

Emissions Inventories and Atmospheric Concentrations

Greenhouse gases trap heat within the atmosphere. While most greenhouse gases occur naturally and serve to keep the Earth hospitable to life, they are also generated by human activities. Naturally occurring greenhouse gases include water vapor (H₂O), carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and ozone (O₃). Man-made activities have produced additional emissions of CO₂, methane, nitrous oxide, and the precursors to ozone (NO_x, VOCs), as well as the production of entirely new “engineered” chemicals, such as halocarbons and related compounds including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), which are powerful greenhouse gases. As these gases are emitted into the atmosphere, the concentration of greenhouse gases changes. An increase in the concentrations of greenhouse gases suggests that increasing levels of emissions are altering the earth’s atmosphere.

Central to any study of climate change is the understanding of concentrations and emissions inventories, which identify the primary sources and sinks of greenhouse gases.ⁱ Two of the most commonly referenced sources of data on greenhouse gas emissions in the United States are *Emissions of Greenhouse Gases in the United States*, published by the US Department of Energy (DOE) and *Inventory of US Greenhouse Gas Emissions and Sinks*, by the US Environmental Protection Agency (EPA). Both publications compile a broad range of information, and much of the information presented in this chapter refers to data presented in these two documents.

Measuring greenhouse gas concentrations is a fairly reliable procedure, as concentrations are directly measured using air samples. However, emissions inventories have inherent limitations in their accuracy since emissions cannot be directly measured at a national level and must be estimated. As a result, greenhouse gas emissions inventories are calculated based on available data and methodologies, just as emissions of criteria pollutants—such as NO_x and VOC—are estimated based on specific methodologies.

The calculation of CO₂ emissions from fossil fuels is straightforward: emissions are calculated by multiplying reported energy consumption by the estimated carbon content of fossil fuels. According to the DOE, this is a fairly reliable estimate since energy statistics and estimates of carbon content are probably accurate within a few percent.¹ Methane and nitrous oxide emissions estimates are much more uncertain since they are generally inferred by extrapolating experiments conducted on a small number of samples across a large national population. Detailed methodologies for estimating emissions are presented in *Emissions of Greenhouse Gases in the United States*, published by the US DOE.

2.1 UNITS FOR MEASURING EMISSIONS

Emissions of carbon dioxide are usually reported in terms of million metric tons of carbon equivalent (mmtCE) in US DOE and EPA publications.ⁱⁱ Carbon units are defined as the weight of the carbon content of carbon dioxide (i.e., just the “C” in CO₂). Carbon units are the most common measure by the scientific

ⁱ Sinks are natural features such as forests and oceans that absorb greenhouse gases from the atmosphere.

ⁱⁱ In addition, CO₂ emissions are reported in carbon equivalent units by the US Department of Transportation in *Transportation Statistics Annual Report 1995* (BTS, p. 79) and in the US *Climate Change Action Plan* submitted under the United Nations Framework Convention on Climate Change.

community since not all carbon from combustion is emitted in the form of carbon dioxide and carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration.² Emissions of other greenhouse gases are often reported in terms of the full molecular weight of the gas but may be converted into a “carbon equivalent.”ⁱⁱⁱ

2.2 ANTHROPOGENIC AND BIOGENIC SOURCES

The majority of greenhouse gases are emitted from natural (biogenic) sources, while human activities (anthropogenic sources) generate smaller amounts of greenhouse gases. Powerful natural mechanisms absorb these gases from the atmosphere. Estimates of global emissions are presented in Exhibit 2-1.

