000).

**Table A9. Average Pre-Slaughter Live Weights for U.S. Cattle and Calves, 1990 - 2001 (Pounds)**

Animal Class	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Cattle	1,136	1,163	1,169	1,161	1,189	1,183	1,169	1,173	1,203	1,210	1,220	1,221
Calves	281	346	376	388	384	372	341	339	285	291	316	320

P = preliminary data.

Source: U.S. Department of Agriculture, web site [www.usda.gov/nass/](http://www.usda.gov/nass/)

**Other Animals.** For sheep, pigs, goats, and horses, populations are not desegregated below the species level. Emissions factors for each animal group are multiplied by their respective populations. Emission factors are drawn from the work of Crutzen et al.<sup>31</sup>

## Data Sources

Population and slaughter weight data for cattle and population data for sheep and swine were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch web site at [www.usda.gov/nass/](http://www.usda.gov/nass/). Population data for goats and horses are extrapolated from the USDA's *Census of Agriculture* for the years 1987, 1992 and 1997.<sup>32</sup> Emissions factors for dairy cattle scaled to milk production from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 -1998*, EPA-236-R-00-001 (Washington, DC, April 2000) p. H-2.

## Solid Waste of Domesticated Animals

### Emission Sources

When the solid waste of animals is allowed to decompose under anaerobic conditions, methane is produced. The volume of methane produced varies according to the amount of organic material susceptible to decomposition within the waste (volatile solids) and the manner in which the waste is managed. Liquid-based waste management systems, in addition to providing a suitable anaerobic environment, provide the moisture necessary for methanogenic bacterial cell production and acid stabilization.<sup>33</sup> Thus, they result in the greater methane emissions.

### Estimation Method

Methane emissions from the solid waste of domesticated animals are estimated by linking emissions to the volume of solid waste produced by a given animal, the volatile solids in that waste, and the manner in which the waste is handled. The volume of waste produced is controlled by the animal's size, diet, and energy requirements. As a proxy for these variables, typical animal mass as estimated in a 1990 inventory of livestock and poultry prepared by the U.S. Environmental Protection Agency<sup>34</sup> is used to determine emissions per animal. Animal sizes are adopted directly for all animals except cattle, for which masses are adjusted annually based on live pre-slaughter weights as reported by the U.S. Department of Agriculture. Volatile solids produced per kilogram of animal weight, maximum methane-producing capacity of each animal's waste and the share of waste handled in each management system are adopted from the work of Safley et al.<sup>35</sup> For all animals except dairy cattle, the share of waste handled in each management system is also drawn from Safley et al.

Methane conversion factors for dairy cattle are adopted on a State-by-State basis and are calculated from a weighted average of each State's manure management technique. Dairy cattle size and volatile solid production are drawn from the EPA. Resulting emissions factors are applied to State population data acquired from the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch.

<sup>31</sup> 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. 274-275.

<sup>32</sup> U.S. Department of Agriculture, National Agricultural Statistics Service, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Series," Part 51 (Washington, DC, 1987, 1992, and 1997).

<sup>33</sup> U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993).

<sup>34</sup> U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993).

<sup>35</sup> L.M. Safley, M.E. Casada, J. Woodbury, and K. Roos, *Global Methane Emissions from Livestock and Poultry Manure* (Washington, DC: U.S. Environmental Protection Agency, February 1992), p. 18.

## Data Sources

Population and slaughter weight data for cattle, and population data sheep, poultry, and swine were provided by the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), Livestock, Dairy, and Poultry Branch and were obtained via the Internet at [www.usda.gov/nass/](http://www.usda.gov/nass/). Average broiler chicken populations for each year were estimated by multiplying the estimated number of broiler chickens hatched annually by 0.1425 based on their 7 week life cycle as recommended by the USDA's Economic Research Service.<sup>36</sup> Population data for goats and horses were extrapolated from USDA, NASS, *Census of Agriculture, United States Summary and State Data*, Vol. 1, "Geographic Area Studies," Part 51 (Washington, DC, 1987, 1992, 1997). Methane conversion factors weighted on a state-by-state basis are from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 -1998*, EPA-236-R-00-001 (Washington, DC, April 2000) p. I-4.

## Rice Cultivation

### Emissions Sources

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

### Estimation Methods

A range of daily emissions rates has been developed from studies of rice fields in California,<sup>37</sup> Louisiana,<sup>38</sup> and Texas.<sup>39</sup> The high and low ends of the range, 0.1065 and 0.5639 grams of methane per square meter of land cultivated, are applied to the growing season length and the harvested area for each State that produces rice. In states with a second ("ratoon") crop, the additional area harvested is incorporated into the estimates.

### Data Source

The area of rice harvested and the length of growing season data were obtained from the U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (annual reports). For 1990-2000, data on Florida rice harvests are from University of Florida, Institute of Food and Agricultural Sciences, Cooperative Extension Service, "Florida's 2000 Rice Variety Census," "An Overview of the Florida Rice Industry", web site, <http://edis.ifas.ufl.edu>. For 2001, data on Florida rice harvests are from the University of Florida Everglades Research and Education Center. For states with ratoon crop, the percentages of rice harvested in this crop were taken from the U.S. EPA *U.S. Inventory of Greenhouse Gas Emissions* (various years).

## Burning of Crop Residues

### Emissions Sources

Between 40 and 50 percent of dry matter in crop residue is carbon.<sup>40</sup> When crop residues are burned for fodder, land supplementation, or fuel, incomplete combustion produces methane emissions.

### Estimation Methods

This report assumes that 3 percent of all crop residues are burned, with the exception of rice, which is combusted at various levels over time. The share of rice crop residues in California estimated to be combusted declines from 75

<sup>36</sup> Personal communication (May 1993).

<sup>37</sup> R. Sass, F. Fisher, S.Lewis, M. Jund, and F. Turner, "Methane Emissions From Rice Fields: Effect of Soil Properties," *Global Biogeochemical Cycles*, Vol. 8 (1994), p. 135.

<sup>38</sup> R.J. Cicerone, J.D. Shetter, and C.C. Delwiche, "Seasonal Variation of Methane Flux From a California Rice Paddy," *Journal of Geophysical Research*, Vol. 88 (1983), pp. 7203-7209.

<sup>39</sup> C.W. Lindau and P.K. Bolich, "Methane Emissions From Louisiana First and Ratoon Rice Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48.

<sup>40</sup> A. Strehler and W. Stutzle, "Biomass Residues," in D.O Hall and R.P. Overend (eds.), *Biomass: Regenerable Energy* (Chichester, UK: John Wiley and Sons, 1987), p. 85.

percent in 1990 to 23 percent in 2001. The share of rice combusted throughout the remainder of the U.S. declines from 16 percent in 1990 to 9 percent in 2001.<sup>41</sup> To derive methane emissions, the dry weight and carbon content of each crop were determined and then multiplied by estimated combustion efficiencies (Table A10).

**Table A10. Factors Used in Estimating Methane and Nitrous Oxide Emissions from Crop Residue Burning**

Crop Type	Residue/Crop Ratio	Dry Matter Content (Percent)	Carbon Content (Percent)	Nitrogen Content (Percent)
Barley	1.2	0.93	0.4485	0.0077
Beans	2.1	0.8535	0.45	0.023
Corn	1	0.91	0.4478	0.0058
Oats	1.3	0.901	0.42	0.0084
Peas	1.5	0.902	0.45	0.023
Peanut	1	0.86	0.45	0.0106
Potatoes	0.4	0.867	0.4226	0.011
Rice	1.4	0.91	0.3806	0.0072
Rye	1.6	0.9	0.4853	0.007
Sorghum	1.4	0.88	0.34	0.0085
Soybean	2.1	0.867	0.45	0.023
Sugarbeet	0.2	0.9	0.4072	0.0228
Sugarcane	0.8	0.62	0.4235	0.004
Wheat	1.3	0.93	0.4428	0.0062

Sources: A. Strehler and W. Stutzle, "Biomass Residues," in D. Hall and R. Overend (eds.), *Biomass: Regenerable Energy* (Chichester, UK: John Wiley and Sons, 1987), C. Li, S. Frolking and R. Harriss, "Modeling Carbon Biogeochemistry in Agricultural Soils," *Global Biogeochemical Cycles*, Vol. 8 (September 1994), E. Darley, "Emission Factors from Burning Agricultural Wastes Collected in California," Final Report, CAL/ARB Project 4-011 (Riverside, CA: University of California, 1977), U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*, EPA 236-R-01-001 (Washington, DC, April 2001), and G. Barnard, "Use of Agricultural Residues as Fuel," in J. Pasztor and L. Kristoferson (eds.), *Bioenergy and the Environment* (Boulder, CO: Westview Press, 1990)

## Data Sources

Crop harvest sizes were obtained from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (Annual Reports).

## Industrial Processes

### Chemical Production

#### Emissions Sources

A wide variety of organic compounds (those containing carbon) are used as feedstocks in chemical production. High temperatures are often used to "crack" the molecular bonds of the compounds, with different temperatures producing specific chemicals. The process of cracking produces a number of chemical byproducts, including methane.

#### Estimation Methods

The IPCC has published emissions factors for methane emitted during the manufacture of ethylene, ethylene dichloride, styrene, methanol, and carbon black (Table A11). Production figures for the chemicals are multiplied by those emissions factors.

#### Data Source

Chemical production figures for 1990-2000 were obtained from the Chemical Manufacturers Association, *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years); and for 2001 were obtained from the American Chemistry Council, *Guide to the Business of Chemistry* (Table 3.12).

<sup>41</sup>U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 -1998*, EPA-236-R-00-001 (Washington, DC, April 2000) p.5-23.

**Table A11. Methane Emissions Factors for Industrial Processes  
(Grams of Methane Emitted per Kilogram of Product Produced)**

Industrial Product	Methane Emissions Factor
Coke	0.5
Sinter	0.5
Pig Iron	0.9
Carbon Black	11.0
Ethylene	1.0
Dichloroethylene	0.4
Styrene	4.0
Methanol	2.0

Source: Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.6, web site [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm).

## **Iron and Steel Production**

### **Emissions Sources**

Coke, sinter, and pig iron are the principal material inputs for the production of iron and steel. Coke is produced by heating coal in the absence of oxygen. One of the gaseous byproducts of this process is methane. During the next step in the production process, coke, iron ore, and flux materials are combined to form sinter. The coke is burned to create heat, causing the sinter to agglomerate. During agglomeration, methane is released. Coke and iron are then added to flux materials in a blast furnace and reduced to iron, slag, and exhaust gases. Methane is one of the exhaust gases.

### **Estimation Methods**

The IPCC has published emissions factors for methane emitted during the production of coke, sinter, and pig iron.<sup>42</sup> Production figures for iron and steel inputs are multiplied by those emissions factors.

### **Data Source**

Coke, sinter, and pig iron production data are published annually by the American Iron and Steel Institute in its *Annual Statistical Report* (Washington, DC, various years).

## **Nitrous Oxide**

Most anthropogenic nitrous oxide emissions in the United States can be attributed to agricultural and energy sources. In particular, 51 percent of estimated emissions of nitrous oxide were attributable to nitrogen fertilization of agricultural soils. Motor vehicle fuel combustion accounts for another 19 percent of 2001 emissions. It should be noted that the range of uncertainty associated with emissions from mobile combustion and fertilizer use is large. Emissions estimates in this report include: mobile source combustion from passenger cars, buses, motorcycles, trucks, and other mobile sources; stationary source combustion from the commercial, residential, industrial, and electrical utility sectors; fertilizer application; burning of crop residues; livestock manure management; human sewage; waste combustion; and industrial production of adipic acid and nitric acid.

## **Energy Use**

### **Mobile Combustion**

### **Emissions Sources**

Nitrous oxide emissions are produced as a byproduct of fuel combustion. During combustion, nitrous oxide (N<sub>2</sub>O) is produced as a result of chemical interactions between nitrogen oxides (NO, NO<sub>2</sub> and NO<sub>3</sub>) and other combustion products. Since nitrous oxide decomposes at high temperatures, most stationary combustion systems (such as

<sup>42</sup>Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.23, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

electric power generation) emit little nitrous oxide. However, under some conditions, the catalytic converters fitted as pollution control devices on most U.S. vehicles will convert nitrogen oxides into nitrous oxide. The relevant conditions appear to be when the catalytic converter is just warming up, but before it reaches normal operating temperature, if the catalytic converter is not working properly, or if the catalyst is affected by excessive levels of sulfur in the gasoline.

## Estimation Methods

In general, EIA estimates nitrous oxide emissions from highway vehicles by multiplying emissions factors (grams of nitrous oxide per mile driven) by national-level vehicle miles traveled. Research indicates that emissions rates differ among motor vehicles by vehicle type, and by type of catalytic converter (associated with the vintage of the motor vehicle) for light duty vehicles. Consequently, EIA partitions national-level vehicle miles traveled by vehicle type (i.e. by passenger cars, light-duty trucks, buses, motorcycles, and heavy-duty trucks), as well as by motor vehicle vintage (model year) for cars and light duty trucks.

For non-highway sources, an emissions factor in grams of nitrous oxide per unit of fuel consumed is applied to fuel consumption data. Since off-road vehicles rarely have catalytic converters (and vintage data is scarce) no attempt is made to track vehicle vintages for the non-highway sources.

## Data Sources

Emissions factors for motor vehicle nitrous oxide have been the subject of considerable discussion and research. The IPCC's *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (Paris, France, 1997) included revised nitrous oxide emissions factors for motor vehicles that were four times higher those used in the previous reference manual. The EPA's Office of Mobile Sources, stimulated by the IPCC report, undertook an automotive testing program in the summer of 1998. The Office of Mobile Sources results were published in U.S. Environmental Protection Agency, *Emissions of Nitrous Oxide from Highway Mobile Sources*, EPA-420-R-98-009 (Washington, DC, August 1998), and have been used in this report. These emissions factors are considerably lower than the emissions factors in the IPCC report but somewhat higher than emissions factors used in EIA's *Emissions of Greenhouse Gases in the United States* reports for 1996 and before, and higher than the emissions factors suggested by the IPCC for use with European vehicles.

EIA collected data on miles traveled in personal transportation vehicles (cars and light-duty trucks) as part of its triennial Residential Transportation Energy Consumption Survey (RTECS): Energy Information Administration, *Household Vehicles Energy Consumption 1994*, DOE/EIA-0464(94) (Washington, DC, July 1996, and previous years). This survey contains data for the years 1983, 1985, 1988, 1991, and 1994. Vehicle miles traveled for other years are estimated using weighted averages from survey data in conjunction with statistics on the U.S. fleet of cars and trucks by model year, provided by the American Automobile Manufacturers Association, *AAMA Vehicle Facts and Figures* (Detroit, MI, various years) and by Ward's Communications Inc., *Ward's Automotive Yearbook* (Southfield, MI, 2000) and Ward's Automotive Report (Southfield, MI, various years). Vehicle miles traveled for non-household vehicles, motorcycles, buses, and heavy-duty trucks were obtained from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics* (Washington, DC, various years), web site [www.fhwa.dot.gov/ohim/ohimstat.htm](http://www.fhwa.dot.gov/ohim/ohimstat.htm).

Fuel consumption for ships, locomotives, farm and construction equipment is based on data from the Energy Information Administration, *Fuel Oil and Kerosene Sales*, DOE/EIA-0535 (Washington, DC, various years). Jet and piston-powered aircraft fuel consumption data are contained in the Energy Information Administration's *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years). Data on fuel consumption by recreational boats are taken from Oak Ridge National Laboratory: Center for Transportation Analysis, *Transportation Energy Data Book* (Oak Ridge, TN, various years), web site [www.cta.ornl.gov/publications/tebd.html](http://www.cta.ornl.gov/publications/tebd.html).

## Stationary Combustion

### Emissions Sources

As with mobile sources, nitrous oxide emissions are produced as a byproduct of fuel combustion. The three fuels of primary importance burned by stationary sources are coal, fuel oil, and natural gas. Combustion systems powered by coal produce the most nitrous oxide, approximately 62 percent of annual emissions. Since 1990, electric utilities

as a sector, have consistently accounted for more than one-half of total nitrous oxide emissions from stationary combustion. Other important sources are commercial facilities, industrial facilities, and residences.

## Estimation Methods

Nitrous oxide emissions from stationary combustion are estimated by multiplying fuel consumption figures for each fuel type and stationary source by emissions factors for each type of fuel. Nitrous oxide emissions from stationary combustion include emissions from the consumption of wood in the residential, commercial, industrial, and electric utility sectors. Emissions are estimated by applying emissions factors for coal, oil, natural gas, and wood, to EIA's consumption data for each fuel in the commercial, residential, industrial, and electric utility sectors.

## Data Sources

Emissions coefficients for stationary fuel were obtained from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm) Fuel consumption data were drawn from the Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(99) (Washington, DC, September 1999) for 1980-1997; and *Monthly Energy Review*, DOE/EIA-0035(02/07)(Washington, DC, July 2002) for 1998-2001. Residential woodfuel consumption data were derived from EIA's *Annual Energy Review 2001*, DOE/EIA-0384(01) (Washington, DC, October J 2002).

## Agriculture

### Nitrogen Fertilization of Agricultural Soils

#### Emissions Sources

Nitrous oxide is a waste product of certain classes of bacteria normally present in soil. When nitrogen (in the form of natural or artificial fertilizers) is added to natural or agricultural soils, the action of these bacteria is stimulated. However, the extent to which adding nitrogen stimulates nitrous oxide emissions is highly uncertain. The bacteria that emit nitrous oxide have natural competitors, which may be more or less successful in particular settings. In addition, conditions may be more or less propitious for bacterial action: the soil may be too moist or too dry, too compacted, too acid or alkaline, too warm or too cold. The form in which nitrogen is applied may be subject to faster or slower release to the waiting bacteria. Further, excess nitrogen will escape from the location of application through runoff and will be subject to decomposition in diverse natural environments. Thus, measured emissions from even large numbers of specific sites are exceptionally difficult to generalize into an estimate of national emissions.

#### Estimation Methods

Following the IPCC *Reference Manual*, this report estimates nitrogen applications to soils from the following sources:

- Use of nitrogen fertilizers (computed directly from fertilizer data)
- Nitrogen in animal manure applied to agricultural soils (estimated from animal populations)
- Nitrogen in crop residues applied to agricultural soils (estimated from crop production statistics)
- Biological fixation of nitrogen in agricultural soils (estimated from crop production statistics)

For estimating nitrous oxide emissions from the first three sources, following the IPCC guidelines EIA assumes that 1.25 percent of the nitrogen applied is emitted to the atmosphere as nitrous oxide and 30 percent escapes into the environment. Some 2.5 percent of the nitrogen that escapes is ultimately converted into nitrous oxide in the form of emissions from streams and bodies of water. A further 10 percent of the nitrogen applied to soils is assumed to be released as gas in the form of nitrogen oxides and ammonia, and 1 percent of that nitrogen is assumed to be ultimately converted into nitrous oxide.<sup>43</sup>

<sup>43</sup>Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.53, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

To estimate nitrous oxide emissions from the biological fixation of nitrogen in crops, annual production statistics for nitrogen-fixing crops (alfalfa, beans, lentils, peanuts, and soybeans) were obtained from the U.S. Department of Agriculture's *Crop Production* annual reports. Crop product values for these crops were then converted to total crop (crop product plus crop residue) dry biomass in mass units of dry matter, by applying residue-to-crop ratios and dry matter fractions. The total crop values in dry biomass units were then used to calculate the crop nitrogen content that is released in the form of nitrous oxide. Finally, nitrous oxide emissions factors were then applied to calculate nitrous oxide emissions from the biological fixation of nitrogen in crops.<sup>44</sup>

## Data Sources

Estimates of total U.S. fertilizer consumption were obtained from reports by the Tennessee Valley Authority Fertilizer Research Center for various years through 1994: J.T. Berry et al., *Commercial Fertilizers* (Muscle Shoals, AL: Tennessee Valley Authority, Fertilizer Research Center, Reports for 1986-1991 and 1993-1994) and The Fertilizer Institute for 1995 through 2001. Estimates of nitrous oxide from the biological fixation of nitrogen in crops, were based on crop production statistics obtained from the U.S. Department of Agriculture's *Crop Production* annual reports. For nitrogen in animal manure, see the section on "Solid Waste of Domesticated Animals." For nitrogen in crop residues, see the section on "Crop Residue Burning" under methane or nitrous oxide.

## Crop Residue Burning

### Emissions Sources

Crop residues are commonly disposed of by incorporation into the soil, spreading over the soil surface to prevent erosion, as animal bedding, or through burning. Burning crop residues releases nitrous oxide into the atmosphere. The burning of crop residues occurs throughout the United States, although it is illegal in certain areas. There are no accurate estimates of the amount of crop residue burned in the United States.

### Estimation Methods

This report assumes that 3 percent of all crop residues are burned, with the exception of rice, which is combusted at various levels over time. The share of rice crop residues in California estimated to be combusted declines from 75 percent in 1990 to 23 percent in 2001. The share of rice combusted throughout the remainder of the U.S. declines from 16 percent in 1990 to 9 percent in 2001.<sup>45</sup> The amount of crop residue burned is discounted by an assumed combustion efficiency, multiplied by its dry matter content and nitrogen content, and then converted to nitrous oxide using a standard ratio of nitrous oxide to nitrogen content.

## Data Sources

Crop harvest sizes were obtained from U.S. Department of Agriculture, National Agricultural Statistics Service, *Crop Production* (Annual Reports).

## Solid Waste of Domesticated Animals

### Emissions Sources

Nitrous oxide is emitted as part of the denitrification of animal manure. The volume of nitrous oxide emissions is a function of the amount of manure produced, the nitrogen content of the manure, and the method for handling the animal waste. Waste managed by a solid storage or pasture range method may emit 20 times the nitrous oxide per unit of nitrogen content that is emitted from anaerobic lagoon or other liquid systems.

<sup>44</sup>Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.85-4.94, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

<sup>45</sup>U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 -1999*, EPA-236-R-01-001 (Washington, DC, April 2001) p.5-23.

## Estimation Methods

Nitrous oxide emissions from the solid waste of domesticated animals are estimated by linking emissions to the volume of solid waste produced by a given animal, the volatile solids in that waste, the nitrogen content of the waste, and the manner in which the waste is managed. Animal populations are divided into distinct, relatively homogeneous groups. The U.S. cattle population is separated into dairy and beef cattle. Emissions of nitrous oxide from poultry, sheep, pigs, goats, and horses are also estimated. For each group of animals, a per-head volatile solids production and an associated nitrogen content within the volatile solids are assigned. These values are multiplied by animal populations to derive total nitrogen excreted. For each animal group, excretions are distributed among the manure management systems used. The ratio of nitrous oxide production to nitrogen content for each management technique is applied to provide an emissions estimate for each animal group, broken down by manure management system. The emissions are then summed to calculate an overall emissions estimate.

## Data Sources

Population and slaughter weight data for cattle and population data for sheep, poultry, and swine were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, Livestock, Dairy, and Poultry Branch, web site [www.usda.gov/nass/](http://www.usda.gov/nass/). Average broiler chicken populations for each year were estimated by multiplying the estimated number of broiler chickens slaughtered annually by 0.1425, based on their 7-week life cycle as recommended by the USDA's Economic Research Service.<sup>46</sup> Population data for goats and horses were extrapolated from U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, *Census of Agriculture, United States Summary and State Data*, (Washington, DC, 1982, 1987, 1992, and 1997). Volatile solids content, nitrogen content of wastes by species, manure management systems, and nitrogen to nitrous oxide conversion rates were taken from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.88-4.93, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

## Waste Management

### Waste Combustion

#### Emissions Sources

Like other stationary and mobile combustion processes, the burning of garbage and nonhazardous solid waste produces nitrous oxide emissions. There are 160 municipal waste combustion plants in the United States, with 114 plants generating energy. Emission levels are dependent on the composition of waste burned and combustion temperatures.<sup>47</sup> Very high temperatures reduce nitrous oxide emissions.

#### Estimation Methods

The total annual volume of municipal solid waste generated in the United States was multiplied by the share of waste incinerated. Total waste incinerated was then multiplied by a factor of 30 grams of nitrous oxide per metric ton of waste incinerated to calculate total nitrous oxide emissions from this source.

#### Data Sources

Waste generation data and share incinerated were drawn from *Biocycle* magazine, "The State of Garbage in America" (various years). Waste generation data for 2001 were based on 2000 data scaled to GDP growth of 0.3 percent with the share of waste combusted held steady. The emissions factor was taken from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-0010 (Washington, DC, April 2000), web site [www.epa.gov/publications/emissions/index.html](http://www.epa.gov/publications/emissions/index.html).

---

<sup>46</sup> Personal communication, May 1993.

<sup>47</sup> U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *U.S. Greenhouse Gas Emissions and Sinks 1990-1999*, EPA-236-R-01-001 (Washington, DC, April 2001), p. 7-5.

## Human Sewage in Wastewater

### Emissions Sources

When human sewage is treated in wastewater systems, the nitrogen-based organic matter in the waste generates nitrous oxide through nitrification and denitrification. Under aerobic conditions, ammonia is converted to nitrate. As oxygen dissipates and an anaerobic environment governs, nitrate is converted to nitrous oxide.

### Estimation Methods

Nitrous oxide emissions are estimated as a function of national population, per capita protein consumption, and the fraction of nitrogen in protein. The fraction of nitrogen in protein is assumed to be 16 percent, and 1 kilogram of nitrous oxide is assumed to be emitted per 100 kilograms of nitrogen in wastewater.

### Data Sources

U.S. population data are from the Bureau of Census. Per-capita protein intake is from the Food and Agriculture Organization, *FAOSTAT Statistical Database*. Nitrogen content and nitrous oxide conversion factor are from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-0010 (Washington, DC, April 2000), web site [www.epa.gov/publications/emissions/index.html](http://www.epa.gov/publications/emissions/index.html).

## Industrial Processes

### Adipic Acid Production

#### Emissions Sources

Manufacture of adipic acid is one of the two principal sources of nitrous oxide from industrial processes. Adipic acid is used primarily in the manufacture of nylon fibers and plastics in carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizers for polyvinyl chloride and polyurethane resins, lubricants, insecticides, and dyes. In the United States, three companies, which operate a total of four plants, manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid. Creation of nitrous oxide is an intrinsic byproduct of this chemical reaction.

#### Estimation Methods

Emissions of nitrous oxide from production of adipic acid are calculated by multiplying adipic acid production figures by nitrous oxide emissions coefficients. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.<sup>48</sup> Currently, three plants control emissions by thermally decomposing the nitrous oxide, and 98 percent of the potential emissions from the production of adipic acid, subject to abatement controls, are eliminated by this technique.<sup>49</sup> By 2001, 97.4 percent of total estimated U.S. production of adipic acid was subject to abatement control measures.

#### Data Sources

Adipic acid production figures were obtained from *Chemical and Engineering News*, annual report on the "Top 50 Industrial Chemicals" (April issue, various years). For 1996 through 2001, estimated U.S. total adipic acid production was obtained from the American Chemical Council (formerly the Chemical Manufacturers Association). The adipic acid emissions coefficient was taken from M. Thiemens and W. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 22, 1991), p. 932.

<sup>48</sup> M.H. Thiemens and W.C. Trogler, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 22, 1991), p. 932.

<sup>49</sup> Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

## Nitric Acid Production

### Emissions Sources

Nitric acid is a primary ingredient in fertilizers. The process for manufacturing this acid involves oxidizing ammonia (NH<sub>3</sub>) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation.

### Estimation Methods

The IPCC guidelines indicate emissions factors of 2 to 9 grams of nitrous oxide per kilogram of nitric acid manufactured.<sup>50</sup> The emissions estimates presented in this report are calculated by multiplying the annual quantity of nitric acid produced by the midpoint (5.5 grams nitrous oxide per kilogram of product) of the emissions range. There is, however, a considerable degree of uncertainty associated with this estimate.

### Data Sources

Nitric acid production figures were based on data published by the U.S. Department of Commerce, Bureau of the Census, in its annual and quarterly *Current Industrial Reports* on fertilizer materials. The nitric acid emissions coefficient was taken from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

## HFCs, PFCs, and Sulfur Hexafluoride

### Emissions Sources

HFCs, PFCs, and sulfur hexafluoride have hundreds of uses, but the bulk of emissions come from a few broad categories of use:

- As refrigerants or working fluids in air conditioning and refrigeration equipment
- As solvents in various industrial processes
- As blowing agents for making insulating foams
- As fugitive emissions from various industrial processes, including the manufacture of halocarbons.

The emissions profile differs for each emissions source. Refrigerants are used in a closed cycle inside cooling equipment, and they tend to leak out when the equipment is scrapped or serviced. Some portion of the refrigerants is captured and recycled or destroyed, rather than emitted, when equipment is serviced. HFCs solvent applications are often recycled, but net consumption (after recycling) is probably a good indicator of emissions. HFCs used as blowing agents can be characterized by the type of foam manufactured: HFCs used to make "open cell" foam are released to the atmosphere immediately, while HFCs used to make "closed cell" foam are trapped within the foam for the life of the foam, which can vary (depending on the use) from a few weeks to many years.

### Estimation Methods

For the years 1990 through 2000, EIA has relied primarily on estimates of HFC, PFC, and sulfur hexafluoride emissions presented in the U.S. Environmental Protection Agency's *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, EPA-236-R-01-001 (Washington, DC, April 2002). The preliminary 2001 emissions estimates for HFCs, PFCs, and sulfur hexafluoride are advance estimates developed by the EPA and provided to the EIA, courtesy of the EPA's Climate Protection Division.

<sup>50</sup>Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.18, [www.ipcc.ch/pub/guide.htm](http://www.ipcc.ch/pub/guide.htm)

## ***Data Sources***

EPA estimates of emissions of HFCs, PFCs, and sulfur hexafluoride for 1990-2000 are from the U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000*, EPA-236-R-01-001 (Washington, DC, April 2002), web site [www.epa.gov/globalwarming/publications/](http://www.epa.gov/globalwarming/publications/). Estimate for emissions for 2001 are directly from contacts at EPA's Climate Protection Partnerships Division and Global Programs Division.

## Appendix B

# Carbon Coefficients Used in This Report

This appendix presents the background and methodology for estimating the carbon coefficients of fossil fuels combusted in the United States. The carbon coefficient of a particular fossil fuel represents the maximum potential emissions to the atmosphere if all carbon in the fuel is oxidized during combustion. Historically, the carbon coefficients used in earlier editions of this report were developed using methods first outlined in the EIA report, *Emissions of Greenhouse Gases in the United States: 1987 – 1992*. The carbon coefficients in that report were developed to replace, in part, the more general coefficients originally developed by Marland and Pippin and subsequently adopted by the Intergovernmental Panel on Climate Change (IPCC).<sup>1</sup> The IPCC coefficients were intended to be suitable for all countries, and to support the division of petroleum consumption into the products defined by the International Energy Agency (IEA). Because U.S. fuels sometimes differ in composition from those used abroad and EIA divides petroleum product consumption into more than 20 different categories, rather than the six described by the IEA, the development of U.S. specific carbon coefficients improved the precision of U.S. carbon emission estimates.

This appendix provides a detailed list of methods and data sources for estimating the carbon coefficients of coal (by consuming sector), natural gas (broken into pipeline-quality and flared gas), and petroleum products. Though the methods for estimating carbon contents for coal, natural gas, and petroleum products differ in their details, they each follow the same basic approach. First, because carbon coefficients are presented in terms of mass/unit-energy (i.e., million metric tons carbon per quadrillion Btu or MMTC/Qbtu), those fuels that are typically described in volumetric units (petroleum products and natural gas) are converted to units of mass using an estimated density. Next, carbon contents are derived from fuel sample data, using descriptive statistics to estimate the carbon share of the fuel by weight. Finally, the heat content of the fuel is then estimated based on the sample data, or where sample data is unavailable or unrepresentative, by default values that reflect the characteristics of the fuel as defined by market requirements. A summary of carbon coefficients used in this report appears in Table B1.

**Table B1. Carbon Coefficients Used in this Report**  
(Million Metric Tons Carbon per Quadrillion Btu)

Fuel Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
<b>Coal</b>												
Coal (Residential)	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04 <sup>P</sup>
Coal (Commercial)	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04 <sup>P</sup>
Coal (Industrial Coking)	25.55	25.56	25.55	25.53	25.57	25.57	25.56	25.60	25.62	25.60	25.63	25.63 <sup>P</sup>
Coal (Industrial Other)	25.82	25.89	25.87	25.77	25.77	25.80	25.75	25.76	25.79	25.80	25.74	25.74 <sup>P</sup>
Coal (Electric Utility)	25.95	25.97	25.99	25.87	25.88	25.92	25.92	25.91	25.93	25.97	25.98	25.98 <sup>P</sup>
<b>Natural Gas</b>												
Natural Gas (Pipeline)	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Natural Gas (Flared)	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92
<b>Petroleum</b>												
Asphalt and Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Aviation Gasoline	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Crude Oil	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24	20.24	20.19	20.23	20.29
Distillate Fuel	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33	19.33	19.33	19.33	19.33
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
LPG	16.99	16.98	16.99	16.97	17.01	17.00	16.99	16.99	16.99	16.99	16.99	16.99
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Motor Gasoline	19.41	19.41	19.42	19.43	19.45	19.38	19.36	19.35	19.33	19.33	19.34	19.34
Petrochemical Feed.	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Residual Fuel	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Waxes	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81

Note: All coefficients based on Heating (Gross Calorific) Value and assume 100% combustion

<sup>P</sup>=Preliminary

Source: Estimates described in this Appendix

<sup>1</sup>G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol.14 (1990), pp. 319-336, and Intergovernmental Panel on Climate Change, *Estimation of Greenhouse Gases and Sinks* (1991), p. 2.18.

This appendix also supplies a detailed discussion of each fuel and its derived carbon coefficient below. The discussion begins with the carbon contents of coal because about one third of all U.S. carbon emissions from fossil fuel combustion are associated with coal consumption. The estimated carbon coefficients of coal have been revised this year to reflect the composition of a new set of coal samples from the U.S. Geological Survey, Coal Quality Database Version 2.0. This appendix then discusses the methods and sources for estimating the carbon content of natural gas. About one fifth of U.S. greenhouse gas emissions from fossil fuel combustion are attributable to natural gas consumption. Finally, this appendix examines carbon contents of petroleum products. There are more than 20 different petroleum products accounted for in U.S. energy consumption statistics.

## Coal

Approximately one-third of all U.S. carbon dioxide emissions from fossil fuel combustion are associated with coal consumption. Because the EIA collects coal consumption data by consuming sector, EIA adopted carbon coefficients by consuming sector. Because the carbon content of coal varies by the state in which it was mined and by coal rank, and the sources of coal for each consuming sector vary by year, the weighted average carbon coefficient for coal combusted in each consuming sector also varies over time. A time-series of carbon coefficients by coal rank and consuming sector appears in Table A1-2. Since the IPCC guidelines provide carbon coefficients by rank, EIA also adopted carbon coefficients by rank for comparison with other nations carbon coefficients.

**Table B2. Carbon Coefficients for Coal by Consuming Sector and Coal Rank, 1990 - 2001**  
(Million Metric Tons Per Quadrillion Btu)

Consuming Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
<b>Electric Power</b>	25.95	25.97	25.99	25.87	25.88	25.92	25.92	25.91	25.93	25.97	25.98	25.98 <sup>P</sup>
<b>Industrial Coking</b>	25.55	25.56	25.55	25.53	25.57	25.57	25.56	25.60	25.62	25.60	25.63	25.63 <sup>P</sup>
<b>Other Industrial</b>	25.82	25.89	25.87	25.77	25.77	25.80	25.75	25.76	25.79	25.80	25.74	25.74 <sup>P</sup>
	26.23	26.30	26.42	26.19	26.12	26.16	26.06	25.93	26.09	26.02	26.04	26.04 <sup>P</sup>
<b>Residential/Commercial</b>												
<b>Coal Rank</b>												
<b>Anthracite</b>	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26 <sup>P</sup>
<b>Bituminous</b>	25.43	25.45	25.44	25.45	25.46	25.47	25.47	25.48	25.47	25.48	25.49	25.49 <sup>P</sup>
<b>Sub-bituminous</b>	26.50	26.49	26.49	26.48	26.49	26.49	26.49	26.49	26.49	26.49	26.48	26.48 <sup>P</sup>
<b>Lignite</b>	26.19	26.21	26.22	26.21	26.24	26.22	26.17	26.20	26.23	26.26	26.30	26.30 <sup>P</sup>

<sup>P</sup>=Preliminary

Sources: U.S. Geological Survey, US Coal Quality Database Version 2.0 (1998) and analysis prepared by Science Applications International Corporation (SAIC) for the U.S. Environmental Protection Agency, Office of Air and Radiation, Market Policies Branch, October 2002.

## Estimation Methods

Carbon coefficients are estimated on the basis of 6,588 coal samples collected by the US Geological Survey between 1973 and 1989. These coal samples are classified according to rank and state of origin. For each rank in each state, the average heat content and carbon content of the coal samples are calculated. Dividing the carbon content (reported in pounds carbon dioxide) by the heat content (reported in million Btu) yields an average carbon coefficient. This coefficient is then converted into units of million metric tons per quadrillion Btu.

U.S. energy statistics provide data on the origin of coal used in four areas: 1) the electric power industry 2) industrial coking, 3) all other industrial uses, and 4) the residential and commercial end-use sectors. Because U.S. energy statistics do not provide the distribution of coal rank consumed by each consuming sector, it is assumed that each sector consumes a representative mixture of coal ranks from a particular state that matches the mixture of all coal produced in that state during the year. Sectoral carbon coefficients are then calculated by multiplying the share of coal purchased from each state by rank by the carbon coefficient estimated above. The resulting partial carbon coefficients are then totaled across all states and ranks to generate a national sectoral carbon coefficient.

Although not used to calculate emissions, national-level carbon contents by rank are more easily compared to carbon contents of other countries than are sectoral carbon contents. State-level carbon coefficients by rank developed above are weighted by overall coal production by state and rank (consumption by rank is unavailable in U.S. energy statistics) to support this comparison. Each state-level carbon coefficient by rank is multiplied by the share of national production of that rank that each state represents. The resulting partial carbon coefficients are then summed across all states to generate an overall carbon coefficient for each rank.

The estimates of carbon coefficients for coal were updated and revised in 2002. The methodology employed for these estimates was unchanged from previous years, however, the underlying coal data sample set was updated. Previously, a set of 5,426 coal samples from the EIA coal analysis file were used to develop carbon content estimates. The results from that sample set appear below in Table B3. The EIA Coal Analysis File was originally developed by the U.S. Bureau of Mines and contained over 60,000 coal samples obtained at numerous coal seams throughout the United States. Many of the samples were collected as early as the 1940s and 1950s, with sample collection continuing until the 1980s. The updated sample set included 6,588 coal samples collected by the U.S. Geological Survey between 1973 and 1989.

**Table B3. 1990–2000 Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank**  
(Million Metric Tons Per Quadrillion Btu)

Consuming Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
<b>Electric Power</b>	25.68	25.69	25.69	26.71	25.72	25.74	25.74	25.76	25.76	25.76	25.76
<b>Industrial Coking</b>	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56	25.56
<b>Other Industrial</b>	25.58	25.59	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63	25.63
<b>Residential/ Commercial</b>	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00	26.00	26.00
<b>Coal Rank</b>											
<b>Anthracite</b>	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13
<b>Bituminous</b>	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37
<b>Sub-bituminous</b>	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24
<b>Lignite</b>	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62

Sources: Emission factors by consuming sector from B.D. Hong and E.R. Slatick, "Carbon Dioxide Emission Factors for Coal," U.S. Energy Information Administration, *Quarterly Coal Report, January-March 1994*. (Washington, DC, 1994) and emission factors by rank from Science Applications International Corporation, "Analysis of the Relationship Between Heat and Carbon Content of U.S. Fuels: Final Task Report," prepared for the U.S. Energy Information Administration, Office of Coal, Nuclear, Electric and Alternative Fuels (Washington, DC 1992).

## Data Sources

Ultimate analyses of 6,588 coal samples were obtained from the U.S. Geological Survey, CoalQual Database Version 2.0 (1998). Data contained in the CoalQual Database are largely derived from samples taken between 1973 and 1989, and were largely reported on in State Geological Surveys.

Coal distribution by state and consumption by sector from, Energy Information Administration, *Coal Industry Annual*, (Washington, DC, various years) Table 10 and Table 63. Web site at [www.eia.doe.gov/cneaf/coal/cia/cia\\_sum.html](http://www.eia.doe.gov/cneaf/coal/cia/cia_sum.html).

Coal production by state and rank from, Energy Information Administration, *Coal Industry Annual*, (Washington, DC, various years) Table 9. Web site at [www.eia.doe.gov/cneaf/coal/cia/cia\\_sum.html](http://www.eia.doe.gov/cneaf/coal/cia/cia_sum.html).

## Natural Gas

Natural gas is predominantly composed of methane, which is 75 percent carbon by weight and contains 14.2 million metric tons carbon per quadrillion Btu (Higher Heating Value), but it may also contain many other compounds that can lower or raise its overall carbon content. These other compounds may be divided into two classes: 1) natural gas liquids (NGLs) and 2) non-hydrocarbon gases. The most common NGLs are ethane (C<sub>2</sub>H<sub>6</sub>), propane (C<sub>3</sub>H<sub>8</sub>), butane (C<sub>4</sub>H<sub>10</sub>), and, to a lesser extent, pentane (C<sub>5</sub>H<sub>12</sub>) and hexane (C<sub>6</sub>H<sub>14</sub>). Because the NGLs have more carbon atoms than methane (which has only one) their presence increases the overall carbon content of natural gas. NGLs have a commercial value greater than that of methane, and therefore are usually separated from raw natural gas at gas processing plants and sold as separate products. Ethane is typically used as a petrochemical feedstock, propane and butane have diverse uses, and natural gasoline<sup>2</sup> contributes to the gasoline/naphtha "octane pool" used primarily to make motor gasoline.

Raw natural gas can also contain varying amounts of non-hydrocarbon gases, such as carbon dioxide, nitrogen, helium and other noble gases, and hydrogen sulfide. The share of non-hydrocarbon gases is usually less than 5 percent of the total, but there are individual natural gas reservoirs where the share can be much larger. The treatment of non-hydrocarbon gases in raw gas varies. Hydrogen sulfide is always removed. Inert gases are removed if their presence is substantial enough to reduce the energy content of the gas below pipeline

<sup>2</sup>A term used in the gas processing industry to refer to a mixture of liquid hydrocarbons (mostly pentanes and heavier hydrocarbons) extracted from natural gas.

specifications. Otherwise, inert gases will usually be left in the natural gas. Because the raw gas that is usually flared contains NGLs and carbon dioxide, it will typically have a higher overall carbon content than gas that has been processed and moved to end-use customers via transmission and distribution pipeline.

## Estimation Methods

In the United States, pipeline-quality natural gas is expected to have an energy content greater than 970 Btu per cubic foot but less than 1,100 Btu per cubic foot. Hydrogen sulfide content must be negligible. Typical pipeline-quality natural gas is about 95 percent methane, 3 percent NGLs, and 2 percent non-hydrocarbon gases, of which perhaps 1 percent is carbon dioxide.

However, there is a range of gas compositions that are consistent with pipeline specifications. The minimum carbon coefficient for natural gas would match that for pure methane, which equals 1,005 Btu per standard cubic foot. Gas compositions with higher or lower Btu content tend to have higher carbon emissions factors, because the "low" Btu gas has a higher content of inert gases (including carbon dioxide offset with more NGLs), while "high" Btu gas tends to have more NGLs.

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

- There may be no market for some batches of natural gas, the amount may be too small or too variable, or the quality might too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of carbon dioxide). All natural gas flared for these reasons is probably "rich" associated gas, with relatively high energy content, high NGL content, and a high carbon content.
- Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

Data on the energy content of flare gas, as reported by states to EIA, indicates an energy content of 1,130 Btu per standard cubic foot. Flare gas may have a higher energy content than reported by EIA since rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot.

A relationship between carbon content and heat content may be used to develop a carbon coefficient for natural gas consumed in the United States. In 1994, EIA examined the composition (and therefore carbon contents) of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 States. To demonstrate that these samples were representative of actual natural gas "as consumed" in the US, their heat content was compared to that of the national average. For the most recent year, the average heat content of natural gas consumed in the U.S. was 1,025 Btu per cubic foot, varying by less than 1 percent (1,025 to 1,031 Btu per cubic foot) over the past 5 years. Meanwhile the average heat content of the 6,743 samples was 1,027 Btu per cubic foot and the median heat content was 1,031 Btu per cubic foot. Thus, the average heat content of the sample set falls well within the typical range of natural gas consumed in the United States, suggesting that these samples continue to be representative of natural gas "as consumed" in the U.S. The average and median composition of these samples appears in Table B4.

**Table B4. Composition of Natural Gas**  
(Percent)

Compound	Average	Median
<b>Methane</b>	93.07	95.00
<b>Ethane</b>	3.21	2.79
<b>Propane</b>	0.59	0.48
<b>Higher Hydrocarbons</b>	0.32	0.30
<b>Non-hydrocarbons</b>	2.81	1.43
<b>Higher Heating Value (Btu per cubic foot)</b>	1,027	1,032

Source: Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*.

Carbon coefficients were then calculated for eight separate sub-samples based on heat content and shown in Table B5.

**Table B5. Carbon Content of Pipeline-Quality Natural Gas by Energy Content**

Sample	Average Carbon Coefficient (Million Metric Tons per Quadrillion Btu)
GRI Full Sample	14.51
Greater than 1,000 Btu	14.47
1,025 to 1,035 Btu	14.45
975 to 1,000 Btu	14.73
1,000 to 1,025 Btu	14.43
1,025 to 1,050 Btu	14.47
1,050 to 1,075 Btu	14.58
1,075 to 1,100 Btu	14.65
Greater than 1,100 Btu	14.92
<b>Weighted National Average</b>	<b>14.47</b>

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573 (Washington, DC, November, 1994,) Appendix A.

Because there is some regional variation in the energy content of natural gas consumed, a weighted national average carbon content was calculated using the average carbon contents for each sub-sample of gas that conformed with each individual state's typical cubic foot of natural gas. The result was a weighted national average of 14.47 million metric tons per quadrillion Btu. This was identical to the average carbon coefficient for all samples with more than 1,000 Btu per cubic foot and the average carbon coefficient for all samples with a heat content between 1,025 and 1,050 Btu per cubic foot. Because those samples with a heat content below 1,000 Btu had an unusually high carbon coefficient attributable to large portions of carbon dioxide (not seen in the median sample), they were excluded from the final sample so as not to bias the carbon coefficient upwards.

Selecting a carbon coefficient for flare gas was much more difficult than for pipeline natural gas because of the uncertainty of its composition. Because EIA estimates the heat content of flare gas at 1,130 Btu per cubic foot, the average carbon coefficient for samples with more than 1,100 Btu per cubic foot, 14.92 million metric tons per quadrillion Btu, was adopted as the coefficient for flare gas. It should be noted that the sample data set did not include any samples with more than 1,130 Btu per cubic foot.

## Data Sources

Natural gas samples were obtained from a Gas Technology Institute (formerly Gas Research Institute) database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States*.

Average heat content of natural gas consumed in the U.S. from the Energy Information Administration, *Monthly Energy Review*, (Washington, DC), Table A4. Web site at [www.eia.doe.gov/mer/txt/mer-a4](http://www.eia.doe.gov/mer/txt/mer-a4).

Average heat content consumed on a state by state basis from the Energy Information Administration, *State Energy Data Report*, (Washington, DC), Table 1 and 2. Web site at [www.eia.doe.gov/emeu/sedr/contents.html#PDF%20Files](http://www.eia.doe.gov/emeu/sedr/contents.html#PDF%20Files).

## Petroleum

There are four critical determinants of the carbon coefficient for a petroleum-based fuel:

1. The density of the fuel (e.g., the weight in kilograms of one barrel of fuel);
2. The fraction by mass of the product that consists of hydrocarbons, and the fraction of non-hydrocarbon impurities;
3. The specific types of 'families' of hydrocarbons that make up the hydrocarbon portion of the fuel; and
4. The heat content of the fuel.

Petroleum products vary between 5.6 degrees API gravity (dense products such as asphalt and road oil) and 247 degrees (ethane).<sup>3</sup> This is a range in density of 60 to 150 kilograms per barrel, or  $\pm 50$  percent. The variation in carbon content, however, is much smaller ( $\pm 5$  to 7 percent): ethane is 80 percent carbon by weight, while petroleum coke is 90 to 92 percent carbon. The tightly bound range of carbon contents can be explained by basic petroleum chemistry.

## Petroleum Chemistry

Crude oil and petroleum products are typically mixtures of several hundred distinct compounds, predominantly hydrocarbons. All hydrocarbons contain hydrogen and carbon in various proportions. When crude oil is distilled into petroleum products, it is sorted into fractions by the boiling temperature of these hundreds of organic compounds. Boiling temperature is strongly correlated with the number of carbon atoms in each molecule. Petroleum products consisting of relatively simple molecules and few carbon atoms have low boiling temperatures and, larger molecules with more carbon atoms have higher boiling temperatures.

Products that boil off at higher temperatures are usually more dense, which implies greater carbon content as well. Petroleum products with higher carbon contents, in general, have lower energy content per unit mass and higher energy content per unit volume than products with a lower carbon content. Empirical research led to the establishment of a set of quantitative relationships between density, energy content per unit weight and volume, and carbon and hydrogen content. Figure B1 compares carbon coefficients calculated on the basis of the derived formula with actual carbon coefficients for a range of crude oils, fuel oils, petroleum products, and pure hydrocarbons. The actual fuel samples were drawn from the sources described below in the discussions of individual petroleum products.

The derived empirical relationship between carbon content per unit heat and density is based on the types of hydrocarbons most frequently encountered. Actual petroleum fuels can vary from this relationship due to non-hydrocarbon impurities and variations in molecular structure among classes of hydrocarbons. In the absence of more exact information, this empirical relationship offers a good indication of carbon content.

## Non-hydrocarbon Impurities

Most fuels contain a certain share of non-hydrocarbon material. This is also primarily true of crude oils and fuel oils. The most common impurity is sulfur, which typically accounts for between 0.5 and 4 percent of the mass of most crude oils, and can form an even higher percentage of heavy fuel oils. Some crude oils and fuel oils also contain appreciable quantities of oxygen and nitrogen, typically in the form of asphaltenes or various acids. The nitrogen and oxygen content of crude oils can range from near zero to a few percent by weight. Lighter petroleum products have much lower levels of impurities, because the refining process tends to concentrate all of the non-hydrocarbons in the residual oil fraction. Light products usually contain less than 0.5 percent non-hydrocarbons by mass. Thus, the carbon content of heavy fuel oils can often be several percent lower than that of lighter fuels, due entirely to the presence of non-hydrocarbons.