Exhibit 2-1. Global Natural and Anthropogenic Sources and Absorption of Greenhouse Gases

Gas	Biogenic Sources	Anthropogenic Sources	Absorption	Annual Increase in Gas in Atmosphere
CO ₂ (mmtCE)	150,000	7,100	154,000	3,100–3,500
CH ₄ (mmt gas)	110-210	300-450	460-660	35–40
N ₂ O (mmt gas)	6-12	4-8	13-20	3–5

Source: US Department of Energy, Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 1995*, p. 3, citing ranges from Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

According to data from the US Department of Energy presented in Exhibit 2-1, carbon dioxide is by far the most prevalent greenhouse gas emitted into the atmosphere aside from water vapor. Increasing concentrations of CO₂, CH₄, and N₂O in the atmosphere indicate that more gases are being emitted than absorbed each year, despite the ability of natural mechanisms to absorb greenhouse gases. Records from the Antarctic ice core reveal that the carbon cycle has been in a state of imbalance for the past 200 years, with emissions of carbon dioxide exceeding absorption capacities.³

Both naturally-occurring and human-induced greenhouse gas emissions arise from a variety of processes and activities. The following list is summarized from US DOE’s 1995 report.⁴

BIOGENIC SOURCES

Carbon Dioxide

CO₂ is a common compound on Earth. Large quantities can be found in the atmosphere, in soils, in carbonate rocks, and dissolved in ocean water. All life on earth participates in the “carbon cycle:” CO₂ is extracted from the air by plants and the carbon is incorporated into plant biomass, and the oxygen is then released to the atmosphere; plant biomass ultimately decays (oxidizes), releasing CO₂ back into the atmosphere or storing organic carbon in soil or rock. Primary sources of carbon dioxide include: the oceans (100 billion metric tons per year), aerobic decay of vegetation (30 billion metric tons), and plant and animal respiration (30 billion metric tons).

ⁱⁱⁱ Carbon dioxide units at full molecular weight can be converted into carbon units by dividing by 3.67, or multiplying by 12/44 (the weight of the carbon content of CO₂). Emissions of other gases, such as methane, can also be measured in “carbon equivalents” by multiplying their emissions (in metric tons) by their global warming potential and then dividing by 3.67.

Methane

Methane (CH₄) is also a common compound, though the methane cycle is not understood as well as the carbon cycle. Known biogenic sources of methane include anaerobic decay of vegetation, emissions from animal sources, and several other sources.

Nitrous Oxide

The sources and absorption of N₂O are much more speculative than those for other greenhouse gases. The principal biogenic sources are thought to be bacterial breakdown of nitrogen in soils and fluxes from ocean upwellings. The most important sink is thought to be decomposition in the stratosphere.

ANTHROPOGENIC SOURCES

Carbon Dioxide

The primary human source of CO₂ is the combustion of fossil fuels, which accounts for about three-quarters of total anthropogenic emissions of carbon worldwide. Fossil fuels are consumed for transportation, industrial processes, and residential purposes.

Methane

Principal anthropogenic sources are agricultural practices, including the burning of crop residue and animal husbandry, leakages from the production of fossil fuels, anaerobic decay in landfills, and the use of domesticated animals in ranching.

Nitrous Oxide

Primary human-made sources are application of nitrogen fertilizers, combustion of fuels, and certain industrial processes.

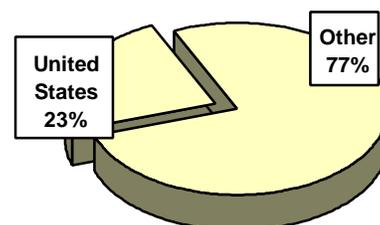
2.3 US CONTRIBUTION TO WORLD EMISSIONS

The US is currently the world's leading emitter of carbon dioxide. As shown in Exhibit 2-2, the US accounts for about 23 percent of global energy-related carbon emissions.