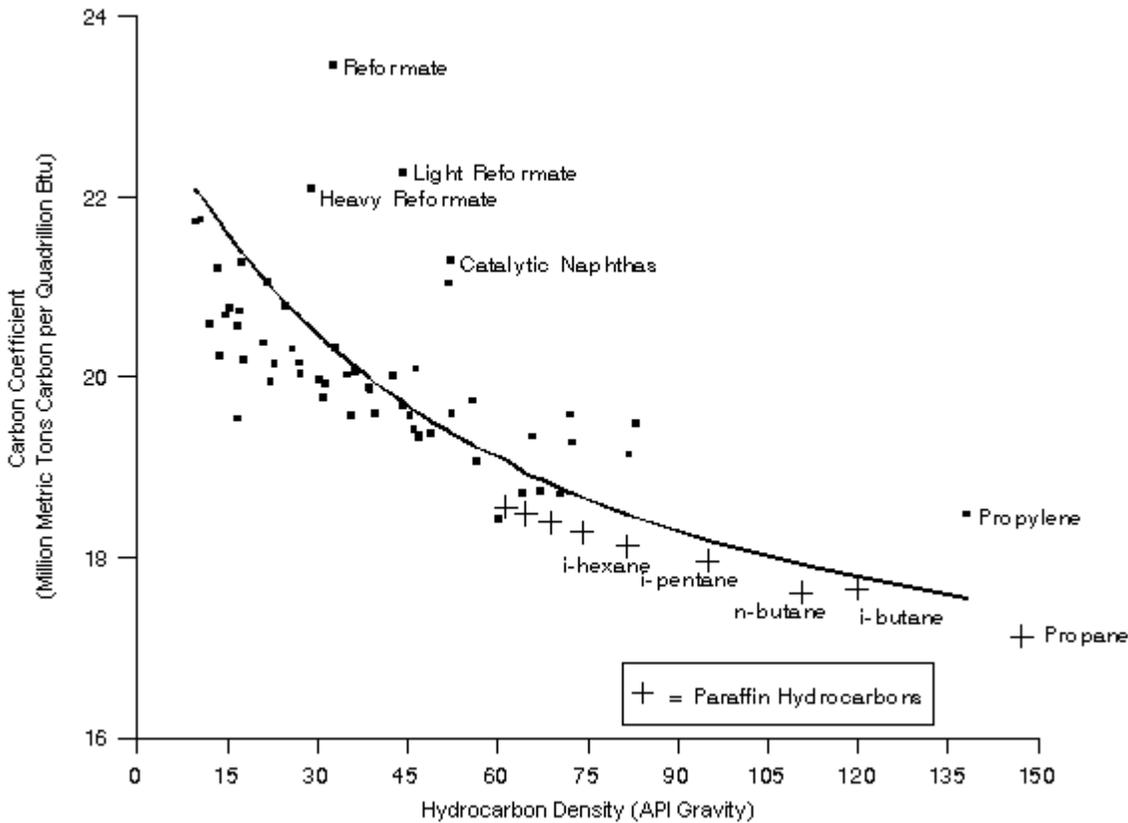
## Variations in Hydrocarbon Classes

Hydrocarbons can be divided into five general categories, each with a distinctive relationship between density and carbon content and physical properties. Refiners tend to control the mix of hydrocarbon types in particular products in order to give petroleum products distinct properties. The main classes of hydrocarbons are described below.

**Paraffins.** Paraffins are the most common constituent of crude oil, usually comprising 60 percent by mass. Paraffins are straight-chain hydrocarbons with the general formula  $C_nH_{2n+2}$ . Paraffins include ethane ( $C_2H_6$ ), propane ( $C_3H_8$ ), butane ( $C_4H_{10}$ ), and octane ( $C_8H_{18}$ ). As the chemical formula suggests, the carbon content of the paraffins increases with their carbon number: ethane is 80 percent carbon by weight, octane 84 percent. As the size of paraffin molecules increases, the carbon content approaches the limiting value of 85.7 percent asymptotically (See Figure B2).

<sup>3</sup> API gravity is an arbitrary scale expressing the gravity or density of liquid petroleum products, as established by the American Petroleum Institute (API). The measuring scale is calibrated in terms of degrees API. The higher the API gravity, the lighter the compound. Light crude oils generally exceed 38 degrees API and heavy crude oils are all crude oils with an API gravity of 22 degrees or below. Intermediate crude oils fall in the range of 22 degrees to 38 degrees API gravity. API gravity can be calculated with the following formula Degrees API =  $(141.5/\text{Specific Gravity}) - 131.5$ . Specific gravity is the density of a material relative to that of water. At standard temperature and pressure, there are 62.36 pounds of water per cubic foot, or 8.337 pounds water per gallon.

**Figure B1. Estimated and Actual Relationships Between Petroleum Carbon Coefficients and Hydrocarbon Density**



Source: Carbon content factors for paraffins are calculated based on the properties of hydrocarbons in V. Guthrie (ed.), *Petroleum Products Handbook* (New York: McGraw Hill, 1960) p. 33. Carbon content factors from other petroleum products are drawn from sources described below. Relationship between density and emission factors based on the relationship between density and energy content in U.S. Department of Commerce, National Bureau of Standards, *Thermal Properties of Petroleum Products*, Miscellaneous Publication, No. 97 (Washington, D.C., 1929), pp.16-21, and relationship between energy content and fuel composition in S. Ringen, J. Lanum, and F.P. Miknis, "Calculating Heating Values from the Elemental Composition of Fossil Fuels," *Fuel*, Vol. 58 (January 1979), p.69.

**Cycloparaffins.** Cycloparaffins are similar to paraffins, except that the carbon molecules form ring structures rather than straight chains, and consequently require two fewer hydrogen molecules than paraffins. Cycloparaffins always have the general formula  $C_nH_{2n}$  and are 85.7 percent carbon by mass, regardless of molecular size.

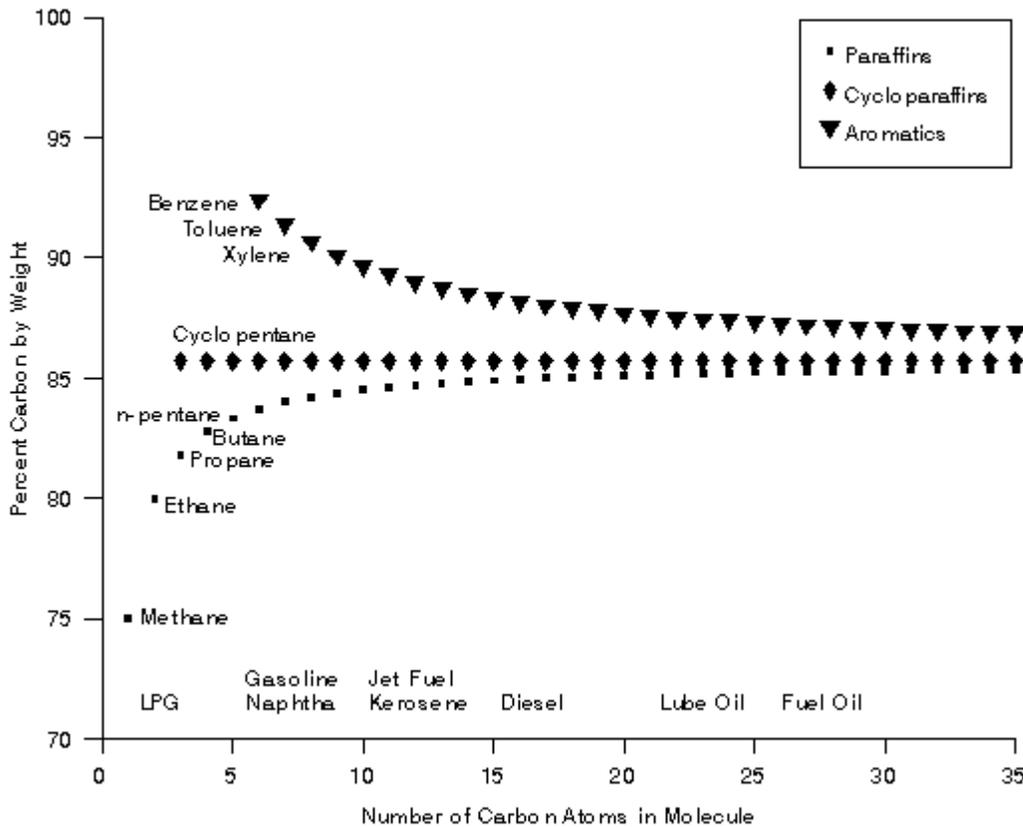
**Olefins.** Olefins are a reactive and unstable form of paraffin: a straight chain with the two hydrogen atoms at each end of the chain missing. They are never found in crude oil but are created in moderate quantities by the refining process. Thus, gasoline, for example, may contain 2 percent olefins. They also have the general formula  $C_nH_{2n}$ , and hence are also always 85.7 percent carbon by weight. Propylene ( $C_3H_6$ ), a common intermediate petrochemical product, is an olefin.

**Aromatics.** Aromatics are very reactive hydrocarbons that are relatively uncommon in crude oil (10 percent or less). Light aromatics increase the octane level in gasoline, and consequently are deliberately created by steam reforming of naphtha. Aromatics also take the form of ring structures with some double bonds between carbon atoms. The most common aromatics are benzene ( $C_6H_6$ ), toluene ( $C_7H_8$ ), and xylene ( $C_8H_{10}$ ). The general formula for aromatics is  $C_nH_{2n-6}$ . Benzene is 92 percent carbon by mass, while xylene is 90.6 percent carbon by mass. Unlike the other hydrocarbon families, the carbon content of aromatics declines asymptotically toward 85.7 percent with increasing carbon number and density. (See Figure B2)

**Polynuclear Aromatics.** Polynuclear aromatics are large molecules with a multiple ring structure and few hydrogen atoms, such as naphthalene ( $C_{10}H_8$  and 94.4 percent carbon by mass) and anthracene ( $C_{14}H_{10}$  and 97.7 percent carbon). They are relatively rare but do appear in heavier petroleum products.

Figure B2 illustrates the share of carbon by weight for each class of hydrocarbon. Hydrocarbon molecules containing 2 to 4 carbon atoms are all natural gas liquids; hydrocarbons with 5 to 10 carbon atoms are predominantly found in naphtha and gasoline; and hydrocarbon compounds with 12 to 20 carbons comprise "middle distillates," which are used to make diesel fuel, kerosene and jet fuel. Larger molecules are generally used as lubricants, waxes, and residual fuel oil.

**Figure B2. Carbon Content of Pure Hydrocarbons as a Function of Carbon Number**



Source: J.M. Hunt, *Petroleum Geochemistry and Geology* (San Francisco, CA, W.H. Freeman and Company, 1979), pp. 31-37.

If one knows nothing about the composition of a particular petroleum product, assuming that it is 85.7 percent carbon by mass is not an unreasonable first approximation. Since denser products have higher carbon numbers, this guess would be most likely to be correct for crude oils and fuel oils. The carbon content of lighter products is more affected by the shares of paraffins and aromatics in the blend.

## Energy Content of Petroleum Products

The exact energy content (gross heat of combustion) of petroleum products is not generally known. EIA estimates energy consumption in Btu on the basis of a set of industry-standard conversion factors. These conversion factors are generally accurate to within 3 to 5 percent.

### Individual Petroleum Products

The U.S. maintains data on the consumption of more than 20 separate petroleum products and product categories. The carbon contents, heat contents, and density for each product are provided below in Table B6. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

**Table B6. Carbon Content Coefficients and Underlying Data for Petroleum Products**

Fuel	2001 Carbon Content (MMTC/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.34	5.253	59.6	86.60
LPG	16.99	*	*	*
Jet Fuel	19.33	5.670	42.0	86.30
Distillate Fuel	19.95	5.825	35.5	86.34
Residual Fuel	21.49	6.287	11.0	85.68
Asphalt and Road Oil	20.62	6.636	5.6	83.47
Lubricants	20.24	6.065	25.6	85.80
Petrochemical Feedstocks	19.37	5.248 <sup>a</sup>	67.1 <sup>a</sup>	84.11 <sup>a</sup>
Aviation Gas	18.87	5.048	69.0	85.00
Kerosene	19.72	5.670	41.4	86.01
Petroleum Coke	27.85	6.024	-	92.28
Special Naphtha	19.86	5.248	51.2	84.76
Petroleum Waxes	19.81	5.537	43.3	85.29
Still Gas	17.51	6.000	-	-
Crude Oil	20.29	5.800	30.5	85.49
Unfinished Oils	20.29	5.825	30.5	85.49
Miscellaneous Products	20.29	5.796	30.5	85.49
Pentanes Plus	18.24	4.620	81.7	83.70
Natural Gasoline	18.24	4.620	81.7	83.70

<sup>a</sup>Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Petrochemical feedstocks with higher boiling points are assumed to have the same characteristics as distillate fuel.

\* LPG is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and carbon content, see table B9.

-(No sample data available)

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, Washington, DC, (November, 1994), DOE/EIA 0573

### **Motor Gasoline and Motor Gasoline Blending Components**

Motor gasoline is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines.<sup>4</sup> "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline; but excludes aviation gasoline.

Gasoline is the most widely used petroleum product in the United States, and its combustion accounts for nearly 20 percent of all U.S. carbon dioxide emissions. EIA collects consumption data (i.e., "petroleum products supplied" by wholesalers) for several types of gasoline: leaded regular, unleaded regular, and unleaded high octane. The American Society for Testing and Materials (ASTM) standards permit a broad range of densities for gasoline, ranging from 50 to 70 degrees API gravity, which implies a range of possible carbon and energy contents per barrel. Table B7 reflects changes in the density of gasoline over time and across grades of gasoline through 2001.

<sup>4</sup>Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 degrees to 158 degrees Fahrenheit at the 10-percent recovery point to 365 degrees to 374 degrees Fahrenheit at the 90-percent recovery point.

**Table B7. Motor Gasoline Density, 1990 – 2001**  
(Degrees API)

Fuel Grade	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
<b>Winter Grade</b>												
Low Octane	62.0	61.8	61.4	61.0	60.1	59.8	60.6	61.5	61.8	61.6	61.6	61.7
Mid Octane	60.8	60.4	60.2	59.9	59.4	59.1	59.9	60.7	61.2	61.3	61.2	61.2
High Octane	59.0	59.3	59.0	58.7	58.5	58.0	58.5	59.3	60.0	60.3	59.7	59.1
<b>Summer Grade</b>												
Low Octane	58.2	58.0	57.4	56.1	55.7	56.1	56.9	57.1	57.6	57.7	56.8	57.2
Mid Octane	57.4	57.1	56.4	55.5	54.8	55.6	56.2	56.6	56.7	57.4	58.0	58.0
High Octane	55.5	55.7	55.6	54.4	53.8	55.1	55.3	56.4	55.7	57.4	55.8	55.5

Source: National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* and *Motor Gasoline Winter* (1990-2001).

The density of motor gasoline increased across all grades through 1994, partly as a result of the leaded gasoline phase-out. In order to maintain the “anti-knock” quality and octane ratings of gasoline in the absence of lead, the portion of aromatic hydrocarbons used in gasoline increased. As discussed above, aromatic hydrocarbons have a lower ratio of hydrogen to carbon than other hydrocarbons typically found in gasoline, and therefore increase fuel density.

The trend in gasoline density was reversed beginning in 1996 with the development of fuel additives that raised oxygen content. In 1995, a requirement for reformulated gasoline in non-attainment areas implemented under the Clean Air Act Amendments further changed the composition of gasoline consumed in the United States. In reformulated gasoline, methyl tertiary butyl ether (MTBE) and tertiary amyl methyl ether (TAME) are often added to standard gasoline to boost its oxygen content. The increased oxygen reduces the emissions of carbon monoxide and unburned hydrocarbons. These oxygen-rich blending components are also much lower in carbon than standard gasoline. The average gallon of reformulated gasoline consumed in 2001 contained 8 percent MTBE and 0.5 percent TAME. The characteristics of reformulated fuel additives appear in Table B8.

**Table B8. Characteristics of Major Reformulated Fuel Additives**

Additive	Density (Degrees API)	Carbon Share (Percent)	Carbon Content (MMTC/Qbtu)
MTBE	59.1	68.2	16.92
ETBE	59.1	70.5	17.07
TAME	52.8	70.5	17.00

Source: American Petroleum Institute, *Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components*, API 4261.

### Estimation Methods

U.S. gasoline consumption was divided by product grade and season for both standard gasoline and reformulated gasoline. Carbon coefficients for each grade and type are derived from three parameters: gasoline density, share of the gasoline mixture that is carbon; and the energy content of a gallon of gasoline. Carbon coefficients for reformulated fuels were calculated by applying the carbon coefficient for the fuel additives listed in Table B8 to the increased share of reformulated gasoline represented by these additives (standard gasoline contains small amounts of MTBE and TAME) and weighting the gasoline carbon content accordingly. The carbon content for each grade and type of fuel is multiplied by the share of overall consumption that the grade and fuel type represent. Individual coefficients are then summed to yield an overall carbon content coefficient.

The carbon coefficient for motor gasoline varies annually based on the density of and proportion of additives in a representative sample of motor gasoline examined each year. However, in 1997 EIA began incorporating the effects of the introduction of reformulated gasoline into its estimate of carbon coefficients for motor gasoline. This change resulted in a downward step function in carbon coefficients for gasoline of approximately 0.3 percent beginning in 1995.

### Data Sources

The density of motor gasoline is drawn from the National Institute for Petroleum and Energy Research, *Motor Gasolines, Summer* (various years) and the National Institute for Petroleum and Energy Research, *Motor Gasolines, Winter* (various years).

The characteristics of reformulated gasoline additives is taken from American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components, API 4261.

The carbon content of motor gasoline is found in Mark DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, Volume 2, ANL/ESD/TM-22, Vol. 2 (Chicago, IL: Argonne National Laboratory, November 1993), Appendix C, pp. C-1 to C-8 and ultimate analyses of one sample of shale-oil derived gasoline from Applied Systems Corp., *Compilation of Oil Shale Test Results* (Submitted to the Office of Naval Research, April 1976), p. 3-2, three varieties of gasoline from C.C. Ward, "Petroleum and Other liquid Fuels," in *Marks' Standard Handbook for Mechanical Engineers* (New York, NY: McGraw-Hill, 1978), pp. 7-14, and one sample of gasoline from J.W. Rose and J.R. Cooper, *Technical Data on Fuel*, The British National Committee, World Energy Conference, London, England (1977).

Standard heat contents for motor gasoline of 5.253 million Btu per barrel conventional gasoline and 5.150 million Btu per barrel reformulated gasoline were adopted from the Energy Information Administration, *Annual Energy Review 2000* Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

## Jet Fuel

Jet fuel is a refined petroleum product used in jet aircraft engines. There are two classes of jet fuel used in the U.S.: "naphtha-based" jet fuels and "kerosene-based" jet fuels. In 1989, 13 percent of U.S. consumption was naphtha-based fuel, with the remainder kerosene-based jet fuel. In 1993, the U.S. Department of Defense began a conversion from naphtha-based JP-4 jet fuel to kerosene-based jet fuel, because of the possibility of increased demand for reformulated motor gasoline limiting refinery production of naphtha-based jet fuel. By 1996, naphtha-based jet fuel represented less than one-half of one percent of all jet fuel consumption. The carbon coefficient for jet fuel used in this report represents a consumption-weighted combination of the naphtha-based and kerosene-based coefficients.

## Estimation Methods

Because naphtha-based jet fuel is used on a limited basis in the United States, sample data on its characteristics are limited. The density of naphtha-based jet fuel (49 degrees) was estimated as the central point of the acceptable API gravity range published by ASTM. The heat content of the fuel was assumed to be 5.355 million Btu per barrel based on EIA industry standards. The carbon fraction was derived from an estimated hydrogen content of 14.1 percent and an estimated content of sulfur and other non-hydrocarbons of 0.1 percent.<sup>5</sup>

The density and carbon share of kerosene-based jet fuels was based on the average composition of 39 fuel samples taken by Boeing Corporation (the leading U.S. commercial airline manufacturer) in 1989. The EIA's standard heat content of 5.67 million Btu per barrel was adopted for kerosene-based jet fuel.

The carbon content for each jet fuel type is multiplied by the share of overall consumption of that fuel type. Individual coefficients are then summed to yield an overall carbon coefficient.

Between 1994 and 1995, the carbon coefficient for kerosene-based jet fuel was revised downward from 19.71 million metric tons per quadrillion Btu to 19.33 million metric tons per quadrillion Btu. This downward revision was the result of a shift in the sample set used from one collected between 1959 and 1972 and reported on by Martel and Angello in 1977 to one collected by Boeing in 1989 and published by Hadaller and Momenty in 1990. The latter set of fuel samples have a decreased density and slightly lower carbon share than the earlier samples. However, the assumed heat content is unchanged because it is based on an EIA standard and thus, probably yields a downward bias in the revised carbon coefficient.

## Data Sources

The carbon content of naphtha-based jet fuel is from C.R. Martel and L.C. Angello, "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels," in *Current Research in Petroleum Fuels*, Volume I (New York, NY: MSS Information Company, 1977), p. 116.

<sup>5</sup>Martel, C.R., and Angello, L.C. Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels. Current Research in Petroleum Fuels. Vol. I. New York, NY: MSS Information Corporation, 1977.

The density of naphtha-based jet fuel is from the American Society for Testing and Materials, *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985), p. 60.

A standard heat content for naphtha-based jet fuel was adopted from the U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Available online at: [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

Carbon content and density for kerosene-based jet fuels is drawn from O.J. Hadaller and A.M. Momeny, *The Characteristics of Future Fuels*, Part 1, "Conventional Heat Fuels" (Seattle, WA: Boeing Corp., September 1990), pp. 46-50.

A standard heat content for kerosene-based jet fuel was adopted from the Energy Information Administration, *Annual Energy Review 2000* Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

### **Distillate Fuel**

Distillate fuel is a general classification for diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. No. 1, No. 2, and No. 4 fuel oils are also used for space heating and electric power generation.

### **Estimation Methods**

For the purposes of this report, the carbon content of No. 2 fuel oil is assumed to typify the carbon content of distillate fuel generally. The carbon share in No. 2 fuel oil was estimated based on the average of 11 ultimate analyses. This carbon share was combined with EIA's standard heat content of 5.825 million Btu per barrel and the density of distillate assumed to be 35.5 degrees API, in accord with its heat content.

### **Data Sources**

Carbon content and density were derived from the following:

- Four samples of distillate from C. T. Hare and R.L. Bradow, "Characterization of Heavy-Duty Diesel Gaseous and Particulate Emissions, and the Effects of Fuel Composition," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 128;
- Three samples from E.F. Funkenbush, D.G. Leddy, and J.H. Johnson, "The Organization of the Soluble Organic Fraction of Diesel Particulate Matter," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979) p. 128;
- One sample from R.L. Mason, "Developing Prediction Equations for Fuels and Lubricants," SAE Paper 811218, p.34;
- One sample from C.T. Hare, K.J. Springer, and R.L. Bradow, "Fuel and Additive Effects on Diesel Particulate- Development and Demonstration of Methodology," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 179; and
- One Sample from F. Black and L. High, "Methodology for Determining Particulate and Gaseous Diesel Emissions," in Society of Automotive Engineers, *The Measurement and Control of Diesel Particulate Emissions* (1979), p. 128.

A standard heat content was adopted from the Energy Information Administration *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

## Residual Fuel

Residual fuel is a general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Residual fuel conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore power plants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

In the United States, electric utilities purchase about a third of the residual oil consumed. A somewhat larger share is used for vessel bunkering, and the balance is used in the commercial and industrial sectors. The residual oil (defined as No.6 fuel oil) consumed by electric utilities has an energy content of 6.287 million Btu per barrel and an average sulfur content of 1 percent.<sup>6</sup> This implies a density of about 17 degrees API.

## Estimation Methods

For this report, residual fuel was defined as No.6 fuel oil. The National Institute of Petroleum and Energy Research, Fuel Oil Survey shows an average density for fuel oil of 11.3 API gravity and anecdotal evidence suggests that marine residual fuel is also very dense, with typical gravity of 10.5 to 11.5 degrees API.<sup>7</sup> Because the largest share of fuel oil consumption is for marine vessels, a density of 11 degrees API was adopted when developing the carbon coefficient for this report. An average share of carbon in residual fuel of 85.67 percent by mass was used based on ultimate analyses of a dozen samples.

## Data Sources

The carbon content of residual fuel oil is based on the following:

- Three samples of residual fuel from the Middle East and one sample from Texas in F. Mosby, G.B. Hoekstra, T.A. Kleinhenz, and J.M. Sokra, "Pilot Plant Proves Resid Process," in *Chemistry of Petroleum Processing and Extraction* (MSS Information Corporation, 1976), p.227;
- Three samples of heavy fuel oils from J.P. Longwell, "Interface Between Fuels and Combustion," in *Fossil Fuel Combustion: A Sourcebook* (New York, NY: John Wiley & Sons, 1991);
- Three samples of heavy fuel oils from C.C. Ward, "Petroleum and Other Liquid Fuels," in *Marks' Standard Handbook for Mechanical Engineers* (New York, NY: McGraw-Hill, 1978), pp. 7-14;
- Two samples of heavy fuel oils from, D.A. Vorum, "Fuel and Synthesis Gases from Gaseous and Liquid Hydrocarbons," in American Gas Association, *Gas Engineer's Handbook* (New York, NY: Industrial Press, 1974), p. 3/71; and
- One sample of heavy fuel oil from W. Rose and J.R. Cooper, *Technical Data on Fuel*, The British National Committee, World Energy Conference, London, England (1977).