The US Energy Information Administration projects that carbon emissions will increase throughout the world in future years, with continued growth in energy consumption in developing countries as they become more industrialized.⁵

The US share of methane and nitrous oxide emissions, although uncertain, is likely to be much lower than its share of CO₂ emissions, since the principal sources of these emissions are more prevalent outside the US. The US share of

Exhibit 2-2. US Carbon Emissions as a Percent of World Emissions



Source: US DOE/EIA, Emissions of Greenhouse Gases in the United States, 1995. (Pittsburgh, PA: US Government Printing Office, 1996), p. 8.

halocarbons and other engineered gases is likely to be much larger than 23 percent since the use of cooling and refrigeration equipment is more common in the US than elsewhere in the world.⁶

According to estimates from the US Department of Energy presented in Exhibit 2-3, emissions of greenhouse gases from the United States (based on global warming potential) are estimated to have risen by about four percent between 1990 to 1994. During this four year period, methane and halocarbons levels remained constant or decreased slightly. DOE postulated that the reduction in methane during the early 1990s could have resulted from the decline in underground coal mine production and the increased proliferation of glass and paper recycling that has reduced the volume of trash being landfilled, hence reducing methane emissions from landfills.

Exhibit 2-3. US Emissions of Greenhouse Gases, Based on Global Warming Potential, 1988-1995 (million metric tons of Carbon Equivalent)

Gas	1988	1989	1990	1991	1992	1993	1994	1995p
Carbon Dioxide	1375	1384	1372	1359	1380	1405	1431	1442
Methane	177	177	179	180	180	174	178	NA
Nitrous Oxide	36	38	38	38	38	39	40	39
HFCs and PFCs	19	20	19	19	21	20	23	25
Total	1606	1619	1608	1596	1619	1638	1672	NA

p=preliminary

Source: US DOE/EIA, *Emissions of Greenhouse Gases in the United States, 1995*. (Pittsburgh, PA: US Government Printing Office, 1996), p. xi.

Carbon dioxide is the most significant greenhouse gas emitted by human sources, principally because of its abundance. Exhibit 2-3 shows that in 1994, the 1431 million metric tons of carbon dioxide emitted comprised about 86 percent of the 1672 million metric tons of carbon equivalent emitted by the US overall.

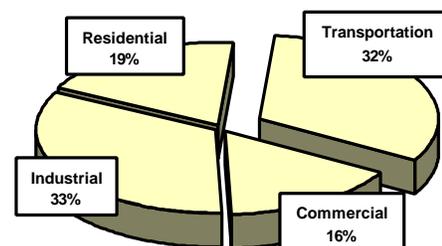
According to DOE, the burning of fossil fuels causes approximately 98.5 percent of anthropogenic carbon dioxide. Due to the economic value of fossil fuels, their consumption is carefully monitored, thus energy-related carbon dioxide emissions can be estimated more reliably than other emissions.⁷

2.4 TRANSPORTATION SECTOR CONTRIBUTION

The transportation sector accounted for about 32 percent of US carbon dioxide emissions in 1990 (See Exhibit 2-4), and it is expected to be the fastest growing source of greenhouse gas emissions through the year 2000.⁸

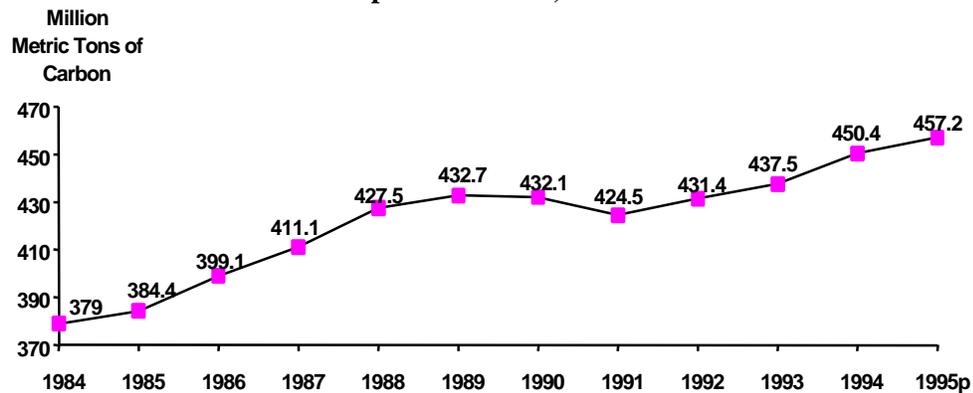
Carbon dioxide emissions from transportation have been increasing, as fuel consumption by transportation sources has grown. Carbon dioxide emissions from the transportation sector accounted for nearly 40 percent of the 25 million metric ton increase in energy-related carbon emissions since 1990, while the industrial and commercial sectors accounted for most of the remainder.⁹

Exhibit 2-4. US Carbon Dioxide Emissions from Fossil Fuels in 1995



Source: US DOE/EIA, *Emissions of Greenhouse Gases in the United States, 1995*. (Pittsburgh, PA: US Government Printing Office, 1996).

Exhibit 2-5. US Carbon Dioxide Emissions from Transportation Sector, 1984-1995



p=preliminary

Source: US DOE/EIA. *Emissions of Greenhouse Gases in the United States, 1995*. (Pittsburgh, PA: US Government Printing Office, 1996), p. 18.

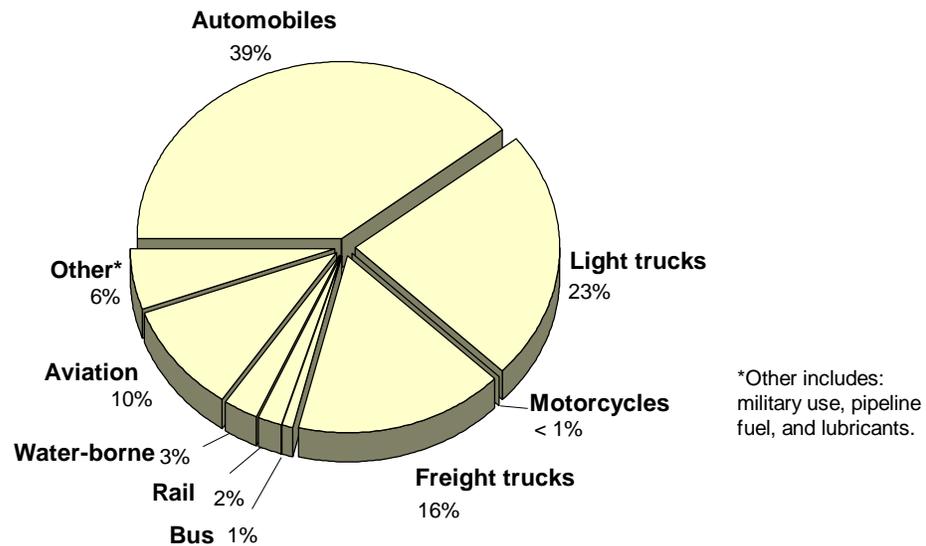
Exhibit 2-5 above illustrates that emissions from the transportation sector are growing rapidly due to increased demand for motor gasoline, jet fuel, and diesel fuel. Transportation sector emissions have grown more rapidly than other sources over the past ten years, and transportation is projected to be the fastest growing sector in the near future.^{iv} Historically, improvements in average fuel economy have curtailed some growth in transportation sector emissions that would have occurred given large increases in travel. However, the growing popularity of luxury cars, trucks, and recreational vehicles stabilized the US average fuel economy for all motor vehicles.¹⁰

In addition to generating carbon dioxide emissions, DOE notes the transportation sector as responsible for about 31 percent of US nitrous oxide emissions, with the remainder stemming from agricultural and industrial sources.¹¹ Transportation is also responsible for less than one percent of US methane emissions, with the majority of methane emissions stemming from agricultural sources, landfills, coal mining, and oil and gas production.¹²

2.5 MODAL CONTRIBUTION

Despite the importance of carbon dioxide as the most significant anthropogenic greenhouse gas emission, there is relatively little published information on the contribution of various transportation modes to national CO₂ emissions. Inventories published by the US DOE and the US Environmental Protection Agency (EPA) only break down the transportation sector's emissions by fuel, not mode of transportation. The contribution of specific mobile sources to CO₂ emissions can be estimated based on fuel consumption information contained in US DOE's *Supplement to the Annual Energy Outlook, 1997*, as shown in Exhibit 2-6. Carbon dioxide emissions are a function of fuel use (Refer to Appendix A for a discussion of CO₂ emissions calculation and data sources).