The density of residual fuel consumed for electric power generation is from Energy Information Administration, *Cost and Quality of Fuels*, (Washington, DC). Web site [www.eia.doe.gov/cneaf/electricity/cq/cq\\_sum.html](http://www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html).

Density of residual fuel consumed in marine vessels from Energy Information Administration, Petroleum Supply Division, *Btu Tax on Finished Petroleum Products*, (unpublished manuscript, April 1993) and the National Institute for Petroleum and Energy Research, *Fuel Oil Surveys* (Bartlesville, OK, 1992).

A standard heat content was adopted from Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

<sup>6</sup>Energy Information Administration, *Cost and Quality of Fuels*, DOE/EIA-0191(Washington, DC). Available online at: [www.eia.doe.gov/cneaf/electricity/cq/cq\\_sum.html](http://www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html).

<sup>7</sup>Energy Information Administration, Petroleum Supply Division, *Btu Tax on Finished Petroleum Products*, (unpublished manuscript, April 1993)

## Liquefied Petroleum Gases (LPG)

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and n-butane. Because each of these compounds is a pure paraffinic hydrocarbon, their carbon shares are easily derived by taking into account the atomic weight of carbon (12) and the atomic weight of hydrogen (1). Thus, for example, the carbon share of propane, C<sub>3</sub>H<sub>8</sub>, is 81.8 percent. The densities and heat content of the compounds are also well known allowing carbon coefficients to be calculated directly. Table B9 summarizes the physical characteristic of LPG.

**Table B9. Physical Characteristics of Liquefied Petroleum Gases**

Compound	Chemical Formula	Density (Barrels Per Metric Ton)	Carbon Content (Percent)	Energy Content (MMBtu/Barrel)	Carbon Coefficient (MMTC/Qbtu)
Ethane	C <sub>2</sub> H <sub>6</sub>	16.88	80.0	2.916	16.25
Propane	C <sub>3</sub> H <sub>8</sub>	12.44	81.8	3.824	17.20
Isobutane	C <sub>4</sub> H <sub>10</sub>	11.20	82.8	4.162	17.75
n-butane	C <sub>4</sub> H <sub>10</sub>	10.79	82.8	4.328	17.72

Source: V.B. Guthrie (ed.), *Characteristics of Compounds*, Petroleum Products Handbook, (New York, NY: McGraw-Hill, 1960), p.3-3.

## Estimation Methods

Based on their known physical characteristics, a carbon coefficient is assigned to each compound contained in the U.S. energy statistics category, Liquefied Petroleum Gases. A weighted carbon coefficient for LPG used as fuel is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics. The mix of LPG consumed for non-fuel use differs significantly from the mix of LPG that is combusted. While the preponderance of LPG consumed for fuel use is propane, the largest single LPG used for non-fuel applications is ethane. A carbon coefficient for LPG used for non-fuel applications is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics. The changing shares of LPG fuel use and non-fuel use consumption appear below in Table B10.

**Table B10. Consumption and Carbon Content Coefficients of Liquefied Petroleum Gases, 1990-2001**  
(Million Metric Tons per Quadrillion Btu)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
<b>Consumption (Quads Fuel Use)</b>												
Ethane	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.05	0.05	0.06	0.06	0.05
Propane	0.79	0.79	0.84	0.86	0.86	0.86	0.95	0.92	0.98	0.98	0.98	0.89
Butane	0.08	0.05	0.07	0.06	0.07	0.05	0.04	0.05	0.05	0.06	0.06	0.06
Total	0.90	0.85	0.94	0.94	0.96	0.93	1.02	1.03	0.99	1.10	1.10	1.01
Carbon Coefficient	17.21	7.21	17.21	17.22	17.22	17.20	17.20	17.18	17.18	17.18	17.18	17.18
<b>Consumption (Quads non-Fuel Use)</b>												
Ethane	0.55	0.62	0.62	0.65	0.65	0.68	0.74	0.71	0.68	0.77	0.81	0.73
Propane	0.53	0.59	0.61	0.55	0.65	0.67	0.65	0.71	0.68	0.76	0.76	0.69
Butane	0.13	0.17	0.16	0.15	0.25	0.24	0.26	0.25	0.24	0.28	0.29	0.27
Total	1.20	1.38	1.39	1.35	1.55	1.59	1.65	1.67	1.60	1.81	1.86	1.69
Carbon Coefficient	16.83	16.84	16.84	16.80	16.88	16.87	16.86	16.88	16.87	16.88	16.87	16.88
<b>Weighted Carbon Coefficient</b>	<b>16.99</b>	<b>16.98</b>	<b>16.99</b>	<b>16.97</b>	<b>17.01</b>	<b>17.00</b>	<b>16.99</b>	<b>16.99</b>	<b>16.99</b>	<b>16.99</b>	<b>16.99</b>	<b>16.99</b>

Sources: Consumption of LPG from Energy Information Administration, Petroleum Supply Annual, various years. Non-fuel use of LPG from American Petroleum Institute, Natural Gas Liquids and Liquefied Refinery Gas Survey, various years.

The carbon coefficient of LPG is updated annually to reflect changes in the consumption mix of the underlying compounds: ethane; propane; isobutane; and normal butane. In 1994, EIA included pentanes plus – assumed to have the characteristics of hexane – in the mix of compounds broadly described as LPG. In 1995, EIA removed pentanes plus from this fuel category. Because pentanes plus is relatively rich in carbon per unit of energy, its removal from the consumption mix lowered the carbon coefficient for LPG from 17.26 million metric tons per quadrillion Btu to 17.02 million metric tons per quadrillion Btu. In 1998, EIA began separating LPG consumption into two categories: energy use; and non-fuel use and providing individual coefficients for each. Because LPG for fuel use typically contains higher proportions of propane than LPG for non-fuel use, the carbon coefficient for fuel use is about 2 percent higher than the coefficient for non-fuel use.

## Data Sources

Carbon share, density and heat content of liquefied petroleum gases from V.B. Guthrie (ed.), *Characteristics of Compounds, Petroleum Products Handbook*, (New York, NY: McGraw-Hill, 1960), p.3-3.

LPG consumption from Energy Information Administration, *Petroleum Supply Annual*, (Washington, DC) various years. Web site [www.eia.doe.gov/oil\\_gas/petroleum/data\\_publications/petroleum\\_supply\\_annual/psa\\_volume1/psa\\_volume1.html](http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html).

Non-fuel use of LPG from American Petroleum Institute, *Natural Gas Liquids and Liquefied Refinery Gas Survey*, various years.

## Aviation Gasoline

Aviation gasoline is used in piston-powered airplane engines. It is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D 910 and Military Specification MIL-G-5572. Aviation gas is a relatively minor contributor to greenhouse gas emissions compared to other petroleum products, representing approximately 0.1 percent of all consumption.

The ASTM standards for boiling and freezing points in aviation gasoline effectively limit the aromatics content to a maximum of 25 percent (ASTM D910). Because weight is critical in the operation of an airplane, aviation gas must have as many Btu per pound (implying a lower density) as possible, given other requirements of piston engines such as high anti-knock quality.

## Estimation Methods

A carbon coefficient for aviation gasoline was calculated on the basis of the EIA standard heat content of 5.048 million Btu per barrel. This implies a density of approximately 69 degrees API gravity or 5.884 pounds per gallon. To estimate the share of carbon in the fuel, it was assumed that aviation gasoline is 87.5 percent iso-octane, 9.0 percent toluene, and 3.5 percent xylene. The maximum allowable sulfur content in aviation gasoline is 0.05 percent, and the maximum allowable lead content is 0.1 percent. These amounts were judged negligible and excluded for the purposes of this analysis. This yielded a carbon share of 85 percent and a carbon coefficient of 18.87 million metric tons per quadrillion Btu.

## Data Sources

Fuel characteristics were taken from the American Society for Testing and Materials, *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

A standard heat content for aviation gas was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

## Still Gas

Still gas, or refinery gas is composed of light hydrocarbon gases that are released as petroleum is processed in a refinery. The composition of still gas is highly variable, depending primarily on the nature of the refining process and secondarily on the composition of the product being processed. Petroleum refineries produce still gas from many different processes. Still gas can be used as a fuel or feedstock within the refinery, sold as a petrochemical feedstock, or purified and sold as pipeline-quality natural gas. In general, still gas tends to include large amounts of free hydrogen and methane, as well as smaller amounts of heavier hydrocarbons. Because different refinery operations result in different gaseous byproducts, it is difficult to determine what represents typical still gas.

## Estimation Methods

The EIA obtained data on four samples of still gas. Table B11 below shows the composition of those samples.

**Table B11. Composition, Energy Content, and Carbon Coefficient for Four Samples of Still Gas**

Sample	Hydrogen (%)	Methane (%)	Ethane (%)	Propane (%)	Btu Per Cubic Foot	Carbon Coefficient (MMTC/Qbtu)
One	12.7	28.1	17.1	11.9	1,388	17.51
Two	34.7	20.5	20.5	6.7	1,143	14.33
Three	72.0	12.8	10.3	3.8	672	10.23
Four	17.0	31.0	16.2	2.4	1,100	15.99

Because gas streams with a large free hydrogen content are likely to be used as refinery or chemical feedstocks, EIA selected the carbon coefficient from the sample with the lowest hydrogen content as the representative value for still gas.

### Data Sources

One still gas sample was drawn from American Gas Association, *Gas Engineer's Handbook*, (New York, NY: Industrial Press, 1974), pp. 3.71, and three still gas samples came from C.R. Guerra, K. Kelton, and D.C. Nielsen, "Natural Gas Supplementation with Refinery Gases and Hydrogen," in Institute of Gas Technology, *New Fuels and Advances in Combustion Technologies* (Chicago, IL, June 1979).

### Asphalt

Asphalt is used to pave roads. Because most of its carbon is retained in those roads, it is a small source of emissions. It is derived from a class of hydrocarbons called "asphaltenes," abundant in some crude oils but not in others. Asphaltenes have oxygen and nitrogen atoms bound into their molecular structure, so that they tend to have lower carbon contents than other hydrocarbons.

### Estimation Methods

Ultimate analyses of twelve samples of asphalts showed an average carbon content of 83.5 percent. The EIA standard heat content for asphalt of 6.636 million Btu per barrel was assumed. The ASTM petroleum measurement tables show a density of 5.6 degrees API or 8.605 pounds per gallon for asphalt. Together, these variables generate a carbon coefficient of 20.62 million metric tons per quadrillion Btu.

### Data Sources

A standard heat content for asphalt was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

The density of asphalt is from American Society for Testing and Materials, *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

### Lubricants

Lubricants are substances used to reduce friction between bearing surfaces, or incorporated into processing materials used in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases. Lubricant consumption is dominated by motor oil for automobiles, but there is a large range of product compositions and end uses within this category.

### Estimation Methods

The ASTM Petroleum Measurement Tables give the density of lubricants at 25.6 degrees API. Ultimate analysis of a single sample of motor oil yielded a carbon content of 85.8 percent. A standard heat content of 6.065 million Btu per barrel was adopted. These factors produce a carbon coefficient of 20.24 million metric tons per quadrillion Btu.

## Data Sources

A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000* (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

The density of asphalt was adopted from American Society for Testing and Materials, *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985).

## Petrochemical Feedstocks

U.S. energy statistics distinguish between two different kinds of petrochemical feedstocks: those with a boiling temperature below 400 degrees Fahrenheit, generally called "naphtha," and those with a boiling temperature 400 degrees Fahrenheit and above.

## Estimation Methods

Because reformed naphtha is used to make motor gasoline (hydrogen is released to raise aromatics content and octane rating), "straight-run" naphtha is assumed to be used as a petrochemical feedstock. Ultimate analyses of five samples of naphtha were examined and showed an average carbon share of 84.11 percent and an average density of 67.1 degrees API gravity. The standard EIA heat content of 5.248 million Btu per barrel is used to estimate a carbon coefficient of 18.14 million metric tons per quadrillion Btu.

Petrochemical feedstocks with a boiling temperature greater than 401 degrees Fahrenheit are part of the "middle distillate" fraction in the refining process, and EIA estimates that these petrochemical feedstocks have the same heat content as distillate fuel. Thus, the carbon coefficient of 19.95 million metric tons per quadrillion Btu used for distillate fuel is also adopted for this portion of petrochemical feedstocks. The weighted average of the two carbon coefficients for petroleum feedstocks equals 19.37 million metric tons per quadrillion Btu.

## Data Sources

The carbon content and density of naphthas is estimated based on G.H. Unzelman, "A Sticky Point for Refiners: FCC Gasoline and the Complex Model," *Fuel Reformulation* (July/August 1992), p. 29.

A standard heat content for petrochemical feedstock was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

## Kerosene

A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps, kerosene is drawn from the same petroleum fraction as jet fuel. Kerosene is generally comparable to No.1 fuel oil.

## Estimation Methods

The average density of 41.4 degrees API and average carbon share of 86.01 percent found in five ultimate analyses of No. 1 fuel oil samples were applied to a standard heat content of 5.67 million Btu per barrel to yield a carbon coefficient of 19.72 million metric tons per quadrillion Btu.

## Data Sources

A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

## Petroleum Coke

Petroleum coke is the solid residue of the extensive processing of crude oil. It is a coal-like solid, usually with a carbon content greater than 90 percent, that is used as a boiler fuel and industrial raw material.

## Estimation Methods

Ultimate analyses of two samples of petroleum coke showed an average carbon share of 92.3 percent. The ASTM standard density of 9.543 pounds per gallon was adopted and the EIA standard energy content of 6.024 million Btu per barrel assumed. Together, these factors produced an estimated carbon coefficient of 27.85 million metric tons per quadrillion Btu.

## Data Sources

Carbon content for petroleum coke was estimated from two samples from S. W. Martin, "Petroleum Coke," in Virgil Guthrie (ed.), *Petroleum Processing Handbook* (New York, NY: McGraw-Hill, 1960), pp. 14-15. Density of petroleum coke adopted from American Society for Testing and Materials, *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985). A standard heat content was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

## Special Naphtha

Special naphtha is defined as a light petroleum product to be used for solvent applications, including commercial hexane and four classes of solvent: stoddard solvent, used in dry cleaning; high flash point solvent, used as an industrial paint because of its slow evaporative characteristics; odorless solvent, most often used for residential paints; and high solvency mineral spirits, used for architectural finishes. These products differ in both density and carbon percentage, requiring the development of multiple coefficients.

## Estimation Methods

Hexane is a pure paraffin containing 6 carbon atoms and 14 hydrogen atoms. Thus, it is 83.7 percent carbon. Its density is 76.6 degrees API or 5.649 pounds per gallon and its derived carbon coefficient is 17.17 million metric tons per quadrillion Btu. The other hydrocarbon compounds in special naphthas are assumed to be either paraffinic or aromatic (see discussion above). The portion of aromatics in odorless solvents is estimated at less than 1 percent, Stoddard and high flash point solvents contain 15 percent aromatics and high solvency mineral spirits contain 30 percent aromatics (Boldt and Hall, 1985). These assumptions, when combined with the relevant densities, yield the carbon coefficients contained in Table B12 below.

**Table B12. Characteristics of Non-hexane Special Naphthas**

Special Naphtha	Aromatic Content (Percent)	Density (Degrees API)	Carbon Content (Percent)	Carbon Coefficient (MMTC/QBtu)
Odorless Solvent	1	55.0	84.51	19.41
Stoddard Solvent	15	47.9	84.44	20.11
High Flash Point	15	47.6	84.70	20.17
Mineral Spirits	30	43.6	85.83	20.99

EIA reports only a single consumption figure for special naphtha. The carbon coefficients of the five special naphthas are weighted according to the following formula: approximately 10 percent of all special naphtha consumed is hexane and the remaining 90 percent is assumed to be distributed evenly among the four other solvents. The resulting emissions coefficient for special naphthas is 19.86 million metric tons carbon per quadrillion Btu.

## Data Sources

A standard heat content for special naphtha was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

Density and aromatic contents for special naphthas are from K. Boldt and B.R. Hall, *Significance of Tests for Petroleum Products* (Philadelphia, PA: American Society for Testing and Materials), p. 30.

## Petroleum Waxes

The ASTM standards define petroleum wax as a product separated from petroleum that is solid or semi-solid at 77 degrees Fahrenheit (25 degrees Celsius). The two classes of petroleum wax are paraffin waxes and microcrystalline waxes. They differ in the number of carbon atoms and the type of hydrocarbon compounds. Microcrystalline waxes have longer carbon chains and more variation in their chemical bonds than paraffin waxes.

### Estimation Methods

For the purposes of this analysis, paraffin waxes are assumed to be composed of 100 percent paraffinic compounds with a chain of 25 carbon atoms. The resulting carbon share for paraffinic wax is 85.23 percent and the density is estimated at 45 degrees API or 6.684 pounds per gallon.

Microcrystalline waxes are assumed to consist of 50 percent paraffinic and 50 percent cycloparaffinic compounds with a chain of 40 carbon atoms, yielding a carbon share of 85.56 percent. The density of microcrystalline waxes is estimated at 36.7 degrees API, based on a sample of 10 microcrystalline waxes found in the *Petroleum Products Handbook*.

A weighted average density and carbon coefficient was calculated for petroleum waxes, assuming that wax consumption is 80 percent paraffin wax and 20 percent microcrystalline wax. The weighted average carbon content is 85.29 percent, and the weighted average density is 6.75 pounds per gallon. EIA's standard heat content for waxes is 5.537 million Btu per barrel. These inputs yield a carbon coefficient for petroleum waxes of 19.81 million metric tons per quadrillion Btu.

### Data Sources

The density of paraffin wax is from American Society for Testing and Materials, *ASTM and Other Specifications for Petroleum Products and Lubricants* (Philadelphia, PA, 1985). The density of microcrystalline waxes is based on 10 samples found in V. Guthrie (ed.), *Petroleum Products Handbook* (New York, NY: McGraw-Hill, 1960).

A standard heat content for petroleum waxes was adopted from the Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

## Crude Oil, Unfinished Oils, and Miscellaneous

U.S. energy statistics include several categories of petroleum products designed to ensure that reported refinery accounts "balance" and cover any "loopholes" in the taxonomy of petroleum products. These categories include crude oil, unfinished oils, and miscellaneous products. Crude oil is rarely consumed directly, miscellaneous products account for less than one percent of oil consumption and unfinished oils are a balancing item that may show negative consumption. For carbon accounting purposes, it was assumed that all these products have the same carbon content as crude oil.

### Estimation Methods

EIA reports on the average density and sulfur content of U.S. crude oil purchased by refineries. To develop a method of estimating carbon content based on this information, ultimate analyses of 182 crude oil samples were collected. Within the sample set, carbon content ranged from 82 to 88 percent carbon, but almost all samples fell between 84 percent and 86 percent carbon. The density and sulfur content of the crude oil data were regressed on the carbon content, producing the following equation:

$$\text{Percent Carbon} = 76.99 + (10.19 * \text{Specific Gravity}) + (-0.76 * \text{Sulfur Content})$$

Absent the term representing sulfur content, the equation had an R-squared of only 0.35.<sup>8</sup> When carbon content was adjusted to exclude sulfur, the R-squared rose to 0.65. While sulfur is the most important nonhydrocarbon impurity, nitrogen and oxygen can also be significant, but they do not seem to be correlated with either density or sulfur

<sup>8</sup>R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

content. Restating these results, density accounts for about 35 percent of the variation in carbon content, impurities account for about 30 percent of the variation, and the remaining 35 percent is accounted for by other factors, including (presumably) the degree to which aromatics and polynuclear aromatics are present in the crude oil. Applying this equation to the 2001 crude oil quality data (30.49 degrees API and 1.42 percent sulfur) produces an estimated carbon content of 85.81 percent. Applying the density and carbon content to the EIA standard energy content for crude oil of 5.8 million Btu per barrel produces an emissions coefficient of 20.29 million metric tons per quadrillion Btu.

### Data Sources

The carbon content for crude oil was developed from an equation based on 182 crude oil samples, including 150 samples from U.S. National Research Council, *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology* (New York, NY: McGraw-Hill, 1927).

A standard heat content for crude oil was adopted from Energy Information Administration, *Annual Energy Review 2000*, Appendix A (Washington, D.C., July 2001). ). Web site.[eia.doe.gov/emeu/aer/contents.html](http://eia.doe.gov/emeu/aer/contents.html).

# Appendix C

## Uncertainty Analysis of Emissions Estimates

### Overview

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*,<sup>1</sup> as established at the UNFCCC 4<sup>th</sup> Conference of the Parties in Kyoto, Japan in December 1997, recommend that nations carry out analyses to estimate the uncertainty in their national greenhouse gas emissions inventories. According to the guidelines, nations should construct 95 percent confidence intervals for their greenhouse gas emission estimates using classical sampling techniques, Monte Carlo techniques, or assessments by national experts. The UNFCCC subsequently requested that the IPCC complete its work on uncertainty and prepare a report on good practice in inventory management. In 2000, the IPCC issued its report *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*.<sup>2</sup> The report established Tier 1 and Tier 2 methods of estimating uncertainty in greenhouse gas inventories as follows:<sup>3</sup>

Tier 1: Estimation of uncertainties by source category using error propagation equations ... and simple combination of uncertainties by source category to estimate overall uncertainty for one year and the uncertainty in the trend.

Tier 2: Estimation of uncertainties by source category using Monte Carlo analysis, followed by the use of Monte Carlo techniques to estimate overall uncertainty for one year and the uncertainty in the trend.

In response to the IPCC's good practices guidelines, EIA in 1998 carried out a Tier 1 uncertainty analysis of U.S. greenhouse gas emissions. This was done for carbon dioxide, methane, nitrous oxide, and other gases. The results of this analysis can be found in Table C1 below. The Tier 1 analysis provides a "weighted uncertainty" for each source calculated as the squared root of the sum of the squared activity factor and emission factor errors multiplied by the point estimate of the share of total emissions for the source. The Tier 1 approach, however, as pointed out by the IPCC may be inappropriate when combining non-normal distributions, as may be the case with some of the distributions for emissions factors and activity data.

In the 2000 to 2001 timeframe, EIA undertook a "Tier 2" uncertainty analysis of U.S. carbon dioxide, methane and nitrous oxide emission estimates to augment its previous "Tier 1" uncertainty analysis. The Tier 2 uncertainty analysis involves Monte Carlo simulations that facilitate the combination of various types of probability density functions. This analysis involved 1999 data, but the uncertainty would be consistent with the uncertainty associated with emissions estimates for the near to medium term.

Both Tier 1 and Tier 2 methods are discussed in detail below. However, they share some attributes in common. For either "Tier I" or "Tier II" analysis the sources of uncertainty fall into the following categories:

- Uncertainty associated with underlying activity data and uncertainty associated with emissions factors
- Random errors and bias errors
- Potential for upward and downward bias errors
- Reliability of emissions estimates by source.

The Tier 1 uncertainty analysis found in Table C1 excludes estimates for emissions and sequestration from land use changes and forestry. The Tier 1 analysis concluded that U.S. national greenhouse gas emissions, taken as a group, may differ by as much as 13 percent from the estimates published in the earlier edition of this report. Much of the uncertainty in national emissions was attributable to estimates of nitrous oxide emissions. If nitrous oxide emissions were excluded, the uncertainty of the total estimate was calculated to be on the order of 10 percent. As a point of comparison, the Tier 2 analysis, estimated total uncertainty about a simulated mean of total carbon dioxide,

<sup>1</sup>Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, 1997.

<sup>2</sup>Intergovernmental Panel on Climate Change, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, May 2000.

<sup>3</sup>Intergovernmental Panel on Climate Change, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, May 2000, p. 6.12.

methane and nitrous oxide emissions to be -4.4% to 4.6%. When expressed as a percentage of total estimated 1999 emissions<sup>4</sup>, the uncertainty becomes -0.4 to 9.0%.

The bulk of the potential uncertainty in the overall national estimate takes the form of bias errors, which are likely to persist from one year to the next and, thus, have relatively little influence on trends, rather than random errors, which would increase the difficulty of determining whether or not a trend exists. This is because estimates of energy-related carbon dioxide are probably accurate to well within 10 percent of estimated emissions, and energy-related carbon dioxide accounts for 81 percent of national emissions of greenhouse gases. There are much larger uncertainties for methane and, particularly, for nitrous oxide emissions, but the present evidence suggests that emissions from these sources account for only a small portion of total emissions.