^{iv} Between 1985 and 1995, US carbon dioxide emissions grew by the following percent within each sector: transportation—18.9 percent; industrial—9.1 percent; residential—10.2 percent; commercial—15.2 percent (US DOE/EIA, *Emissions of Greenhouse Gases in the United States, 1995*. Pittsburgh, PA: US Government Printing Office, 1996., pp.17-18). EIA's *Annual Energy Outlook, 1997* (December 1996, pp. 97-98) projects that transportation will be the fastest growing sector in terms of energy consumption, from 1995 to 2005.

Exhibit 2-6. Estimated US Carbon Dioxide Emissions from Mobile Sources, 1995

Source: Grant, M., M. Corrales, and D. Guruswamy. "Carbon Dioxide Emissions from Transportation by Mode and Submode: Estimates and Implications for Policy Development." Paper presented to Air & Waste Management Conference, Emissions Inventory: Planning for the Future, Research Triangle Park, NC: October 1997.

Exhibit 2-6 does not include carbon dioxide emissions from international bunker fuels, which are fuels purchased by merchant ships and international air carriers in the US. Under the Framework Convention, energy data used by the International Energy Agency exclude bunker fuels from national inventories. As Exhibit 2-6 shows, the majority of transportation-sector carbon dioxide emissions stem from light-duty vehicles, which include automobiles, light trucks, and motorcycles. Based on similar data from the *Annual Energy Outlook 1995*, the Policy Dialogue Advisory Committee asserted that reducing carbon emissions from personal motor vehicles could significantly contribute to overall reduction of greenhouse gases.¹³

Freight trucks contribute about 16 percent of emissions, so that on-road mobile sources contribute nearly 80 percent of all transportation emissions. Non-road sources are not insignificant. In particular, aviation contributes about 10 percent of transportation emissions, and projections suggest that aviation will be the fastest growing mode in terms of energy consumption and carbon dioxide emissions.¹⁴

According to DOE estimates, nearly half of mobile-source methane emissions in 1994 in the US were generated by passenger cars.^v The combination of passenger cars and light-duty trucks comprised 75 percent of mobile sources of methane in 1994.¹⁵ In addition, nitrous oxide emissions from mobile sources were estimated to be 145,000 metric tons in 1995, and DOE approximates that 88 percent of these emissions can be attributed to motor vehicles.¹⁶

According to energy projections through 2010 from US DOE's *Annual Energy Outlook 1997*, light trucks and aviation will comprise a growing share of transportation emissions. An explanation for the increase in light-duty truck emissions is the increasing use of mini-vans, recreational trucks, and other sport utility vehicles. Light trucks comprised 41 percent of light-duty vehicle sales in 1997, up from 17 percent in 1972,

^v Mobile sources are responsible for less than one percent of methane emissions in the US (US DOE, /EIA, *Emissions of Greenhouse Gases in the United States, 1995*. Pittsburgh, PA: US Government Printing Office, 1996, Table 16, p. 31).

and are projected to be a growing portion of the in-use light duty vehicle fleet.¹⁷ Such vehicles are not subject to the same fuel economy standards as automobiles. Thus, the increase in their use is an important consideration when examining strategies to reduce emissions in the transportation sector.

In addition to changes in the share of emissions from each transportation source, the total pie is projected to increase rapidly. Transportation CO₂ emissions are projected to grow by about 25 percent between 1995 and 2010, according to energy consumption estimates from the reference case in the Annual Energy Outlook 1997. Aviation is projected to be the fastest growing mode. Still, light-duty vehicles are projected to contribute the majority of the tonnage increase since they comprise a much larger portion of the emissions inventory. Among light-duty vehicles, nearly all of the emissions growth comes from light duty trucks, rather than automobiles.