The uncertainties in the estimates presented in this report come from the following sources:

- **Evolving Definitions.** In general, this report attempts to measure “anthropogenic” (human-caused) emissions of greenhouse gases in the United States, excluding carbon emissions of biological origin. Although in most cases it is obvious whether emissions from a particular source fall within this definition, there are a number of ambiguous cases, and the range of accepted definitions has shifted over time. Since the first edition of this report, sulfur hexafluoride has been added to the generally accepted definition of “greenhouse gases.” Emissions from bunker fuels are now excluded from the definition of “U.S. emissions.” Definitional changes tend to raise or lower emission estimates systematically.
- **Emissions Sources Excluded From the Report.** An estimate that excludes some sources will be biased downward by the amount of the excluded source. Of course, if the existence or magnitude of the excluded emissions were known, they would be included. But it is probable that there are still sources that have not yet been identified and escape inclusion in both the estimates and the list of sources excluded.
- **Incorrect Models of Emissions Processes.** An estimate based on a belief that emissions are caused by (or can be estimated from) a particular activity or process can produce large, systematically biased errors if the emissions are actually caused by some other process. The incorrect method can produce estimates that are considerably higher or lower than actual emissions and have different time-series properties.
- **Errors in Emissions Factors.** Errors in emissions factors can have diverse causes, the most common of which are definitional errors, sampling errors, and measurement errors. These errors can be either random or systematic. (See discussion of carbon coefficients below).
- **Errors in Activity Data.** Activity data are also subject to definitional errors, frame errors, sampling errors, and measurement errors, which can be either random or systematic.
- **Computational Errors.** Computational errors can exist in the estimation of emissions factors by EIA, in the calculation of emissions by EIA, or in the computation of the underlying activity data by the source organization.

Although any single computational error will usually produce a systematic error, computational errors as a group tend to produce very small (about 0.1 percent) random errors in the estimate.

---

<sup>4</sup>Total 1999 emissions of carbon dioxide, methane and nitrous oxide as estimated in *EIA, Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99), October 2000.

**Table C1. Estimate of the Reliability of 1999 U.S. Emissions Estimates (Tier 1 Method)**

Greenhouse Gas Source	Share of Total Emissions	Activity Data			Emissions Factor			Weighted by Total Emissions	
		Bias		Random	Bias		Random	Min	Max
		Min	Max		Min	Max			
Percent of Source								Percent of Total	
<b>Carbon Dioxide</b>									
Petroleum	35.2%	2.1%	2.4%	0.5%	1.7%	1.7%	0.5%	1.0%	1.1%
Coal	29.9%	0.6%	4.3%	0.6%	1.0%	1.0%	0.5%	0.4%	1.4%
Natural Gas	17.2%	0.5%	2.8%	0.5%	0.0%	0.0%	0.4%	0.1%	0.5%
Other	0.6%	-9.3%	7.8%	11.1%	23.3%	23.3%	4.4%	0.2%	0.2%
Missing Sources	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%
<b>Total</b>	<b>82.9%</b>	<b>1.1%</b>	<b>3.7%</b>	<b>0.6%</b>	<b>1.2%</b>	<b>1.2%</b>	<b>0.5%</b>	<b>1.7%</b>	<b>3.5%</b>
<b>Methane</b>									
Energy-Related	3.2%	13.2%	14.0%	4.9%	20.8%	25.0%	4.5%	0.8%	0.9%
Agricultural	2.8%	3.1%	5.0%	3.0%	36.4%	36.4%	10.6%	1.1%	1.1%
Industrial & Waste	3.2%	9.7%	29.4%	5.0%	50.5%	13.8%	10.1%	1.6%	1.1%
Missing Sources	0.0%	0.0%	4.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
<b>Total</b>	<b>9.2%</b>	<b>8.9%</b>	<b>20.6%</b>	<b>4.3%</b>	<b>35.9%</b>	<b>24.6%</b>	<b>8.3%</b>	<b>3.5%</b>	<b>3.1%</b>
<b>Nitrous Oxide</b>									
Energy-Related	1.3%	0.5%	2.8%	0.5%	55.0%	200.0%	10.0%	0.7%	2.5%
Agricultural	4.1%	4.0%	5.0%	4.5%	90.0%	100.0%	10.0%	3.7%	4.1%
Industrial & Waste	0.4%	2.8%	5.0%	3.5%	55.0%	200.0%	10.0%	0.1%	0.5%
Missing Sources	0.0%	0.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.5%
<b>Total</b>	<b>5.7%</b>	<b>3.1%</b>	<b>19.5%</b>	<b>3.5%</b>	<b>80.0%</b>	<b>128.5%</b>	<b>10.0%</b>	<b>6.5%</b>	<b>7.5%</b>
<b>HFCs, PFCs, SF6</b>									
HFCs, PFCs, SF6	2.2%	4.5%	2.4%	0.9%	13.8%	15.5%	2.5%	0.5%	0.6%
Missing Sources	0%	0.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
<b>Total</b>	<b>2.2%</b>	<b>4.5%</b>	<b>12.4%</b>	<b>0.9%</b>	<b>13.8%</b>	<b>15.5%</b>	<b>2.5%</b>	<b>0.5%</b>	<b>0.6%</b>
<b>Total-All Sources</b>	<b>100.0%</b>	<b>2.0%</b>	<b>6.4%</b>	<b>1.1%</b>	<b>9.2%</b>	<b>11.0%</b>	<b>1.8%</b>	<b>13.2%</b>	<b>12.9%</b>

Notes: The "low" and "high" bias errors provide a subjective estimate of the largest bias error lower or higher than the current point estimate that would be consistent with current understanding of the nature of the activity or emissions mechanism. Each value is calculated as the weighted average of the uncertainties associated with a group of sources in each category. It is calculated as a percentage of the point estimate of emissions from that source. "Random error" is a subjective estimate of the largest random error that is consistent with current understanding of the nature of the activity or emissions estimate. "Weighted uncertainty" is calculated as the square root of the sum of the squared activity factor and emissions factor errors and then multiplied by the point estimate of the share of total emissions for the source. It is calculated as a percentage of the point estimate of total 1997 U.S. emissions.

Source: Estimates prepared for *Emissions of Greenhouse Gases In the United States 1997*.

The different sources of error, as noted above, can produce random or systematic ("bias") errors. Random errors have the appearance of "noise" in the estimate, causing random year-to-year changes in the estimate as compared with (unobservable) actual emissions. Random errors might be caused by data collection and computation errors, the inherent imprecision of metering and measurement, and timing problems. Thus, it should be difficult to distinguish the "signal" of growing or declining emissions until the magnitude of the trend exceeds the "noise" from the random fluctuations. Since, in the case of U.S. energy data, rather small trends in the underlying data can be detected, it is likely that the aggregate magnitude of random errors in U.S. energy data is small, and, in particular, smaller than bias errors.

Bias errors will produce an error of approximately the same magnitude every year. If bias errors are small, they are not likely to affect the estimates of trends. Excluded sources and changes in definition produce bias errors. "Double counting" in activity data surveys will produce upwardly biased estimates of the activity; frame errors or other forms of undercounting will produce estimates that are biased downward. Because EIA, like other statistical agencies, produces data by approximately the same methods every year, double counting and undercounting errors are likely to persist over time.

There is no reason to believe that the distribution of bias errors is symmetrical around the point estimate of the value. In fact, *a priori* or independently gathered information may indicate that the potential size and probability of the existence of bias errors may be skewed: for example, in EIA data it is likely that essentially all the transactions reported to EIA actually occurred; however, it is possible that some transactions were never reported. Thus, EIA energy data are more likely to underestimate than to overestimate actual energy consumption. Further, because there are multiple surveys of energy production and consumption, undertaken for multiple purposes, the results of the surveys can help put bounds on the extent of possible bias errors.

Bias errors can be hard to detect, and it is hard to prove either the presence or absence of bias errors. The best ways of detecting them are to use multiple methods of estimating the source series and compare the results, or to determine the range of possible values from *a priori* information. Comparison methods usually can establish “ceilings” and “floors” for bias errors: that is, it is possible to demonstrate that if the bias error exceeded a certain percent, then a separate, independently collected series must also have a bias error of the same sign. An investigation of how the data are collected may also uncover information about the magnitude or scale of potential bias errors.

The reliability of emissions data varies by category and by source. In general, estimates of carbon dioxide emissions are more reliable than estimates for other gases. It is likely that the estimate of carbon dioxide emissions is accurate to within 5 percent. Estimates of methane emissions are much more uncertain. The level of uncertainty may exceed 30 percent. Estimates of methane emissions are also likely to understate actual emissions, as a result of the exclusion of sources that are unknown or difficult to quantify such as abandoned coal mines or industrial wastewater. Nitrous oxide emissions estimates are much more unreliable than carbon dioxide or methane emissions estimates, in part because nitrous oxide emissions have been studied far less than emissions from other sources and in part because the largest apparent sources of nitrous oxide emissions are area sources that result from biological activity, which makes for emissions that are highly variable and hard to measure or characterize. The uncertainty for nitrous oxide emissions may exceed 100 percent.

## Tier 2 Analysis of Uncertainty in Greenhouse Gas Emissions

In order to carry out a Monte Carlo analysis, estimates of minimum, maximum and random bias in emission factors and activity data must be established. Table C2 shows the estimated bias and random uncertainties in activity data and emissions factors for carbon dioxide, methane and nitrous oxide delineated by fuel type and activity that was used in the Monte Carlo analysis. For petroleum, the activity data are divided into the following sectors: residential, commercial, and transportation (R,C,T); industrial; electric utility; and non-fuel use. For coal emissions, the division is between electric utility and other sectors (industrial combined with residential, commercial, and transportation). For natural gas emissions the division is the same as those for coal with the addition of flared gas. Methane and nitrous oxide emissions are divided by source categories. For each source category, bias and random errors are combined by assuming an aggregate emission factor and a single scaling factor for activity data.

Because the underlying data are obtained from various EIA surveys, they have different levels of associated uncertainty. For example, the maximum bias error for coal activity associated with electric utilities is estimated to be 4 percent, whereas the maximum bias error for coal activity associated with the other sectors is estimated to be 7 percent. This is because fuel use among the reporting electric power generators is relatively well known, but for the other sectors (especially residential and commercial) the data are less reliable.

Monte Carlo simulations were carried out for each greenhouse gas separately, as well as all greenhouse gases as a group. As such, each column of the Table C3 denotes a separate simulation. Uncertainty about the simulated mean varies by type of gas. There is less uncertainty around the carbon dioxide simulated mean (-1.4% to 1.3%) than methane (-15.6% to 16%) or nitrous oxide (-53.5% to 54.2%). If uncertainty is expressed as a percentage of estimated 1999 emissions, the uncertainty becomes more skewed in the positive direction. This follows from the bias error assumptions above that generally assume that emissions are underestimated. Denominating uncertainty as a percentage of estimated 1999 emissions yields the following uncertainty bands: carbon dioxide (-0.7% to 2.0%), methane (-2.8% to 33.7%) and nitrous oxide (-35.1% to 115.3%). If these uncertainty bands are expressed as a percentage of total estimated 1999 emissions<sup>5</sup>, the following uncertainty bands are derived: carbon dioxide (-0.6% to 1.7%), methane (-0.3% to 3.4%) and nitrous oxide (-1.9% to 6.3%). The final column in the table shows the Monte

<sup>5</sup>Total 1999 emissions of carbon dioxide, methane and nitrous oxide as estimated in *EIA, Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99), October 2000.

Carlo results when all the gases are simulated together. This simulations shows that total uncertainty about the simulated mean is -4.4% to 4.6 percent. Expressed as a percentage of total emissions, the uncertainty is -0.4 to 9.0 percent.

**Table C2. Random and Bias Uncertainties Associated with 1999 Inventory Data**

Source Category	Activity Data Uncertainty			Emission Factor Uncertainty		
	BIAS (Uniform)		Random	BIAS (Uniform)		Random
	Min <sup>a</sup>	Max <sup>b</sup>	Mean	Min <sup>a</sup>	Max <sup>b</sup>	Mean
<b>Carbon Dioxide</b>						
<b>NATURAL GAS</b>						
Other Sectors (R,C,I,T)	0.5%	3.0%	0.5%	0.0%	0.0%	0.4%
Electric Utility	0.5%	2.0%	0.5%	0.0%	0.0%	0.4%
Flared	10.0%	25.0%	2.0%	10.0%	10.0%	5.0%
<b>COAL</b>						
Other Sectors (R,C,I,T)	1.00%	7%	0.70%	1%	1%	0.5%
Electric Utility	0.50%	4%	0.60%	1%	1%	0.5%
<b>PETROLEUM</b>						
R,C,T Sectors	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
Industrial	2.0%	3.0%	0.6%	4.0%	4.0%	0.6%
Electric Utility [Heavy Oil,Light Oil,Petroleum Coke]	0.5%	2.0%	0.5%	3.0%	3.0%	0.6%
Non-Fuel Use	1.0%	4.0%	0.6%	3.0%	3.0%	0.6%
<b>U.S. TERRITORIES</b>	5.0%	10.0%	5.0%	1.0%	1.0%	0.5%
<b>CO2 IN NATURAL GAS</b>	5.0%	5.0%	5.0%	30.0%	30.0%	5.0%
<b>BUNKERS</b>	10.0%	10.0%	0.2%	1.0%	1.0%	2.0%
<b>CEMENT</b>	2.0%	4.0%	1.0%	3.0%	3.0%	1.0%
<b>OTHERS INDUSTRIAL SOURCES</b>	5.0%	10.0%	3.0%	5.0%	5.0%	5.0%
<b>Methane</b>						
<b>COAL</b>						
Underground Coal Mines-Very "Gassy"	5.0%	10.0%	20.0%	0.0%	0.0%	0.0%
Degasification & Underground Mines	5.0%	10.0%	20.0%	35.0%	25.0%	5.0%
Surface Mines & Post-mining Emissions	10.0%	10.0%	10.0%	40.0%	100.0%	10.0%
<b>OIL AND GAS SYSTEMS</b>						
Natural Gas Systems	3%	5%	3%	40%	40%	5%
Petroleum Systems	3%	5%	3%	50.0%	60.0%	5.0%
<b>COMBUSTION</b>						
R&C Wood	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary & Mobile Combustion	0.5%	2.8%	0.5%	30.0%	30.0%	15.0%
<b>WASTE HANDLING</b>						
Landfills - Recovery Systems. (Modeled)	5.0%	20.0%	10.0%	25.0%	25.0%	10.0%
Landfills - Recovery Systems in Place (1992)	10.0%	10.0%	7.0%	0.0%	0.0%	0.0%
Landfills no Recovery Systems	10.0%	30.0%	5.0%	50.0%	10.0%	10.0%
Wastewater Systems	0.0%	3.0%	5.0%	55.0%	200.0%	10.0%
<b>AGRICULTURAL SOURCES</b>						
Livestock - Enteric Fermentation	3.0%	5.0%	3.0%	10.0%	10.0%	10.0%
Livestock Waste	3.0%	5.0%	3.0%	30.0%	40.0%	10.0%
Rice	5.0%	5.0%	3.0%	60.0%	60.0%	20.0%
Crop Residues	5.0%	5.0%	3.0%	60.0%	60.0%	20.0%
<b>INDUSTRIAL PROCESSES</b>						
Chemicals and Steel & Iron	3.00%	5%	3.00%	60%	60%	10.0%
<b>Nitrous Oxide</b>						
<b>AGRICULTURAL SOURCES</b>						
Nitrogen Fertilization	5.0%	10.0%	5.0%	90.0%	200.0%	10.0%
Animal Waste	3.0%	5.0%	3.0%	90.0%	100.0%	10.0%
Crop Residues	5.0%	10.0%	3.0%	60.0%	60.0%	20.0%
<b>ENERGY COMBUSTION</b>						
R&C Wood	10.0%	30.0%	5.0%	90.0%	200.0%	15.0%
Other Stationary Combustion	0.5%	2.8%	0.5%	55.0%	200.0%	10.0%
Waste Combustion	30.0%	30.0%	10.0%	90.0%	200.0%	15.0%
Mobile Sources	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
<b>WASTE MANAGEMENT</b>	2.0%	5.0%	5.0%	55.0%	200.0%	10.0%
<b>INDUSTRIAL PROCESSES</b>	10.0%	10.0%	3.0%	55.0%	200.0%	10.0%

a: The minimum bias is the relative change below the mean value.

b: The maximum bias is the relative change above the mean value.

Key: R,C,T, I: Residential, Commercial, Transportation, and Industrial; GHG: Greenhouse Gases.

Source: EIA-DOE annual data for 1999. Inventory Database.

**Table C3. Preliminary Results of the Tier 2 Monte Carlo Uncertainty Analysis of EIA's Reported Greenhouse Gas Inventory Data, 1999**

Based on 1999 Data (Million Metric Tons of Carbon Equivalent, MMTCe)

	Carbon Dioxide	Methane	Nitrous Oxide	Total
Estimated 1999 Value	1526.8	180.7	98.8	1806.3
Monte Carlo Simulated 1999 Mean	1536.4	208.2	138.0	1882.2
5th Percentile	1515.5	175.6	64.2	1799.5
95th Percentile	1556.8	241.5	212.8	1969.6
Total Uncertainty Around Simulated Mean	41.3	65.9	148.6	170.1
Uncertainty as Percent of Simulated Mean	-1.4% to 1.3%	-15.6% to 16.0%	-53.5% to 54.2%	-4.4% to 4.6%
Uncertainty as Percent of Estimated Value	-0.7% to 2.0%	-2.6% to 33.7%	-35.1% to 115.3%	-0.4% to 9.0%
Uncertainty as Percent of Total Estimated Emissions	-0.6% to 1.7%	-0.3% to 3.4%	-1.9% to 6.3%	-0.4% to 9.0%

<sup>a</sup>Estimated 1999 emissions from EIA, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99), October 2000.

<sup>b</sup>Monte Carlo simulations using 1999 EIA data from Science Applications International Corporation, prepared for the Energy Information Administration, Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emissions and Related Support Work, May 2001.

<sup>c</sup>Expressed as a percentage of total carbon dioxide, methane and nitrous oxide emissions in 1999. Note, that this excludes HFC, PFC and SF6 emissions as these were not included in the uncertainty analysis.

<sup>d</sup>Note that, with the exception of estimated 1999 values, rows will not sum to total because each individual row denotes a separate simulation. Monte Carlo simulations were carried out for each pollutant separately, as well as a group.

## Uncertainty of Carbon Coefficients Used in This Report

Because carbon dioxide emissions are such a large component of total greenhouse gas emissions, EIA has undertaken a review and update of the carbon coefficients for fossil fuels that when combined with combustion factors produce the emission factor for that fuel. A discussion of the uncertainty inherent in those factors is presented below.

### Coal

Carbon coefficients for coal vary considerably by rank and state. Bituminous coal production and sub-bituminous coal production represented 53.4 percent and 38.1 percent of total U.S. supply in 2000, respectively. Carbon coefficients for bituminous coal vary from a low of 200.5 pounds carbon dioxide per million Btu in Kansas to a high of 232.0 pounds carbon dioxide per million Btu in Montana. In 2000, however, just 200 tons of bituminous coal were produced in Kansas and none were produced in Montana. In 2000, more than 60 percent of bituminous coal was produced in three states: West Virginia, Kentucky and Pennsylvania, and this share has remained fairly constant since 1990. These three states show a variation in carbon content for bituminous coals of  $\pm 0.7\%$  that is based on more than 2,000 samples (See Table C4).

Similarly, the carbon coefficients for sub-bituminous coals range from 201.3 pounds carbon dioxide per million Btu in Utah to 217.5 pounds carbon dioxide per million Btu in Washington. Utah showed no sub-bituminous production in 2000 and Washington just 4,000 tons. Wyoming, however, has represented between 75 percent and 82 percent of total sub-bituminous coal production in the United States since 1990. Thus, the carbon content coefficient for Wyoming, based on 435 samples, dominates. The interquartile range of carbon content coefficients among samples of sub-bituminous coal in Wyoming was  $\pm 1.5\%$  from the mean. Similarly this range among samples of bituminous coal from West Virginia, Kentucky, and Pennsylvania was  $\pm 1.0\%$  or less for each State. The large number of samples and the low variability within the sample set of the states that represent the predominant source of supply for U.S. coals suggest that the uncertainty in this factor is very low, on the order of  $\pm 1.0\%$ .

**Table C4. Variability in Carbon Content Coefficients by Rank Across States**  
(Pounds Carbon Dioxide Per Million Btu)

State	Number of Samples	Bituminous	Sub-bituminous	Anthracite	Lignite
Alabama	946	204.7	-	-	218.5
Alaska	90	216.8	216.3	-	217.5
Arizona	11	-	215.0	-	-
Arkansas	70	212.8	-	-	209.4
Colorado	292	208.1	212.7	-	212.7
Georgia	35	209.5	-	-	-
Idaho	1	-	209.2	-	-
Illinois	16	205.8	-	-	-
Indiana	125	204.3	-	-	-
Iowa	89	202.7	-	-	-
Kansas	28	200.5	-	-	-
Kentucky	870	204.1	-	-	-
Louisiana	1	-	-	-	211.7
Maryland	46	208.0	-	-	-
Massachusetts	3	-	-	253.1	-
Michigan	3	204.7	-	-	-
Mississippi	8	-	-	-	216.5
Missouri	91	202.5	-	-	-
Montana	301	232.0	215.5	228.4	219.1
Nevada	2	208.1	-	-	220.1
New Mexico	167	210.0	209.2	229.1	-
North Dakota	186	-	-	-	219.5
Ohio	646	202.5	-	-	-
Oklahoma	46	204.3	-	-	-
Pennsylvania	739	205.9	-	228.5	-
Tennessee	58	204.6	-	-	-
Texas	48	-	-	-	208.9
Utah	152	211.8	201.3	-	-
Virginia	456	206.2	-	217.2	-
Washington	14	210.3	217.5	226.0	234.9
West Virginia	566	207.0	-	-	-
Wyoming	476	208.7	214.3	-	-

- (No Sample Data Available)

Source: U.S. Geological Survey, CoalQual Database Version 2.0 (1998) and analysis prepared by Science Applications International Corporation (SAIC) for the U.S. Environmental Protection Agency, Office of Air and Radiation, Market Policies Branch, October 2002.

## Natural Gas

### Pipeline-Quality

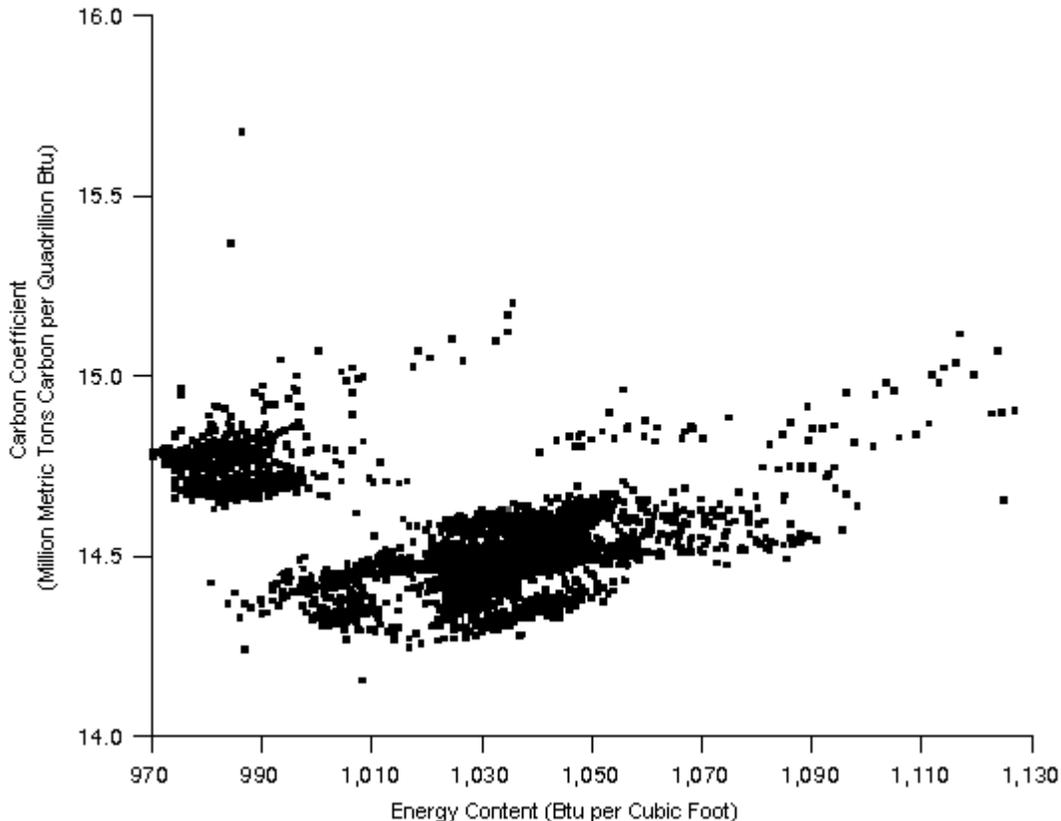
The EIA examined the composition of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 States. Figure C1 shows the relationship between the calculated carbon coefficient for each natural gas sample and its energy content. This figure illustrates the relatively restricted range of variation in both the energy content (which varies by about 6 percent from average) and the carbon coefficient of natural gas (which varies by about 5 percent). Thus, the knowledge that gas has been sold via pipeline to an end use consumer allows us to predict its carbon coefficient with an accuracy of  $\pm 5.0\%$ .

Natural gas suppliers may achieve the same energy contents with a wide variety of methane, higher hydrocarbon, and non-hydrocarbon gas combinations. Thus, the plot reveals large variations in carbon content for a single Btu value. In fact, the variation in carbon content for a single Btu value may be nearly as great as the variation for the whole sample. As a result, while energy content has some predictive value, the specific energy content does not substantially improve the accuracy of an estimated carbon content coefficient beyond the  $\pm 5.0\%$  offered with the knowledge that it is of pipeline-quality.