Carbon dioxide emission growth projections depend heavily on assumptions about fuel prices, economic growth, and technology deployment. While there is considerable uncertainty regarding many of these factors and the total magnitude of emissions growth, the reference case from the Annual Energy Outlook suggests that significant growth in transportation emissions will occur over the next 15 years in the absence of specific measures to address greenhouse gas emissions.

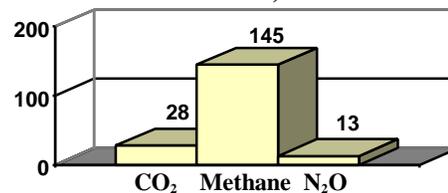
2.6 CHANGES IN GLOBAL CONCENTRATIONS OF GASES

Unlike emissions inventories that are calculated, atmospheric concentration of gases is directly measured using samples of air.^{vi} Using samples of “fossil air” trapped in ice cores from Greenland and Antarctica, scientists have been able to measure historic concentrations.

Empirical observations show that global atmospheric concentrations of greenhouse gases have increased steadily for decades. The US DOE reports that atmospheric concentrations of carbon dioxide have increased by about 28 percent, methane has more than doubled, and nitrous oxide has increased about 13 percent since the start of the industrial era, as shown in Exhibits 2-7. Records indicate that carbon dioxide and methane are currently at concentration levels not previously attained for any prolonged period over the past 160,000 years. The growth in concentrations has occurred largely in the past 200 years.¹⁸ Pre-industrial (1880) and 1992 atmospheric concentrations are compared in Exhibit 2-8.

The atmospheric concentration of carbon dioxide is currently increasing about 30 to 100 times faster than the rate of natural fluctuation in the paleoclimatic record.¹⁹ Similarly, the atmospheric concentration of methane is increasing more than 400 times natural rates of variability.²⁰ Other greenhouse gases—chlorofluorocarbons (CFCs) and halons—are synthetic chemicals that have been introduced into the atmosphere during only the last 50 years.

Exhibit 2-7. Percent Increase in Atmospheric Concentrations, 1880-1992



Note that carbon dioxide is a much larger component of the atmosphere than other gases.

^{vi} Carbon dioxide concentrations have been directly recorded using consistent methods since 1958. Concentrations of methane and nitrous oxide have been recorded since the early 1980s (US DOE, 1995, p. 6).

Exhibit 2-8. Estimated Global Concentrations of Greenhouse Gases, 1880 and 1992

Gas	Preindustrial (1880) Atmospheric Concentrations	1992 Atmospheric Concentrations	Percent Increase in Concentration
Carbon dioxide	278 parts per million	356 parts per million	28%
Methane	0.700 parts per million	1.714 parts per million	145%
Nitrous Oxide	0.275 parts per million	0.311 parts per million	13%
CFC-11	0 parts per trillion	268 parts per trillion	—
CFC-12	0 parts per trillion	503 parts per trillion	—

Source: US DOE/EIA, 1996, p. 2, citing M. Prather et al., "Other Trace Gases and Atmospheric Chemistry," in Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996). Percent increase calculated by Apogee Research, Inc.

According to the US DOE, the timing of the growth in concentrations, variations in observations between the northern and southern hemispheres, and observations of relative concentrations of isotopes in atmospheric CO₂ imply that the prime source for the increase in carbon dioxide concentrations is the combustion of fossil fuels by humans.²¹ However, the mechanisms that link anthropogenic emissions with global concentrations are not entirely understood.