The plot of carbon content also reveals other interesting anomalies. The samples with the lowest emissions coefficients tend to have energy contents of about 1,000 Btu per cubic foot. They are composed of almost pure methane. Samples with a greater proportion of natural gas liquids (NGLs) (e.g., ethane, propane, and butane) tend

to have energy contents greater than 1,000 Btu per cubic foot, along with higher emissions coefficients. Samples with a greater proportion of inert gases tend to have lower energy content, but they usually contain carbon dioxide as one of the inert gases and, consequently, also tend to have higher emissions coefficients (see left side of Figure C1).

**Figure C1. Carbon Content for Samples of Pipeline-Quality Natural Gas Included in the Gas Technology Institute (Formerly Gas Research Institute) Database**



Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA 0573, Appendix A (Washington, DC, November, 1994)

For the full sample (N=6,743), the average carbon content of a cubic foot of gas was 14.51 million metric tons per quadrillion Btu. However, this average was raised by both the samples with less than 1,000 Btu per cubic foot that contained large amounts of inert carbon dioxide and those samples with more than 1,050 Btu per cubic foot that contain an unusually large amount of NGLs. Because typical gas consumed in the U.S. does not contain such a large amount of carbon dioxide or natural gas liquids, a weighted national average of 14.47 million metric tons per quadrillion Btu that represents fuels more typically consumed is used.<sup>6</sup>

## Flare Gas

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

- There may be no market for some natural gas associated with oil wells, as the amount may be too small or too variable, or the quality might be too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of carbon dioxide). All natural gas flared for these reasons is probably "rich" associated gas, with relatively high energy content, high NGL content, and a high carbon content.

<sup>6</sup>The national average was weighted by applying the carbon content associated with the average heat content of natural gas consumed in each state by the portion of national natural gas consumption represented by that state.

- Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

Data on the energy content of flare gas, as reported by states to EIA, indicates an energy content of 1,130 Btu per standard cubic foot. Flare gas may have a higher energy content than reported by EIA because rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot. Rich associated gas will have a much higher proportion of natural gas liquids than pipeline natural gas. The most common NGLs are ethane (C<sub>2</sub>H<sub>6</sub>), propane (C<sub>3</sub>H<sub>8</sub>), butane (C<sub>4</sub>H<sub>10</sub>), and, to a lesser extent, pentane (C<sub>5</sub>H<sub>12</sub>) and hexane (C<sub>6</sub>H<sub>14</sub>). Because the NGLs have more carbon atoms than methane (which has only one) their presence increases the overall carbon content of natural gas. Hexane is 83.7 percent carbon compared to the 75 percent carbon share found in methane.

Another important source of uncertainty associated with the carbon coefficient for flare gas is the definition of flare gas as reported to EIA by the States. EIA collects data on natural gas vented and flared without a clear distinction between gas flared and gas vented. For the purposes of this report all gas reported to EIA as vented or flared is assumed to be flared. Further, States may report a broad array of gases under the vented and flared category, some of which, such as hydrogen sulfide, are quite different in composition from the natural gas samples used for deriving the carbon coefficient adopted for this report. In some States, carbon dioxide that is vented is reported as vented and flared and its contribution to overall national emissions is not accurately reflected by treating it as combusted natural gas. Thus, there is a wide band of uncertainty associated with the carbon coefficient for flared natural gas.

## Petroleum

### Motor Gasoline and Motor Gasoline Blending Components

There are two primary contributors to the uncertainty of carbon coefficients for motor gasoline. The first is the small number of motor gasoline samples and ultimate analyses from the work by Mark DeLuchi.<sup>7</sup> However, the amount of variation in carbon content of gasoline is restricted by the compounds in the fuel to  $\pm 4\%$ . The second primary contributor to uncertainty is the assumed heat content. The heat contents are industry standards established many years ago. The heat contents are standard conversion factors used by EIA to convert volumetric energy data to energy units. Because the heat contents of fuels change over time, without necessarily and directly altering their volume, the conversion of known volumetric data to energy units may introduce bias. Thus, a more precise approach to estimating emissions factors would be to calculate carbon content per unit of volume, rather than per unit of energy. Adopting this approach, however, makes it difficult to compare U.S. carbon coefficients with those of other nations. The changes in density of motor gasoline over the last decade suggest that the heat content of the fuels is also changing. However, that change within any season grade has been less than 1% over the decade. Of greater concern is the use of a standardized heat content across grades which show a variation in density of  $\pm 1.5\%$ .

### Jet Fuel

Variability in jet fuel is relatively small with the average carbon share of kerosene-based jet fuel varying by less than  $\pm 1\%$  and the density varying by  $\pm 1\%$ . This is because jet fuel is used to transport passengers long distances on commercial airliners. The ratio of fuel mass to useful energy must be tightly bounded to maximize safety and range. There is more uncertainty associated with the density and carbon share of naphtha-based jet fuel because sample data were unavailable and default values were used. This uncertainty has only a small impact on the overall uncertainty of the carbon coefficient for jet fuels, however, because naphtha-based jet fuel represents a small and declining share of total jet fuel consumption in the United States.

### Distillate Fuel

The primary source of uncertainty for the estimated carbon coefficient of distillate fuel is the selection of No.2 fuel oil as the typical distillate fuel. No.2 fuel oil is generally consumed for home heating. No.1 fuel oil is generally less dense and if it is consumed in large portions for mobile sources, the carbon content estimated for this report is likely to be too high. The five No.1 fuel oil samples obtained by EIA contained an average of 86.01 percent carbon

<sup>7</sup> DeLuchi, Mark, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, Volume 2, ANL/ESD/TM-22, Vol. 2 (Chicago, IL: Argonne National Laboratory, November 1993).

compared to the 86.34 percent contained in samples of No.2 fuel oil. A carbon coefficient based on No.1 fuel oil would equal 19.72 million metric tons per quadrillion Btu rather than the 19.95 million metric tons per quadrillion Btu for No.2 fuel oil. There is also small uncertainty in the share of carbon based on the limited sample size of  $\pm 1$  percent.

## Residual Fuel

The largest source of uncertainty for estimating the carbon coefficient of residual fuel centers on the estimates of density, which differ from power generation to marine vessel fuels. The difference between the density implied by the energy content of electric power sector fuels and the density observed in the NIPER surveys is probably due to nonsulfur impurities, which reduce the energy content without greatly affecting the density of the product. Impurities of several percent are commonly observed in residual oil. The presence of these impurities also affects the share of the fuel that is carbon. Overall, the uncertainty associated with the carbon coefficient of residual fuel is probably  $\pm 1$ %.

## Liquefied Petroleum Gases

Because LPG consists of pure paraffinic compounds whose density, heat content and carbon share are physical constants, there is limited uncertainty associated with the carbon coefficient for this petroleum product. Overall uncertainty is derived mainly from the collection of consumption data and non-fuel data in U.S. energy statistics. This uncertainty is probably less than  $\pm 3$ %.

## Aviation Gasoline

The uncertainty associated with the carbon content coefficient for aviation gasoline is larger than that for other liquid petroleum products examined because no ultimate analyses of samples were conducted. However, given the requirements for safe operation of piston-powered aircraft the composition of aviation gas is well bounded and the uncertainty of the carbon coefficient is likely to be  $\pm 5$ %.

## Still Gas

Because the composition of still gas is highly heterogeneous, the carbon coefficient for this product is highly uncertain, with an accuracy of  $\pm 33$ %. The carbon coefficient used for this report is probably at the high end of the plausible range.

## Asphalt

The share of carbon in asphalts ranges somewhat broadly from 79 percent to 88 percent by weight with the remainder of the mixture also being variable; hydrogen shares vary by weight from seven to 13 percent and sulfur shares vary from trace levels to eight percent. Because carbon share and total heat content in asphalts do vary systematically, the overall carbon coefficient is likely to be accurate to  $\pm 5$ %.

## Lubricants

Uncertainty in the estimated carbon coefficient for lubricants is driven by the large range of product compositions and end uses in this category combined with an inability to establish the shares of the various products captured under this category in U.S. energy statistics. Because lubricants may be produced from either the distillate or residual fractions during refining, the possible carbon content coefficients range from just under 20.0 million metric tons per quadrillion Btu to about 21.5 million metric tons per quadrillion Btu, or an uncertainty band from  $-1$ % to  $+6$ % of the estimated value.

## Petrochemical Feedstocks

Petrochemical feedstocks are not so much distinguished on the basis of chemical composition as on the identity of the purchaser, who may be presumed to be a chemical company or petrochemical unit co-located on the refinery grounds. This produces a considerable degree of uncertainty about the exact composition of petrochemical feedstocks. Since the carbon coefficient for petrochemical feedstocks is a weighted average of the coefficients for

naphtha and some class of middle distillates, the accurate coefficient is likely bounded by the two individual coefficients suggesting an uncertainty of  $\pm 6\%$ .

## **Kerosene**

Uncertainty in the estimated carbon coefficient for kerosene is driven by the selection of No. 1 fuel oil as a proxy for kerosene. If kerosene is more like kerosene-based jet fuel, the true carbon coefficient is likely to be some 2 percent lower. If kerosene is more aptly compared to No. 2 fuel oil, then the true carbon content coefficient is likely to be about 1 percent higher.

## **Petroleum Coke**

The uncertainty associated with the estimated carbon coefficient of petroleum coke can be traced to two factors: the use of only two samples to establish carbon contents and a standard heat content which may be too low. Together, these uncertainties are likely to bias the carbon coefficient upwards by as much as 6 percent.

## **Special Naphtha**

The principal uncertainty associated with the estimated carbon coefficient for special naphtha is the allocation of overall consumption across individual solvents. The overall uncertainty is bounded on the low end by the carbon content of hexane and on the upper end by the carbon content of high solvency mineral spirits. This implies an uncertainty band of  $-15$  percent to  $+6$  percent.

## **Petroleum Waxes**

Although there is considerable qualitative uncertainty associated with the allocation of petroleum waxes and microcrystalline waxes, the quantitative variation in the carbon contents for all waxes is limited to  $\pm 1\%$  because of the nearly uniform relationship between carbon and other elements in petroleum waxes broadly defined.

## **Crude Oil, Unfinished Oils and Miscellaneous**

The uncertainty of the estimated carbon content for crude oil centers on the 35 percent of variation that cannot be explained by density and sulfur content. However, as crude is not currently directly consumed in the United States this does not add to the overall uncertainty of the U.S. emissions estimate. Because unfinished oils and miscellaneous products are difficult to define, the uncertainty of applying a crude oil carbon content is likely to be bounded by the range of petroleum products described in this chapter at  $\pm 10\%$ . This has a larger implication for the overall uncertainty of the emissions estimate than does crude oil directly. Miscellaneous products have been relatively stable in recent years with consumption in the range of 100 to 120 trillion Btu. However, in 2001, the volume of unfinished oils was estimated to contain an energy value of 69 trillion Btu, a value that is subtracted from the total supply disposition in order to avoid double counting with finished products. In 2000 this value was about 401 trillion Btu. Because this is a negative number in the energy consumption total, this fluctuation effectively added about one-third a quad of energy to the balance – or 6 million metric tons of carbon equivalent from 2000 to 2001. Therefore, the uncertainty associated with emission coefficients for unfinished oils could contribute to the overall uncertainty of the emissions estimate to a measurable degree.

# Appendix D

## Emissions Sources Excluded

### Overview

Certain sources of emissions of greenhouse and related gasses are not included in the estimates presented in this report. The omissions have been made on the basis of lack of essential data, highly speculative estimation methods, ambiguity of overall climate effect, or classification as “natural” sources.

### Carbon Dioxide

#### Biofuel Combustion

The carbon found in biofuels is the result of atmospheric uptake. During the combustion of biofuels, and the biogenic component of municipal solid waste, there is an immediate release of the carbon in the form of carbon dioxide. Thus, as part of the natural carbon cycle, carbon is reabsorbed over time. Because they produce no net change in the overall carbon budget, such emissions are not included in this report. If the initial flux had been counted, carbon dioxide emissions in 2001 would have been approximately 65 million metric tons of carbon higher than reported in Chapter 2. Table D1, below, delineates biofuel sources excluded.

**Table D1. Carbon Dioxide Emissions from Biofuels Combustion, 1990-2001**  
(Million Metric Tons Carbon)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
Municipal Solid Waste (biogenic only)	6.4	5.1	6.3	5.8	6.3	6.5	6.4	5.5	4.6	5.0	5.4	5.4
Alcohol Fuel	1.6	1.3	1.5	1.7	1.9	2.1	1.5	1.9	2.1	2.2	2.2	2.2
Wood and Wood Waste	58.0	58.1	60.7	58.9	61.1	63.9	65.1	61.7	57.1	58.1	59.3	57.1
<b>Total Biofuels</b>	<b>66.1</b>	<b>64.5</b>	<b>68.6</b>	<b>66.5</b>	<b>69.3</b>	<b>72.4</b>	<b>73.0</b>	<b>69.2</b>	<b>63.9</b>	<b>65.3</b>	<b>67.0</b>	<b>64.7</b>

P=Preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2000*, DOE/EIA-0573(2000) (Washington, DC, November 2001).

Sources: Underlying energy data from Energy Information Administration, Annual Energy Review 2001, DOE/EIA-0384(2001) (Washington, DC, November 2002), pp. 299-300. Emissions coefficients for municipal solid waste combustion and wood and wood waste from Energy Information Administration, Electric Power Annual 1999, Vol. 2, DOE/EIA-0348(99/2) (Washington, DC, October, 2000), Table A-3, p. 123.

Emissions are estimated by multiplying Energy Information Administration (EIA) energy consumption data for biofuels by the applicable emissions factors. Carbon dioxide emissions factors for combustion of wood fuels are taken from the EIA report, *Electric Power Annual 1999*.<sup>1</sup> The emissions coefficient for alcohol fuels, 17.99 million metric tons of carbon per quadrillion Btu, was derived specifically for use in this report.

#### Enhanced Oil Recovery

Carbon dioxide is injected into petroleum reservoirs for the purpose of retrieving additional oil. Over time, the carbon dioxide seeps into the producing well, creating a mixture of oil, natural gas, and carbon dioxide. If the energy content is sufficiently high, the gaseous portion of this mix will probably be sent to a gas plant. If the energy content is low, the gas is likely to be vented or flared. At this time, there is no basis for EIA to estimate the quantity of added carbon dioxide that is vented or flared. EIA believes that most of the carbon dioxide recovered with the oil is re-injected, so that annual emissions are a fraction of the carbon dioxide recovered. The annual amount of carbon dioxide used for enhanced oil recovery is probably on the order of 8 million metric tons,<sup>2</sup> and emissions would be some fraction of that figure. Emissions from this source may be included in future reports if more data become available.

<sup>1</sup>Energy Information Administration, *Electric Power Annual 1999*, Vol. 2, DOE/EIA-0348(99/2) (Washington, DC, October, 2000), Table A3, p. 123.

<sup>2</sup>The U.S. Department of Commerce reports total sales of industrial carbon dioxide in 2000 were approximately 13 million metric tons annually, while past Freedonia Group, Inc. reports have reported that approximately 5 million metric tons are used for purposes other than enhanced oil recovery.

## “Off Spec” Gases

Combustion of “off spec” gases and fuels is not covered as a separate line item in this report, but much of the emissions from this source may be included in the “flaring” category, which is covered in this report, or as industrial consumption of “still gas” by refineries.

## Forest Fires

Forest fires are known to create greenhouse gas fluxes within the atmosphere over extensive time periods. Specifically, forest fires produce carbon dioxide, methane, and nitrous oxide. Considering that carbon uptake occurs with subsequent regrowth (assumed to balance out the initial carbon flux), and because emissions from natural forest fires cannot be distinguished from those from human-induced fires, estimates from this source are not included in this report.

## Unaccounted for Natural Gas

The editions of *Emissions of Greenhouse Gases in the United States* published by EIA before 1997 included an emissions category called “unmetered natural gas.” In those years, U.S. natural gas producers consistently reported selling about 3 percent more natural gas than U.S. consumers reported buying. In EIA natural gas statistics, this “missing” gas is described as “the balancing item” or “unaccounted for gas.” The balancing item can be viewed as the sum of leakage, measurement errors, data collection problems, and undetected over- and underreporting, as well as undetected nonreporting. Only a fraction of this amount can credibly be attributed to leakage from transmission systems.

Estimates of carbon dioxide emissions from this source were included in early reports, on the grounds that there was an element of systematic underreporting of consumption in the balancing item. In 1996 and 1997, however, the sign of the balancing item changed to positive, and in 1998, 1999 and 2000 it was an increasing, negative number. These changes in sign reduce the credibility of the undercounting theory, and consequently this report no longer carries “unmetered natural gas” consumption as a source of emissions. The balancing item does serve as a basis for understanding the uncertainty inherent in natural gas combustion emissions estimates (see Appendix C). It should be noted that if this amount were included, U.S. emissions for 2000 would be about 12 MMTCE higher.

## Fermentation

During the fermentation process, complex organic compounds are decomposed through a variety of chemical reactions. The most common is the anaerobic conversion of sugar into carbon dioxide and alcohol. Fermentation does not create a net flux of emissions, however, because the carbon dioxide produced is of biological origin.

## Lead Smelting

Smelting of lead includes a stage in which limestone undergoes calcination. As described in Chapter 2, carbon dioxide is released as a byproduct of the calcination reaction. Emissions estimates cannot be calculated for this report because there are no known statistics regarding the amount of limestone used in lead smelting. EIA is currently researching alternative data sources in an effort to include estimates of these emissions in future reports.

## Methane

### Industrial Wastewater Treatment

Methane emissions from industrial wastewater treatment are believed to be a function of the volume of wastewater generated, the organic content of the wastewater, and the method used to treat the wastewater. Methane emissions will be much more greater if the wastewater is treated anaerobically (in the absence of oxygen) than if it is treated aerobically. Because data on volumes of wastewater generated by industry and the methods for treating that wastewater are limited, EIA does not present estimates of methane emissions from industrial wastewater. There is anecdotal evidence that very little industrial wastewater is treated anaerobically. Further, when industrial wastewater is treated anaerobically, the methane generated may be flared or recovered for energy use. Thus, 500,000 metric tons is likely to be at the high end of the emissions estimate range.

## Abandoned Coal Mines

The Mine Safety and Health Administration estimate that some 7,500 underground coal mines have been abandoned in the United States since 1970.<sup>3</sup> Measurements taken from 20 abandoned mines showed a total of 25,000 metric tons of emissions.<sup>4</sup> Data gathered from these mines suggest a range in emissions from abandoned mines of 25,000 to 700,000 metric tons.<sup>5</sup> U.S. EPA is currently developing a comprehensive database of abandoned mines in the U.S. This database will include date of abandonment, specific emissions, seam thickness, mine depth, mining method, and ventilation emissions. Upon completion, this data should provide the ability to develop improved estimation methods. Until then, existing estimates are too uncertain to appear in this report.

## Emissions from Wetlands

Wetlands are a known source of methane. Environments low in oxygen, combined with abundant organic matter, are conducive to the creation of methane, and wetlands meet both criteria. Wetlands cover approximately 274 million acres of land in the United States and are a potentially important source of atmospheric methane.

The stock of natural wetlands in the United States has diminished considerably over the past two centuries, which should, in principle, have reduced methane emissions from wetlands (EIA is not aware of research proving or disproving this principle). A recent study of wetland losses concluded that the United States had lost approximately 30 percent of its wetlands between colonial times and the mid-1980s. Almost all of the loss has occurred in the lower 48 States, which have lost 53 percent of their original wetlands.<sup>6</sup> Ten States— Arkansas, California, Connecticut, Illinois, Indiana, Iowa, Kentucky, Maryland, Missouri, and Ohio—have lost 70 percent or more of their original wetland acreage. By the mid-1980s, a total of approximately 119 million acres had been lost from the original U.S. total.

An update of the wetlands study indicates that 654,000 acres were converted from wetlands to other uses between 1982 and 1987, and that an additional 431,000 acres were converted between 1987 and 1991.<sup>7</sup> Extrapolating from these data, it is estimated that wetlands in the United States are currently destroyed at a rate of approximately 86,000 acres per year. Wetlands, also known as swamps and marshes, have historically been drained or filled in for agriculture, land development, and mosquito control, although it is currently illegal to drain or fill a wetland without a permit from the U.S. Army Corps of Engineers. It is difficult to find information on the conversion of other land categories to wetlands. It is assumed that the number and extent of wetland creations is small enough to leave the above loss estimates essentially unchanged.

Estimates of global methane fluxes from wetlands suggest that methane emissions from temperate-zone wetlands are minimal—typically between 5 and 10 million metric tons of methane per year for worldwide temperate-zone wetlands (which include U.S. wetlands)<sup>8</sup>—when compared with estimated global wetlands emissions of 115 to 237 million metric tons.<sup>9</sup> The U.S. share of all temperate-zone wetlands is about 57 percent, and temperate-zone wetlands lost during the 1980s accounted for about 0.5 percent of U.S. wetlands at the beginning of the period. Consequently, the reduction in natural methane emissions from wetlands lost might be on the order of  $0.57 \times 0.005 \times 5$  to 10 million metric tons of methane, or from 10,000 to 20,000 metric tons of methane annually over the decade.

<sup>3</sup>U.S. Environmental Protection Agency, Coalbed Methane Outreach Program, *Draft Analysis of Abandoned Coal Mine Methane Emissions Estimation Methodology* (December 18, 1998)

<sup>4</sup>S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

<sup>5</sup>U.S. Environmental Protection Agency, 1997, *Introductory Analysis of Opportunities to Reduce Methane Emissions from Abandoned Coal Mines*, unpublished internal report.

<sup>6</sup>T. Dahl, U.S. Department of the Interior, Fish and Wildlife Service, *Wetlands Losses in the United States: 1780's to 1980's* (Washington, DC, 1990).

<sup>7</sup>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.

<sup>8</sup>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 (1993), p. 280.

<sup>9</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), Table 4.2, p. 250. See also web site [www.ipcc.ch](http://www.ipcc.ch).

## Nitrous Oxide

### Emissions from Industrial Wastewater

Just as industrial wastewater may contain large volumes of organic matter, so, under certain circumstances, industrial wastewater may be a source of nitrogen, leading ultimately to nitrous oxide emissions. However, the problems associated with estimating methane emissions from industrial wastewater are even more difficult with respect to nitrous oxide emissions from industrial wastewater. The nitrogen content of industrial wastewater is more problematic, and the extent to which bacterial action converts the nitrogen into nitrous oxide (as opposed to molecular nitrogen or nitrogen oxides) is more uncertain.

### Land Use Changes Affecting Methane and Nitrous Oxide

The scientific literature suggests that both grasslands and forest lands are weak natural sinks for methane and weak natural sources for nitrous oxide. Natural soils apparently serve as methane sinks: well-aerated soils contain a class of bacteria called “methanotrophs” that use methane as food and oxidize it into carbon dioxide. Experiments indicate that cultivation reduces methane uptake by soils and increases nitrous oxide emissions.

One report indicates that methane uptake in temperate evergreen and deciduous forests in the United States ranges from 0.19 to 3.17 milligrams (measured in carbon units) per square meter per day, equivalent to the uptake of 36.8 to 624.4 metric tons of methane per million acres per year. The range is larger for agricultural lands: 0.2 to 6.3 milligrams per square meter per day. Estimates for methane uptake resulting from the abandonment of farmland range from 0.6 to 6.1 milligrams per square meter per day. While all of these ranges are wide, the total amount of methane in question is less than 1 percent of methane emissions from anthropogenic sources.

Of all the greenhouse gases discussed in this report, the least amount of data is available for nitrous oxide. It is known that conversion of forests and grasslands to cropland accelerates nitrogen cycling and increases nitrous oxide emissions from the soil. It is not known with certainty by how much.<sup>10</sup> Some estimates have been made of the difference between fertilized and unfertilized soils. According to one study, unfertilized soils produce emissions of 0.25 to 0.35 milligrams (measured in nitrogen units) per square meter per day, while emissions from fertilized soils range from 0.6 to 1.65 milligrams per square meter per day.<sup>11</sup> Thus, abandoning fertilization should reduce nitrous oxide emissions by 0.35 to 1.3 milligrams per square meter per day—the equivalent of 86 to 321 metric tons of nitrous oxide per million acres per year.

Applying this figure to the 35 million acres of cropland idled between 1982 and 1992 implies a reduction in nitrous oxide emissions ranging from 3,010 to 11,235 metric tons annually. In principle, however, about three-quarters of the reduction in emissions from this source should be captured by reduced application of nitrogen fertilizers; thus, reporting emissions reductions using this method would result in significant double counting of units already included in the agriculture statistics in Chapter 4.

If such estimates are to be applied to emissions inventories, a problem of crediting the uptakes applies. Removing an acre of farmland from production in a particular year creates a *permanent* annual methane sink that will absorb small additional amounts of methane each year thereafter, or at least until the use of the land changes. The method that should be used to credit such permanent reductions to a particular year is not obvious.

### Ozone-Depleting Substances and Criteria Pollutants

The impact of ozone-depleting substances on global climate is ambiguous, because they have indirect effects that tend to offset their direct warming effects. Furthermore these manufactured substances are being phased out pursuant to the Montreal Protocol. They are not included among the greenhouse gases to be controlled under the Kyoto Protocol. Emissions estimates for chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), bromofluorocarbons (halons), and other ozone-depleting gases are excluded from the main body of this report. However, emissions estimates for these substances are presented in this appendix, in Table D2.

<sup>10</sup> See A. Mosier, “Nitrous Oxide Emissions From Agricultural Soils,” paper presented at RIVM International Workshop on Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control (Amersfoort, The Netherlands, February 3-5, 1993).

<sup>11</sup> A. Mosier and D. Schimel, “Influence of Agricultural Nitrogen on Atmospheric Methane and Nitrous Oxide,” *Chemistry & Industry*, Vol. 2 (December 1991), p. 875.

**Table D2. Estimated U.S. Emissions of Ozone-Depleting Substances, 1990-2001**  
(Thousand Metric Tons)

Item	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	P2001
<b>CFCs</b>												
CFC-11	53.5	48.3	45.1	45.4	36.6	36.2	26.6	25.1	24.9	24.0	22.8	22.8
CFC-12	112.6	103.5	80.5	79.3	57.6	51.8	35.5	23.1	21.0	14.0	17.2	21.3
CFC-113	52.7	41.1	34.2	34.2	17.1	17.1	*	*	*	*	*	*
Other CFCs	2.3	1.5	*	*	*	*	*	*	*	*	*	*
<b>Halons</b>	2.8	2.9	2.7	2.8	2.4	2.5	2.5	2.4	2.4	2.4	2.4	2.3
<b>HCFCs</b>												
HCFC-22	34.0	35.4	35.2	35.3	37.7	39.3	41.0	42.4	43.8	74.1	79.1	80.5
HCFC-141b	0.8	1.4	1.9	2.6	3.3	3.6	4.0	4.3	4.7	5.0	5.4	5.8
HCFC-142b	1.3	1.7	1.7	2.9	6.2	9.9	9.9	8.8	9.7	10.9	10.9	10.7
Other HCFCs	*	*	*	3.0	5.8	6.3	6.7	7.1	7.4	7.6	7.7	7.7
<b>Other Chemicals</b>												
Carbon Tetrachloride	32.3	27.0	21.7	18.6	15.5	4.7	*	*	*	*	*	*
Methyl Chloroform	316.6	309.4	216.6	185.7	154.7	92.8	*	*	*	*	*	*

\*Less than 50 metric tons of gas.

P=Preliminary data.

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, web site [www.epa.gov/globalwarming/](http://www.epa.gov/globalwarming/).

Similarly, carbon monoxide, nitrogen oxides, and non-methane volatile organic compounds are excluded from the Kyoto Protocol and from the main body of this report. These gases, termed "criteria pollutants" because they are regulated based on health criteria, have an indirect effect on global climate due to their effect on atmospheric concentrations of greenhouse gases (including carbon dioxide, methane, and ozone). Emission estimates for criteria pollutants are provided in Table D3.

**Table D3. U.S. Emissions of Criteria Pollutants, 1990-2001**  
(Million Metric Tons of Gas)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Carbon Monoxide	89.3	91.7	89.2	89.8	93.4	84.6	94.1	94.9	91.0	91.8	98.1	NA
Nitrogen Oxides	21.8	21.9	22.3	22.6	22.9	22.5	23.1	23.3	23.0	22.4	21.9	NA
Nonmethane VOCs	19.1	19.3	18.9	19.1	19.7	19.0	18.0	18.4	17.5	17.6	18.5	NA

Note: Revised.

Source: U.S. EPA, Office of Air Quality Planning and Standards, National Air Pollutant Emission Trends Summaries (May 2002), Tables A2, A4, and A5.

## Appendix E

# Emissions of Energy-Related Carbon Dioxide in the United States, 1949-2001

This appendix presents estimates of U.S. carbon dioxide emissions for the period 1949-2001. U.S. energy data have undergone a number of changes over the years. The estimates are divided into three periods as outlined below:

- **1989-2001.** The emissions estimates for this period were developed using the methods and sources described in this report. As this is the first year that the EIA has included Independent Power Producers whose primary business is the generation of electricity in the Electric Power Sector, the *Annual Energy Review* is used for the time period from 1989 to 2001 as this is the first integrated data series to incorporate these changes and the only available at the time of publication.<sup>1</sup> The State Energy Data Report will follow this new data structure in the 2003 report that will include data for 2001 and earlier. When this series is available, it will be used for this report.
- **1960-1988.** Before 1980, EIA did not maintain a detailed accounting of carbon sequestration due to nonfuel use of fossil fuels. Hence, the data for industrial sector petroleum use, particularly in the category “other petroleum,” are more accurate in the period 1980 through 1988 than they are in prior years. EIA has also not attempted to develop annual emissions coefficients for fuels in use before 1980, therefore the estimates do not reflect any changes in fuel quality that may have occurred prior to 1980. The energy data for this period are drawn from the database of the *State Energy Data Report*.<sup>2</sup>
- **1949-1959.** EIA has made no attempt to distinguish between residential and commercial energy consumption for historical data earlier than 1960. To provide consistent estimates for this appendix, the combined data for residential and commercial energy consumption have been prorated by fuel according to the ratio of consumption in 1960. Composite sectoral petroleum emissions factors are used for this period, based on 1960-weighted petroleum products emissions. The energy data for this period are also drawn from the *Annual Energy Review*.

---

<sup>1</sup>Energy Information Administration, *Annual Energy Review 2001*, DOE/EIA-0384(2001) (Washington, DC, November 2002), Web site [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

<sup>2</sup>Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(97) (Washington, DC, September 1999), pp. 21-26, Web site [www.eia.doe.gov/emeu/sep/states.html](http://www.eia.doe.gov/emeu/sep/states.html).

**Table E1. Energy-Related Carbon Dioxide Emissions from the Residential and Commercial Sectors, by Fuel Type, 1949-2001**  
(Million Metric Tons of Carbon)

Year	Residential					Commercial				
	Natural Gas	Petroleum	Coal	Electricity	Total	Natural Gas	Petroleum	Coal	Electricity	Total
1949	15.1	23.2	30.2	19.0	87.4	5.0	13.2	42.2	15.0	75.3
1950	17.8	27.6	29.9	20.2	95.4	5.9	15.7	41.7	15.9	79.2
1951	21.8	30.1	26.4	22.5	100.8	7.2	17.1	36.8	17.8	78.8
1952	23.9	30.8	24.0	24.0	102.8	7.9	17.5	33.5	19.0	77.9
1953	24.8	31.3	20.6	26.2	103.0	8.2	17.8	28.8	20.7	75.4
1954	27.8	33.5	17.9	27.5	106.7	9.2	19.0	25.0	21.7	74.9
1955	30.9	36.0	17.8	30.0	114.7	10.2	20.4	24.9	23.7	79.2
1956	34.1	37.6	16.6	32.4	120.7	11.2	21.3	23.1	25.6	81.3
1957	36.7	36.5	12.7	34.7	120.7	12.1	20.7	17.7	27.4	78.0
1958	40.2	39.1	12.4	35.3	127.0	13.2	22.2	17.3	27.9	80.6
1959	43.5	39.9	10.6	39.1	133.1	14.3	22.6	14.8	30.9	82.6
1960	46.2	43.8	10.6	42.3	142.9	15.2	24.9	14.5	33.4	88.0
1961	48.4	45.1	9.6	44.4	147.5	16.0	25.3	13.2	34.6	89.2
1962	51.8	47.1	9.2	47.4	155.5	18.0	25.9	13.0	37.0	93.9
1963	53.2	47.4	8.0	51.9	160.5	18.7	25.5	11.1	41.7	97.0
1964	56.1	45.7	7.1	55.9	164.9	20.3	25.2	9.5	44.5	99.6
1965	57.9	47.8	6.6	60.2	172.5	21.4	28.1	9.0	47.9	106.4
1966	61.3	47.5	6.3	66.6	181.7	24.0	29.1	9.1	52.9	115.1
1967	63.9	49.2	5.4	69.8	188.4	29.0	30.1	7.8	55.7	122.6
1968	65.9	51.6	4.9	79.0	201.5	30.7	30.6	7.0	61.7	130.0
1969	70.0	52.5	4.6	87.1	214.2	33.3	30.7	6.6	66.4	137.0
1970	71.3	52.8	4.0	95.9	224.0	35.3	31.4	5.5	72.5	144.7
1971	73.3	53.3	3.7	100.8	231.1	37.0	30.5	5.2	76.3	149.0
1972	75.7	55.5	2.9	109.0	243.1	38.5	30.9	4.0	83.6	156.9
1973	72.0	54.2	2.7	117.5	246.4	38.3	31.6	3.8	90.3	164.0
1974	70.5	49.4	2.7	114.6	237.1	37.6	28.7	3.8	87.2	157.4
1975	72.3	47.9	2.2	113.1	235.5	36.8	26.3	3.1	90.1	156.3
1976	74.1	52.3	2.1	119.4	247.9	39.1	29.4	3.0	96.8	168.4
1977	70.8	51.8	2.2	129.0	253.7	36.7	30.4	3.1	102.8	173.0
1978	71.8	50.4	2.2	130.8	255.2	38.0	29.1	3.3	103.2	173.6
1979	72.7	40.8	1.9	134.1	249.5	40.8	26.9	2.9	106.7	177.3
1980	69.9	33.6	1.6	142.9	247.9	38.4	26.1	2.3	111.3	178.0
1981	67.0	29.6	1.8	141.0	239.4	37.1	22.0	2.5	116.3	177.9
1982	68.4	27.6	1.9	139.9	237.9	38.5	20.3	2.9	116.7	178.4
1983	65.0	25.9	1.9	143.4	236.3	36.1	22.5	3.0	118.6	180.1
1984	67.5	25.6	2.1	146.5	241.6	37.3	23.8	3.2	124.7	189.2
1985	65.7	28.4	1.8	149.5	245.4	36.0	20.6	2.7	129.8	189.3
1986	63.8	27.9	1.8	150.7	244.2	34.3	21.9	2.7	131.6	190.6
1987	63.9	28.8	1.7	157.1	251.5	36.0	21.5	2.6	137.6	197.6
1988	68.5	29.9	1.7	164.4	264.5	39.5	20.7	2.6	144.5	207.3
1989	70.9	29.7	1.5	166.3	268.4	40.3	19.3	3.0	150.6	213.3
1990	65.1	24.0	0.7	167.7	257.5	38.9	18.2	3.3	152.2	212.6
1991	67.6	24.5	0.6	170.3	263.0	40.5	17.1	3.1	152.5	213.2
1992	69.6	24.9	0.6	167.9	263.0	41.6	16.1	3.1	152.6	213.4
1993	73.4	26.3	0.6	179.3	279.6	42.4	14.9	3.1	159.7	220.0
1994	71.8	25.3	0.5	179.6	277.2	42.9	14.8	3.1	162.6	223.4
1995	71.7	25.7	0.4	182.3	280.1	44.8	14.0	3.0	166.6	228.5
1996	77.5	28.1	0.4	191.0	297.0	46.7	14.6	3.1	172.9	237.4
1997	73.7	27.4	0.4	193.5	295.0	47.5	13.8	3.3	184.6	249.3
1998	67.2	24.9	0.3	205.1	297.6	44.6	12.9	2.4	194.1	253.9
1999	69.9	27.2	0.4	204.9	302.5	45.1	12.8	2.7	197.6	258.0
2000	73.7	27.5	0.3	216.5	318.1	47.5	14.0	2.3	210.5	274.4
P2001	71.1	27.2	0.3	216.3	314.9	48.0	14.0	2.3	215.4	279.7

Notes: P = Preliminary.

Sources: **1989-2001:** Estimates documented in this report, based on energy data in the *Annual Energy Review*. **1960-1988:** Calculated from energy data in the *State Energy Data Report*. **1949-1959:** Calculated from energy data in the *Annual Energy Review*.

**Table E2. Energy-Related Carbon Dioxide Emissions from the Industrial and Transportation Sectors, by Fuel Type, 1949-2001**  
(Million Metric Tons of Carbon)

Year	Residential					Commercial				
	Natural Gas	Petroleum	Coal	Electricity	Total	Natural Gas	Petroleum	Coal	Electricity	Total
1949	45.9	57.7	131.6	33.1	268.4	1.9	119.1	42.9	0.5	164.5
1950	51.1	66.0	140.2	38.4	295.7	2.8	129.7	38.9	0.6	172.0
1951	58.3	70.5	149.9	42.6	321.2	3.1	142.7	34.2	0.6	180.6
1952	60.2	71.6	133.5	43.7	309.0	3.4	149.1	24.5	0.6	177.6
1953	61.9	73.5	143.6	49.1	328.1	3.4	156.1	18.2	0.6	178.4
1954	62.2	75.1	114.5	48.5	300.3	3.7	157.8	11.5	0.6	173.6
1955	67.7	82.9	136.0	60.5	347.0	4.5	169.9	10.5	0.7	185.5
1956	70.1	85.1	137.1	65.3	357.7	4.5	176.4	8.5	0.7	190.0
1957	73.6	84.0	133.8	65.4	356.8	4.6	179.8	6.0	0.7	191.2
1958	75.0	85.8	109.7	61.3	331.8	5.2	183.3	2.9	0.7	192.1
1959	81.3	90.3	106.8	67.4	346.0	5.2	190.6	2.2	0.8	198.7
1960	86.0	89.5	110.2	68.1	353.8	5.2	195.5	1.9	0.7	203.2
1961	86.9	89.1	105.3	69.7	350.9	5.6	199.3	0.5	0.7	206.1
1962	90.8	92.0	106.4	73.2	362.4	5.7	207.9	0.4	0.7	214.7
1963	95.2	93.5	111.3	78.1	378.2	6.3	215.5	0.4	0.6	222.8
1964	100.3	98.6	119.1	83.4	401.4	6.5	221.9	0.4	0.6	229.4
1965	103.5	102.1	124.0	88.8	418.3	7.5	228.9	0.4	0.6	237.3
1966	110.0	105.6	125.9	97.4	438.8	8.0	241.1	0.4	0.6	250.0
1967	113.6	105.5	119.4	99.6	438.0	8.5	253.1	0.3	0.6	262.5
1968	121.4	107.2	117.5	107.9	454.0	8.8	274.2	0.3	0.5	283.7
1969	129.8	111.3	113.4	114.1	468.6	9.3	285.7	0.2	0.5	295.8
1970	133.7	111.1	111.5	117.4	473.6	10.7	295.2	0.2	0.5	306.6
1971	138.7	111.3	94.8	119.0	463.8	11.0	307.0	0.1	0.5	318.6
1972	139.1	121.4	96.0	129.8	486.3	11.3	325.5	0.1	0.5	337.4
1973	147.2	128.4	97.7	139.2	512.5	10.7	343.8	0.1	0.5	355.1
1974	141.1	121.2	94.7	135.7	492.7	9.8	335.5	0.0	0.5	345.9
1975	120.7	114.6	88.9	132.3	456.4	8.6	339.6	0.0	0.6	348.8
1976	124.0	127.0	88.2	148.5	487.6	8.0	356.9	0.0	0.6	365.6
1977	122.3	137.8	83.7	157.2	501.0	7.8	371.3	0.0	0.6	379.7
1978	121.2	135.9	83.1	157.0	497.1	7.8	386.8	0.0	0.5	395.1
1979	120.9	143.6	88.3	165.4	518.1	8.8	383.2	0.0	0.6	392.7
1980	118.4	128.2	76.3	162.3	484.2	9.4	368.1	0.0	0.6	378.1
1981	116.3	110.0	76.2	161.2	463.3	9.5	364.0	0.0	0.6	374.1
1982	100.1	104.0	61.8	142.9	408.2	8.8	356.1	0.0	0.6	365.6
1983	95.2	96.0	60.6	148.2	399.6	7.3	359.0	0.0	0.6	366.9
1984	104.1	105.8	69.6	157.3	436.5	7.8	370.5	0.0	0.7	379.0
1985	98.9	99.9	68.1	157.6	424.1	7.5	376.0	0.0	0.7	384.3
1986	93.1	101.8	65.1	152.8	412.5	7.2	391.0	0.0	0.7	399.0
1987	101.8	101.4	65.9	158.6	427.9	7.7	402.5	0.0	0.7	411.0
1988	106.9	104.8	70.1	165.1	447.9	9.1	417.5	0.0	0.7	427.3
1989	112.6	98.8	68.6	171.8	452.5	9.3	422.0	0.0	0.7	432.1
1990	118.1	100.5	67.8	171.6	458.0	9.8	420.9	0.0	0.7	431.4
1991	119.9	94.9	63.9	168.7	447.6	8.9	414.4	0.0	0.7	424.1
1992	125.4	103.5	61.2	174.5	465.6	8.8	421.3	0.0	0.7	430.8
1993	127.1	97.0	60.8	176.2	461.7	9.3	426.1	0.0	0.7	436.1
1994	126.7	100.4	61.2	179.5	469.2	10.2	437.8	0.0	0.9	448.9
1995	133.8	94.9	60.8	177.1	468.0	10.4	446.1	0.0	0.9	457.4
1996	138.3	102.0	59.3	181.8	482.2	10.6	457.1	0.0	0.9	468.5
1997	138.4	103.0	58.3	185.8	486.9	11.2	461.1	0.0	0.9	473.2
1998	135.0	98.9	54.5	189.1	479.5	9.6	470.8	0.0	0.9	481.3
1999	130.3	99.5	53.3	189.4	474.2	9.7	484.7	0.0	0.9	495.3
2000	133.2	96.0	54.0	193.2	478.4	9.7	496.7	0.0	1.0	507.3
P2001	123.4	97.9	51.0	179.0	452.4	9.2	501.4	0.0	1.0	511.6

Notes: P = Preliminary.

Sources: **1989-2001:** Estimates documented in this report, based on energy data in the *Annual Energy Review*. **1960-1988:** Calculated from energy data in the *State Energy Data Report*. **1949-1959:** Calculated from energy data in the *Annual Energy Review*.

**Table E3. Total Energy-Related Carbon Dioxide Emissions by End-Use Sector, and the Electric Power Sector, by Fuel Type, 1949-2001**  
(Million Metric Tons of Carbon)

Year	End-Use Sector					Electric Power Sector				
	Residential	Commercial	Industrial	Transportation	Total	Natural Gas	Petroleum	Coal	Total	
1949	87.4	75.3	268.4	164.5	595.6	8.2	8.7	50.7	67.6	
1950	95.4	79.2	295.7	172.0	642.2	9.4	10.0	55.7	75.1	
1951	100.8	78.8	321.2	180.6	681.5	11.4	8.5	63.6	83.5	
1952	102.8	77.9	309.0	177.6	667.3	13.5	8.9	64.9	87.3	
1953	103.0	75.4	328.1	178.4	684.9	15.4	10.8	70.4	96.7	
1954	106.7	74.9	300.3	173.6	655.6	17.4	8.9	72.0	98.3	
1955	114.7	79.2	347.0	185.5	726.3	17.1	10.0	87.7	114.8	
1956	120.7	81.3	357.7	190.0	749.7	18.4	9.5	96.0	124.0	
1957	120.7	78.0	356.8	191.2	746.6	19.9	10.6	97.8	128.3	
1958	127.0	80.6	331.8	192.1	731.4	20.4	10.4	94.3	125.1	
1959	133.1	82.6	346.0	198.7	760.3	24.3	11.7	102.1	138.1	
1960	142.9	88.0	353.8	203.2	787.9	25.7	11.7	107.1	144.5	
1961	147.5	89.2	350.9	206.1	793.7	27.2	11.8	110.3	149.4	
1962	155.5	93.9	362.4	214.7	826.6	29.3	11.9	117.1	158.3	
1963	160.5	97.0	378.2	222.8	858.6	32.0	12.4	127.9	172.3	
1964	164.9	99.6	401.4	229.4	895.2	34.7	13.4	136.3	184.4	
1965	172.5	106.4	418.3	237.3	934.5	34.7	15.3	147.5	197.4	
1966	181.7	115.1	438.8	250.0	985.7	39.1	18.7	159.6	217.4	
1967	188.4	122.6	438.0	262.5	1011.5	41.1	21.4	163.2	225.7	
1968	201.5	130.0	454.0	283.7	1069.2	47.0	25.0	177.1	249.2	
1969	214.2	137.0	468.6	295.8	1115.6	52.0	33.3	182.8	268.1	
1970	224.0	144.7	473.6	306.6	1149.0	58.3	45.0	183.0	286.3	
1971	231.1	149.0	463.8	318.6	1162.5	58.9	52.9	184.8	296.6	
1972	243.1	156.9	486.3	337.4	1223.7	58.8	65.5	198.6	322.9	
1973	246.4	164.0	512.5	355.1	1277.9	53.8	74.4	219.3	347.5	
1974	237.1	157.4	492.7	345.9	1233.1	50.6	71.2	216.2	338.0	
1975	235.5	156.3	456.4	348.8	1197.0	46.5	67.0	222.6	336.1	
1976	247.9	168.4	487.6	365.6	1269.5	45.4	73.6	246.4	365.4	
1977	253.7	173.0	501.0	379.7	1307.4	47.3	82.6	259.8	389.6	
1978	255.2	173.6	497.1	395.1	1320.9	47.4	84.5	259.6	391.5	
1979	249.5	177.3	518.1	392.7	1337.7	51.9	69.6	285.3	406.9	
1980	247.9	178.0	484.2	378.1	1288.2	54.8	55.3	306.9	417.0	
1981	239.4	177.9	463.3	374.1	1254.7	54.1	46.3	318.7	419.1	
1982	237.9	178.4	408.2	365.6	1190.1	48.0	33.0	319.1	400.1	
1983	236.3	180.1	399.6	366.9	1182.9	43.1	32.5	335.3	410.9	
1984	241.6	189.2	436.5	379.0	1246.3	46.3	27.0	355.7	429.1	
1985	245.4	189.3	424.1	384.3	1243.0	45.5	22.9	369.2	437.6	
1986	244.2	190.6	412.5	399.0	1246.2	38.7	30.6	366.5	435.9	
1987	251.5	197.6	427.9	411.0	1287.9	42.2	26.4	385.2	454.0	
1988	264.5	207.3	447.9	427.3	1347.0	39.0	32.9	402.8	474.8	
1989	268.4	210.8	451.1	432.1	1362.4	46.0	35.8	409.4	491.3	
1990	257.5	212.6	458.0	431.4	1359.5	47.8	27.0	417.3	492.3	
1991	263.0	213.2	447.6	424.1	1347.8	48.9	25.3	417.8	492.2	
1992	263.0	213.4	465.6	430.8	1372.8	50.9	21.1	423.7	495.7	
1993	279.6	220.0	461.7	436.1	1397.3	51.3	24.1	440.4	515.9	
1994	277.2	223.4	469.2	448.9	1418.7	57.6	22.6	442.2	522.5	
1995	280.1	228.5	468.0	457.4	1434.1	62.3	16.3	448.2	526.8	
1996	297.0	237.4	482.2	468.5	1485.2	55.9	17.6	472.9	546.5	
1997	295.0	249.3	486.9	473.2	1504.3	59.7	20.0	484.9	564.8	
1998	297.6	253.9	479.5	481.3	1512.3	67.6	28.2	493.3	589.2	
1999	302.5	258.0	474.2	495.3	1530.1	70.9	26.1	495.7	592.8	
2000	318.1	274.4	478.4	507.3	1578.3	76.5	24.5	520.1	621.2	
P2001	314.9	279.7	452.4	511.6	1558.7	77.7	27.5	506.4	611.7	

Notes: P = Preliminary. Emissions from the electric power sector are apportioned to each end-use sector according to their share of electricity sales.

Sources: **1989-2001:** Estimates documented in this report, based on energy data in the *Annual Energy Review*. **1960-1988:** Calculated from energy data in the *State Energy Data Report*. **1949-1959:** Calculated from energy data in the *Annual Energy Review*.

## Appendix F

# Common Conversion Factors

### Mass

1 kilogram	=	$10^3$ grams	=	2.20462 pounds
1 megagram (metric ton)	=	$10^6$ grams	=	2,204.62 pounds
1 gigagram	=	$10^9$	=	1,000 metric tons
1 teragram	=	$10^{12}$	=	1 million metric tons
1 short ton	=	$.9072 * 10^6$ grams	=	2,000 pounds

### Energy

1 joule	=	.2388 calories	=	.0009478 Btu
1 terajoule	=	$10^{12}$ joules	=	$9.478 * 10^8$ Btu
1 exajoule	=	$10^{18}$ joules	=	$0.9478 * 10^{15}$ Btu
1 Mbtu	=	1000 Btu	=	$1 * 10^3$ Btu
1 Mmbtu	=	1 million Btu	=	$1 * 10^6$ Btu
1 Bbtu	=	1 billion Btu	=	$1 * 10^9$ Btu
1 Tbtu	=	1 trillion Btu	=	$1 * 10^{12}$ Btu
1 Qbtu	=	1 quadrillion Btu	=	$1 * 10^{15}$ Btu

### Area

1 acre	=	0.4047 hectare (ha)	=	4,047 m <sup>2</sup>
1 hectare	=	10,000m <sup>2</sup>	=	2.47 acres

### Volume

1 cubic centimeter	=	$3.5318 * 10^{-5}$ cubic feet
1 cubic foot	=	0.02832 cubic meters
1 cubic meter	=	35.3147 cubic feet
1 barrel	=	42 gallons

### Density

1 thousand cubic feet methane	=	42.28 pounds methane
1 thousand cubic feet carbon dioxide	=	115.97 pounds carbon dioxide

# Appendix G

## Global Warming Potentials

### Overview

Global warming potentials (GWPs) are indices used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative forcing effects<sup>1</sup> (heat-absorbing ability) of each gas relative to that of carbon dioxide (CO<sub>2</sub>), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO<sub>2</sub>. The GWP for a gas provides a construct for converting emissions of each GHG into a common measure, which allows analysts to aggregate and compare the radiative impacts of various greenhouse gases into a uniform measure denominated in carbon dioxide equivalents (CO<sub>2</sub>e). Thus, applying the appropriate GWP to a greenhouse gas will yield the CO<sub>2</sub>e of the greenhouse gas being measured. GWPs can also serve as an important quantitative tool for governments and policymakers seeking consensus in formulating an effective climate policy.