It is particularly striking that there was a sudden slowing in the growth rate of atmospheric concentrations of CO₂ and methane over the period 1990-93, which cannot be explained by changes in fossil fuel consumption, suggesting that either natural sources of emissions have declined or natural absorption has increased. The causes of reduced growth in methane concentrations have eluded scientists, although some theorize that global cooling from sulfate aerosols deposited in the atmosphere by the eruption of Mount Pinatubo in the Philippines may have stimulated absorption mechanisms. Clearly, concentrations have been increasing, but the forces that influence biogenic sources and sinks are not well understood.²²

2.7 GLOBAL WARMING POTENTIAL

Some greenhouse gases have a more potent effect on global temperatures than others based on their heat-absorption potential. Research on this topic has led to the development of the concept of "global warming potential (GWP)." GWP is a measure of the relative effectiveness of various gases in trapping the Earth's heat, in comparison to CO₂. Exhibit 2-9 lists the GWPs of key greenhouse gases for time horizons of twenty and one hundred years.

Exhibit 2-9. Global Warming Potentials

Gas	Lifetime (years)	GWP, Direct Effect for Time Horizon of:	
		20 years	100 years
Carbon dioxide	variable	1	1
Methane	12 ± 3	56	21
Nitrous Oxide	120	280	310
CFC-11	na	4900	3800
CFC-12	na	7800	8100

Source: D.L. Albritton et al., "Trace Gas Radiative Forcing Indices," reported in US DOE/EIA, 1996, p. 6.

The IPCC's work has established that the effects of various gases on global warming are too complex to be summarized as a single number. The "atmospheric lifetime" of gases—the period of time it takes for natural processes to remove a unit of emissions from the atmosphere—differs widely for different gases. As a result, over different periods of time the relative GWP of gases differs. In addition, many gases react in the atmosphere to promote or hinder the formation of other greenhouse gases. These indirect effects are not summarized in the GWPs.^{vii}

^{vii} For example, CFCs tend to destroy atmospheric ozone, thus promoting global cooling. It is unclear whether CFCs have a net warming or cooling effect on the earth (US DOE, p. 5).

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- ¹ US Department of Energy/Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 1987-1994*. (Pittsburgh, PA: US Government Printing Office, 1995) p. 2.
- ² *Ibid.*
- ³ *Ibid.* pp. 2-3.
- ⁴ *Ibid.*
- ⁵ *Ibid.*, p. 10.
- ⁶ *Ibid.*
- ⁷ US Department Of Energy/Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 1995*. (Pittsburgh, PA: US Government Printing Office, 1996), p. xi.
- ⁸ *Ibid.*
- ⁹ *Ibid.*, p. 13.
- ¹⁰ US Department Of Energy/Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 1987-1994*. (Pittsburgh, PA: US Government Printing Office, 1995), p. 12.
- ¹¹ US Department Of Energy/Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 1995*. (Pittsburgh, PA: US Government Printing Office, 1996), p. 41.
- ¹² *Ibid.*
- ¹³ *Ibid.*, p. 7.
- ¹⁴ US Department Of Energy/Energy Information Administration, *Supplement to the Annual Energy Outlook, 1995*.
- ¹⁵ US Department Of Energy/Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 1995*. (Pittsburgh, PA: US Government Printing Office, 1996), p.34.
- ¹⁶ *Ibid.*, p.39.
- ¹⁷ US Department of Energy, Oak Ridge National Laboratory. *Transportation Energy Databook: Edition 17*. Washington, DC. August 1997. p. 3-21.
- ¹⁸ US Department Of Energy/Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 1987-1994*. (Pittsburgh, PA: US Government Printing Office, 1995), p. 6.
- ¹⁹ Barnola, J.M., *et. al.*, "Vostok Ice Core Provides 160,000-year Record of Atmospheric CO₂", *Journal of Geophysical Research* 92: 14722-14780 (1987).
- ²⁰ Intergovernmental Panel on Climate Change, *First Scientific Assessment of Climate Change*, Summary and Report, World Meteorological Organization/UN Environment Program (Cambridge, UK: Cambridge University Press, 1990).
- ²¹ US Department Of Energy/Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 1987-1994*. (Pittsburgh, PA: US Government Printing Office, 1995), p. 7.
- ²² *Ibid.*