In preparing the estimations of emissions provided in *Emissions of Greenhouse Gases in the United States*, the Energy Information Administration (EIA) seeks to employ the most current data sources. In doing so, EIA has generally relied on the GWPs published in assessment reports by the Intergovernmental Panel on Climate Change (IPCC) prepared every five years. Over the past decade, the IPCC has conducted an extensive research program aimed at determining the sources and effects of various greenhouse gases and their effect on the climate system. The results of that work were originally released in 1995 in an the IPCC first assessment report, *Climate Change 1994*,<sup>2</sup> and subsequently updated in their second assessment report (SAR) *Climate Change 1995*<sup>3</sup> and third assessment report (TAR) *Climate Change 2001*.<sup>4</sup>

There has been some discussion about which GWPs to utilize in preparing estimates of greenhouse gas emissions, largely stemming from the different stages of publication and formal approval of the IPCC's SAR, published in 1996, and the TAR, published in 2001. The United Nations Framework Convention on Climate Change (UNFCCC) requirements for developing national inventories—provided under the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* and the UNFCCC's *Guidelines on Reporting and Review*<sup>5</sup> for national inventories—were developed prior to the publication of the TAR. Both documents continue to require national inventories to be based on the GWPs in the IPCC SAR,<sup>6</sup> and the UNFCCC negotiating body, called the Conference of Parties (COP), has yet to adopt decisions to approve the TAR.<sup>7</sup> As a result, the U.S. Environmental Protection Agency (EPA) and a number of national governmental bodies responsible for publishing and submitting national emissions inventories to the UNFCCC utilize the GWPs published in the SAR.

In contrast, EIA's *Emissions of Greenhouse Gases* has relied on the high likelihood that the TAR, as published, will be adopted and approved by the COP in the near future, and that there is little reason not to utilize the TAR GWP values but for the fact that the COP has yet to formally adopt the TAR. For this year's *Emissions* report, EIA has added this new appendix to address the differences between the GWPs presented in the SAR and TAR, and to explain the rationale for applying the GWPs from the TAR.

---

<sup>1</sup>Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in Watts per square meter (W/m<sup>2</sup>).

<sup>2</sup>Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

<sup>3</sup>Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

<sup>4</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

<sup>5</sup>Conference of Parties, Fifth Session, United Nations Framework Convention on Climate Change (UNFCCC) Guidelines on Reporting and Review, FCCC/CP/1999/7 (16 February 2000).

<sup>6</sup>See *Revised Guidelines for the Preparation of National Communications by Parties included in Annex I to the Convention*, FCCC/CP/1996/15/Add.1 (1996).

<sup>7</sup>See decision 2/CP.3 of the UNFCCC.

## Understanding Global Warming Potentials

A global warming potential (GWP) is defined as the cumulative radiative forcing—both in terms of direct effects and indirect effects (such as resulting from chemical transformations)—over a period of time, relative to a reference gas.<sup>8</sup> GWP values are derived from laboratory experiments on molecular attributes of greenhouse gases and data modeling of the gases' radiative transfer properties.<sup>9</sup> While any time period can be selected, the IPCC recommends using 100-year GWPs. According to the IPCC, the direct GWPs for gases with distinguished lifetimes have an estimated uncertainty within  $\pm 35\%$ , but the indirect GWPs are less certain, particularly those for which lifetimes are not yet understood.<sup>10</sup> Table G1 illustrates the differences in estimated GWP values as a factor of time horizons.

**Table G1. Numerical Estimates of Global Warming Potentials Compared With Carbon Dioxide**  
(Kilogram of Gas per Kilogram of Carbon Dioxide)

Gas	Lifetime (Years)	Direct Effect for Time Horizons of		
		20 Years	100 Years	500 Years
<b>Carbon Dioxide</b>	5 – 200 <sup>a</sup>	1	1	1
<b>Methane</b>	12	62	23	7
<b>Nitrous Oxide</b>	114	275	296	156
<b>Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride</b>				
HFC-23	260	9,400	12,000	10,000
HFC-125	29	5,900	3,400	1,100
HFC-134a	13.8	3,300	1,300	400
HFC-152a	1.4	410	120	37
HFC-227ea	33	5,600	3,500	1,100
Perfluoromethane (CF <sub>4</sub> )	50,000	3,900	5,700	8,900
Perfluoroethane (C <sub>2</sub> F <sub>6</sub> )	10,000	8,000	11,900	18,000
Sulfur Hexafluoride (SF <sub>6</sub> )	3,200	15,100	22,200	32,400

<sup>a</sup> No single lifetime can be defined for carbon dioxide due to different rates of uptake by different removal processes.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), pp. 38 and 388-389.

Greenhouse gases with relatively long atmospheric lifetimes (e.g., carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. Short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, and other ambient air pollutants (e.g., nitrogen oxide, and non methane volatile organic compounds), and tropospheric aerosols (e.g., sulfur dioxide products and black carbon), however, are present in very different quantities spatially around the world, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially heterogeneous in the atmosphere.<sup>11</sup>

## Changes between the Second and Third Assessment Reports

More than two decades of research have provided a progressively improved understanding of the interaction between anthropogenic emissions of greenhouse gases and their potential to alter the Earth's atmosphere. In the five years between the publication of the SAR in 1996 and the TAR in 2001, considerable progress was achieved in reducing the scientific uncertainty associated with the direct and indirect relationship of atmospheric responses to various external influences.

The IPCC's TAR includes GWP estimates for several gases that have been modified from the SAR, as well as new GWPs for a more complete set of gases. In keeping with IPCC protocol, the use of all GWPs continues to be based

<sup>8</sup>U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002. See also Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

<sup>9</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001) Section 6.12.

<sup>10</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001) Section 6, Executive Summary.

<sup>11</sup>U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002.

on the effect of that greenhouse gas over a 100-year time period. Included among the new gases are certain ozone depleting substances (ODSs), originally considered only to be harmful to stratospheric ozone but now recognized as potent greenhouse gases. In addition, the TAR includes new categories for ethers and halogenated ethers.

In general, the TAR served to confirm and reinforce the conclusions put forth in the SAR. Table G2 provides a comparison of 100-year GWP estimates from the SAR and TAR. The bulk of changes to the GWPs, as described below, have also shown to have little overall impact on the quantification of total greenhouse gases emitted at the U.S. national level. Table G3 presents a comparison of GWPs and lifetimes in the SAR and TAR, while Table G4 illustrates the effect SAR and TAR 100-year GWPs have on U.S. emissions estimates.

**Table G2. Comparison of 100-Year GWP Estimates from the IPCC's Second (SAR) and Third (TAR) Assessment Reports**

Gas	GWP		Absolute Change	Percentage Change
	SAR	TAR		
<b>Carbon Dioxide</b>	1	1	No Change	No Change
<b>Methane</b>	21	23	2	10%
<b>Nitrous Oxide</b>	310	296	-14	-5%
<b>Hydrofluorocarbons</b>				
HFC-23	11,700	12,000	300	3%
HFC-32	650	550	-100	-15%
HFC-41	150	97	-53	-35%
HFC-125	2,800	3,400	600	21%
HFC-134	1,100	1,100	100	10%
HFC-134a	1,300	1,300	No Change	No Change
HFC-143	300	330	30	10%
HFC-143a	3,800	4,300	500	13%
HFC-152	NA	43	NA	NA
HFC-152a	140	120	-20	-14%
HFC-161	NA	12	NA	NA
HFC-227ea	2,900	3,500	600	21%
HFC-236cb	NA	1,300	NA	NA
HFC-236ea	NA	1,200	NA	NA
HFC-236fa	6,300	9,400	3,100	49%
HFC-245ca	560	640	80	14%
HFC-245fa	NA	950	NA	NA
HFC-365mfc	NA	950	NA	NA
HFC-4310mee	1,300	1,500	200	15%
<b>Iodocarbons</b>				
FIC-1311	<1	1	No Change	No Change
<b>Fully Fluorinated Species</b>				
SF <sub>6</sub>	23,900	22,000	-1,900	-8%
CF <sub>4</sub>	6,500	5,700	-800	-12%
C <sub>2</sub> F <sub>6</sub>	9,200	11,900	2,700	29%
C <sub>3</sub> F <sub>8</sub>	7,000	8,600	1,600	23%
C <sub>4</sub> F <sub>10</sub>	7,000	8,600	1,600	23%
c-C <sub>4</sub> F <sub>8</sub>	8,700	10,000	1,300	15%
C <sub>5</sub> F <sub>12</sub>	7,500	8,900	1,400	19%
C <sub>6</sub> F <sub>14</sub>	7,400	9,000	1,600	22%

Sources: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

## Improvements to GWP Estimates in the Third Assessment Report

Improvements to the IPCC's GWP values in the TAR were a result of an improved calculation of CO<sub>2</sub> radiative forcing, an improved CO<sub>2</sub> response function, and recalculations of some atmospheric lifetimes. GWPs presented in the TAR are drawn from the SAR and the World Meteorological Organization (WMO),<sup>12</sup> and include specific updates drawn from new published cases of laboratory or radiative transfer results.

<sup>12</sup>World Meteorological Organization, *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project-Report No. 44*, Geneva, Switzerland (1999).

As stated in the TAR:

*The direct GWPs have been calculated relative to CO<sub>2</sub> using an improved calculation of the CO<sub>2</sub> radiative forcing, the SAR response function for a CO<sub>2</sub> pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons. [TAR 2001]*

To determine the direct radiative forcings (per ppbv or parts per billion volume), the IPCC “derived from infrared radiative transfer models based on laboratory measurements of the molecular properties of each substance and considering the molecular weights.”<sup>13</sup> The radiative forcing of CO<sub>2</sub> was found to be about 12 percent lower than that reported in the SAR. For example, the improved formula, for fixed changes in gas concentrations, decreased CO<sub>2</sub> and N<sub>2</sub>O radiative forcing by 15%, increased CFC-11 and CFC-12 radiative forcing by 10 to 15%, and yielded no change in the case of CH<sub>4</sub>. As a consequence of changes in the radiative forcing for CO<sub>2</sub> and CFC-11, the revised GWPs are typically 20% higher than listed in the SAR.<sup>14</sup>

The response function for a CO<sub>2</sub> pulse can be explained in simple terms as the response from adding an additional ton of CO<sub>2</sub> to the atmosphere, and the function specifies the proportion of CO<sub>2</sub> that remains in the atmosphere after a designated amount of time (an average of single exponential decay functions). The GWP of any substance therefore expresses the integrated forcing of a pulse (of given small mass) of that substance relative to the integrated forcing of a pulse (of the same mass) of the reference gas over some time horizon.

Many atmospheric lifetimes were recalculated in the TAR. The lifetimes of non-CO<sub>2</sub> greenhouse gases are dependent largely on atmospheric photochemistry, which controls photo-lysis and related removal processes. When the lifetime of the gas in question differs substantially from the response time of the reference gas (CO<sub>2</sub>), the GWP becomes sensitive to the choice of time horizon. For example, for longer time horizons (greater than 100 years), those gases that decay more rapidly than the CO<sub>2</sub> display decreasing GWPs; and conversely those gases with lifetimes much longer than that of the CO<sub>2</sub> display increasing GWPs. Table G3 provides a comparison of the lifetimes and GWPs for the greenhouse gases provided in the SAR and TAR, showing a range of between -15 and + 49 percent in GWP values.

As a result of the adjustments to the radiative forcing of CO<sub>2</sub> and the recalculation of atmospheric lifelines of several gases, the GWPs of the other gases, relative to CO<sub>2</sub>, have overall increased. Other variables, such as the radiative efficiency or chemical lifetime, have also altered the GWP values.<sup>15</sup> Because much detailed laboratory data are not yet available, however, some of the GWPs have larger uncertainties than others. As mentioned above, the IPCC estimates that GWPs generally have an uncertainty of ±35 percent.

Because GWP values are based on the concept of radiative forcing, and these forcings do not appear to stay constant over time, the values for GWPs also will continue to fluctuate, particularly if the amounts and composition of the various gases in the atmosphere increase. In some cases, where concentrations of a greenhouse gas are low, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, the marginal effects of additional emissions may not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or CO<sub>2</sub>, tends to be less than that of a rare gas, such as sulfur hexafluoride (SF<sub>6</sub>). This “diminishing return” effect implies that increasing concentrations of a particular gas reduces the impact of additional quantities of that gas. Thus, the relative impacts of various gases will change as their relative concentrations in the atmosphere change.

Figure G1 shows the comparative global and annual mean radiative forcing of a range of gases from 1750 to the late 1990s. Note that greenhouse gases are provided in the left-most bar in the graphic. The IPCC notes that, all the forcings shown have distinct spatial and seasonal features such that the global, annual means appearing on this plot do not yield a complete picture of the radiative perturbation. They are only intended to give, in a relative sense, a first-order perspective on a global, annual mean scale, and cannot be readily employed to obtain the climate response to the total natural and/or anthropogenic forcings. As in the SAR, it is emphasized that the positive and negative global mean forcings cannot be added up and viewed a priori as providing offsets in terms of the complete global climate impact.

<sup>13</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), Section 6.12.1.

<sup>14</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

<sup>15</sup>U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002.

**Table G3. Comparison of GWPs and Lifetimes Used in the SAR and the TAR**

Gas	Lifetime (years)		GWP (100 year)		Absolute Change	Percent Change
	SAR	TAR	SAR	TAR		
<b>Carbon Dioxide</b>	50-200	5-200 <sup>a</sup>	1	1	NC	NC
<b>Methane<sup>b</sup></b>	12±3	8.4/12 <sup>c</sup>	21	23	2	10%
<b>Nitrous Oxide</b>	120	120/114 <sup>c</sup>	310	296	(14)	-5%
<b>Hydrofluorocarbons</b>						
HFC-23	264	260	11,700	12,000	300	3%
HFC-32	5.6	5.0	650	550	(100)	-15%
HFC-41	3.7	2.6	150	97	(53)	-35%
HFC-125	32.6	29	2,800	3,400	600	21%
HFC-134	10.6	9.6	1,000	1,100	100	10%
HFC-134a	14.6	13.8	1,300	1,300	NC	NC
HFC-143	3.8	3.4	300	330	30	10%
HFC-143a	48.3	52	3,800	4,300	500	13%
HFC-152	NA	0.5	NA	43	NA	NA
HFC-152a	1.5	1.4	140	120	(20)	-14%
HFC-161	NA	0.3	NA	12	NA	NA
HFC-227ea	36.5	33.0	2,900	3,500	600	21%
HFC-236cb	NA	13.2	NA	1,300	NA	NA
HFC-236ea	NA	10	NA	1,200	NA	NA
HFC-236fa	209	220	6,300	9,400	3,100	49%
HFC-245ca	6.6	5.9	560	640	80	14%
HFC-245fa	NA	7.2	NA	950	NA	NA
HFC-365mfc	NA	9.9	NA	890	NA	NA
HFC-4310mee	17.1	15	1,300	1,500	200	15%
<b>Iodocarbons</b>						
FIC-1311	<0.005	0.005	<1	1	NC	NC
<b>Fully Fluorinated Species</b>						
SF <sub>6</sub>	3,200	3,200	23,900	22,000	(1,900)	-8%
CF <sub>4</sub>	50,000	50,000	6,500	5,700	(800)	-12%
C <sub>2</sub> F <sub>6</sub>	10,000	10,000	9,200	11,900	2,700	29%
C <sub>3</sub> F <sub>8</sub>	2,600	2,600	7,000	8,600	1,600	23%
C <sub>4</sub> F <sub>10</sub>	2,600	2,600	7,000	8,600	1,600	23%
c-C <sub>4</sub> F <sub>8</sub>	3,200	3,200	8,700	10,000	1,300	15%
C <sub>5</sub> F <sub>12</sub>	4,100	4,100	7,500	8,900	1,400	19%
C <sub>6</sub> F <sub>14</sub>	3,200	3,200	7,400	9,000	1,600	22%
<b>Ethers &amp; Halogenated Ethers</b>						
CH <sub>3</sub> OCH <sub>3</sub>	NA	0.015	NA	1	NA	NA
(CF <sub>3</sub> ) <sub>2</sub> CFOCH <sub>3</sub>	NA	3.4	NA	330	NA	NA
(CF <sub>3</sub> )CH <sub>2</sub> OH	NA	0.5	NA	57	NA	NA
CF <sub>3</sub> CF <sub>2</sub> CH <sub>2</sub> OH	NA	0.4	NA	40	NA	NA
(CF <sub>3</sub> ) <sub>2</sub> CHOH	NA	1.8	NA	190	NA	NA
HFE-125	NA	150	NA	14,900	NA	NA
HFE-134	NA	26.2	NA	6,100	NA	NA
HFE-143a	NA	4.4	NA	750	NA	NA
HCFE-235da2	NA	2.6	NA	340	NA	NA
HFE-245cb2	NA	4.3	NA	580	NA	NA
HFE-245fa2	NA	4.4	NA	570	NA	NA
HFE-254cb2	NA	0.22	NA	30	NA	NA
HFE-347mcc3	NA	4.5	NA	480	NA	NA
HFE-356pcf3	NA	3.2	NA	430	NA	NA
HFE-374pcf2	NA	5.0	NA	540	NA	NA
HFE-7100	NA	5.0	NA	390	NA	NA
HFE-7200	NA	0.77	NA	55	NA	NA
H-Galden 1040x	NA	6.3	NA	1,800	NA	NA
HG-10	NA	12.1	NA	2,700	NA	NA
HG-01	NA	6.2	NA	1,500	NA	NA

See notes at end of table.

**Table G3. Comparison of GWPs and Lifetimes Used in the SAR and the TAR (Continued)**

Gas	Lifetime (years)		GWP (100 year)		Absolute Change	Percent Change
	SAR	TAR	SAR	TAR		
<b>Others<sup>d</sup></b>						
NF3	NA	740	NA	10,800	NA	NA
SF5CF3	NA	>1,000	NA	>17,500	NA	NA
c-C3F6	NA	>1,000	NA	>16,800	NA	NA
HFE-227ea	NA	11	NA	1,500	NA	NA
HFE-236ea2	NA	5.8	NA	960	NA	NA
HFE-236fa	NA	3.7	NA	470	NA	NA
HFE-245fa1	NA	2.2	NA	280	NA	NA
HFE-263fb2	NA	0.1	NA	11	NA	NA
HFE-329mcc2	NA	6.8	NA	890	NA	NA
HFE-338mcf2	NA	4.3	NA	540	NA	NA
HFE-347-mcf2	NA	2.8	NA	360	NA	NA
HFE-356mec3	NA	0.94	NA	98	NA	NA
HFE-356pcc3	NA	0.93	NA	110	NA	NA
HFE-356pcf2	NA	2.0	NA	260	NA	NA
HFE-365mcf3	NA	0.11	NA	11	NA	NA
(CF3)2CHOCF2	NA	3.1	NA	370	NA	NA
(CF3)2CHOCH3	NA	0.25	NA	26	NA	NA
(CF2)4CH(OH)-	NA	0.85	NA	70	NA	NA

<sup>a</sup> No single lifetime can be determined for carbon dioxide. (See IPCC 2001)

<sup>b</sup> The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO<sub>2</sub> is not included.

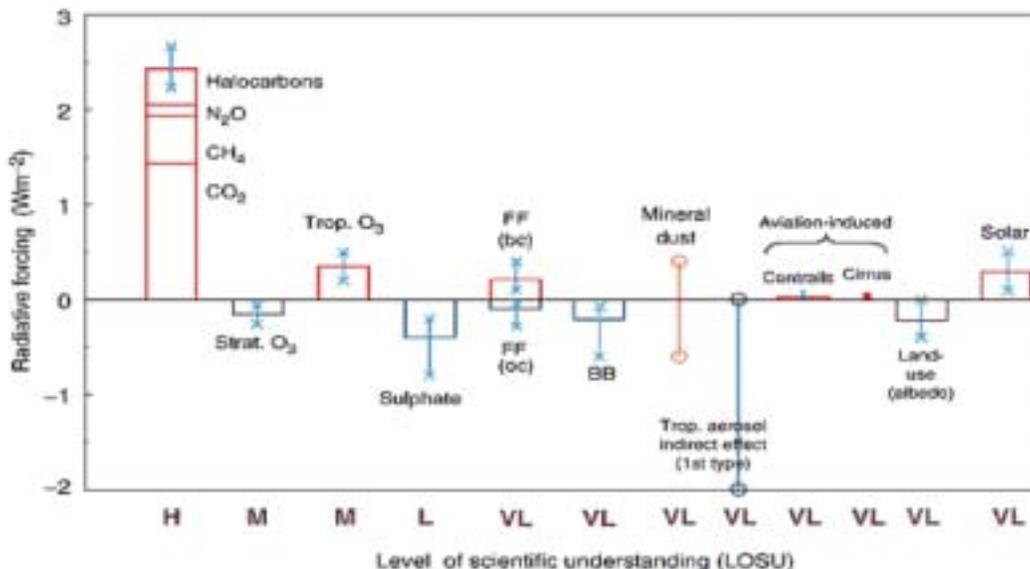
<sup>c</sup> Methane and nitrous oxide have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT).

<sup>d</sup> Gases whose lifetime has been determined only via indirect means of for whom there is uncertainty over the loss process.

Sources: U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the inventory of u.s. Greenhouse Emissions and Sinks: 1990-2000*, April 2002; Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

Notes: NC (No Change); NA (Not Applicable)

**Figure G1. Global and Annual Mean Radiative Forcing (1750 to Present)**



Notes: This figure illustrates the global, annual mean radiative forcings (Wm<sup>-2</sup>) due to a number of agents for the period from pre-industrial (1750) to the late 1990s (about 2000). The height of the rectangular bar denotes a central or best estimate value while its absence denotes no best estimate is possible. The vertical line about the rectangular bar with "x" delimiters indicates an estimate of the uncertainty range, guided by the spread in the published values of the forcing and physical understanding. A vertical line without a rectangular bar and with "o" delimiters denotes a forcing for which no central estimate can be given owing to large uncertainties. The uncertainty range specified here has no statistical basis and therefore differs from the use of the term elsewhere in this document. A "level of scientific understanding" (LOSU) index is accorded to each forcing, with H, M, L and VL denoting high, medium, low and very low levels, respectively. This represents our subjective judgment about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of our knowledge of the physical/chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing. The well-mixed greenhouse gases are grouped together into a single rectangular bar with the individual mean contributions due to CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and halocarbons shown; halocarbons refers to all halogen-containing compounds listed in "FF" denotes fossil fuel burning while "BB" denotes biomass burning aerosol. Fossil fuel burning is separated into the "black carbon" (bc) and "organic carbon" (oc) components with its separate best estimate and range. The sign of the effects due to mineral dust is itself an uncertainty. Only the first type of indirect effect due to aerosols as applicable in the context of liquid clouds is considered here.

Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

## Effect of Using TAR GWPs for Greenhouse Gas Emissions Estimations

As shown in Table G4, when estimating U.S. greenhouse gas emissions for 1990, 2000 and 2001, the values calculated with the TAR GWPs are 0.7 to 0.8 percent higher than the estimate calculated with SAR GWPs. When applying the TAR GWPs, the greatest overall difference to the SAR estimates, in terms of having a significant effect on the atmosphere, can be seen in a 10.0 percent increase in carbon-equivalent methane emissions and a 4.0 percent decrease in carbon-equivalent nitrous oxide emissions. Carbon equivalent emissions of HFCs, PFCs, and SF<sub>6</sub> have varied over the years depending on the relative share of the gases. Taken as a whole, however, the differences in GWPs between the SAR and TAR do not prove a significant effect on U.S. emissions trends.

**Table G4. GWP Effects on U.S. Greenhouse Gas Emissions**

Gas	IPCC GWP		Annual GWP-Weighted Emissions (Million Metric Tons Carbon Equivalent)								
			1990			2000			2001		
	1996	2001	1996 GWP	2001 GWP	Percent Change	1996 GWP	2001 GWP	Percent Change	1996 GWP	2001 GWP	Percent Change
Carbon dioxide	1	1	1,364	1,364	0.0%	1,597	1,597	0.0%	1,579	1,569	0.0%
Methane	21	23	181	199	9.5%	162	178	9.5%	160	176	10.0%
Nitrous oxide	310	296	99	94	-4.5%	103	98	-4.5%	102	97	-4.0%
HFCs, PFCs, and SF <sub>6</sub>	—	—	26	25	-3.8%	31	34	9.7%	28	31	10.7%
<b>Total</b>	—	—	<b>1,670</b>	<b>1,682</b>	<b>0.7%</b>	<b>1,891</b>	<b>1,907</b>	<b>0.8%</b>	<b>1,868</b>	<b>1,883</b>	<b>0.8%</b>

Sources: U.S. Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2001* (December 2002); Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

## Conclusions

In the five years between the publication of the SAR in 1996 and the TAR in 2001, progress has been achieved in reducing the scientific uncertainty associated with the direct and indirect relationship of atmospheric responses to various external influences. Improvements have been made to the GWP values published in the TAR, and these are expected to be adopted and approved by the UNFCCC COP. While participating countries are still required to apply the GWPs published in the SAR according to the most recently adopted requirements for the development of national GHG inventories submitted to the UNFCCC, the TAR has been recognized as providing the most scientifically accurate GWPs to date, and has been adopted by EIA in the completion of this report.