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THE POTENTIAL IMPACT OF CONSERVATION, ALTERNATIVE ENERGY SOURCES, AND REDUCED NONENERGY EMISSIONS ON GLOBAL WARMING

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ABSTRACT

In this report, we examine two global energy consumption scenarios and corresponding nonenergy scenarios to determine how each will contribute to the greenhouse effect and global warming. A steady emissions trend scenario assumes only modest energy conservation and little change in the world's energy consumption patterns and nonenergy emissions. A reduced emissions trend scenario assumes significant conservation, switching from a more carbon-intensive energy source mix to a less intensive mix, and reducing nonenergy emissions. Based on the difference between the two scenarios' results, our conclusions are that it is possible to reduce global warming by over 50% using a combination of conservation and efficiency improvements, increased use of nuclear, geothermal, and solar/renewable energy sources, and reduced nonenergy emissions.

ACKNOWLEDGMENTS

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CONTENTS

Chapter I. Introduction

An increase in the world's "greenhouse effect" and consequent global warming poses a threat to our environment which is potentially more serious than any other previously encountered environmental issue. It has the potential to significantly alter global climate, and thereby cause serious agricultural, economic, political, and social disruptions. The greenhouse effect is caused by atmospheric concentrations of various gases which allow solar radiation to pass through to the earth but partially block infrared radiation from radiating back out into space. An increase in the concentrations of these various gases, due to human activity, is almost certainly causing the earth's surface to become warmer than it would be without increasing concentrations.

Global warming of a few degrees is not important in itself, but climatic changes caused by the warming are potentially dangerous because they would occur over a few decades. Adapting with agricultural, economic, and social changes in such a short time would be extremely difficult if not impossible. The most serious effects that have been postulated are changes in global rainfall patterns, increases in the frequency and severity of droughts and storms, dislocation of agricultural and natural fauna and flora, ocean warming with attendant modification of ocean currents and biological systems, and rising ocean levels--especially serious for The Netherlands, Bangladesh, Florida, and coastal cities everywhere. Perhaps the most comprehensive compilation of potential effects can be found in the U.S. EPA's report to Congress (Smith, 1988).

Several researchers have modeled the global greenhouse effect and have agreed that increased atmospheric concentrations of greenhouse gases will lead to average global temperatures which are from 2 to 8 degrees Kelvin higher than at present (Bolin, 1986; Dickinson, 1986; Trebalka, 1986; USDOE, March 1988; Mintzer, 1987; Ramanathan, 1985). However, some researchers believe that increased cloudiness caused by global warming will reduce the effect to some extent (Ramanathan, 1989; Kerr, 1989). In attempting to quantify its effect on the world's agriculture and economy using global circulation models to predict rainfall patterns, researchers have obtained diverse results for specific geographical regions (Edmonds et al., 1986, USDOE, April and May 1988). Thus, although researchers agree on the existence, and to some extent on the magnitude, of the greenhouse effect, there is little agreement on the specific global changes it may cause. Nevertheless, most researchers believe that there will be serious global implications.

The object of this study is to develop a quantitative estimate for the potential reduction of global warming that might be achieved through making reasonable modifications to global energy consumption patterns and to the emission of nonenergy greenhouse gases. The modifications include increased conservation, efficiency improvements, and switching from fossil fuels to alternative energy sources such as nuclear, geothermal, and solar/renewable. Our emphasis will be on the greenhouse effect and the emission of greenhouse gases, but other energy related atmospheric emissions will be discussed as well. We will estimate the magnitude of global warming from the generation of greenhouse gases for two scenarios of global energy consumption and nonenergy anthropogenic (related to human activities) emissions starting with 1986 as a base year and progressing to the year 2050. These scenarios are: a steady emission trend scenario, "Steady Scenario," where little is done to restrict the growth of energy consumption and nonenergy emissions and little is done to change the mix of energy sources, and a reduced emission trend scenario, "Reduced Scenario," where, through conservation, increased energy efficiencies, and a general concern for alleviating the greenhouse effect, the growth of energy consumption, nonenergy emissions, and the mix of energy sources is considerably altered. Associated with each scenario we model the expected concentration increases of greenhouse gases and the potential temperature rise caused by these concentration increases. Estimating the consequences of this warming in terms of changing rainfall patterns, agricultural dislocations, political implications, etc. is far beyond our scope.

The most important greenhouse gases in the earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), tropospheric ozone (O_3), and the chlorofluorocarbons (CFCs): CFC-11 (trichlorofluoromethane, CCl_3F), and CFC-12 (dichlorodifluoromethane, CCl_2F_2). The earth's natural greenhouse effect is basic to the existence of life as we know it. Without the presence of natural greenhouse gases, instead of being a comfortable 288 K, the average temperature of the earth would be about 40 K lower, below the freezing point of water (Campbell, 1986). Before the industrial revolution, the atmospheric concentration of greenhouse gases was fairly constant (Neftel, 1985; Raynaud, 1985; Pearman, 1986; Khalil, 1987) because natural sources and sinks of these gases were in balance. Significantly increased atmospheric concentrations of greenhouse gases since the preindustrial era have been measured (Bolin, 1986), and the increases are mainly due to anthropogenic activity, in particular, increased fossil fuel consumption (Bolin, 1986).

CO_2 is the most serious of the greenhouse gases, due to its radiative effect and its atmospheric concentration, which may double in the next few decades. This gas is the natural product of burning carbon contained in all fossil fuels. In 1986 about 5.8 GtC (metric gigatonnes of carbon) was emitted into the atmosphere due to world energy consumption (WRI, 1989). It has been estimated that an additional 1.6 GtC was emitted from other anthropogenic activity, mostly deforestation (WRI, 1989). Independent of anthropogenic activity, the earth experiences a carbon cycle with a total flux of about 200 GtC in and out of the atmosphere each year (Bolin, 1986). The oceans and plants are a net sink for atmospheric CO_2, while other biota and detritus decomposition are a net source. While the total natural flux of carbon is 35 times greater than anthropogenic emissions, there has been a very close balance between natural sources and sinks (Bolin, 1986; Trebalka, 1986). Anthropogenic carbon sources have upset the balance. Plots of the atmospheric concentration of CO_2 from year 1750 to 1986 versus the cumulative emission of CO_2 from energy use alone and from energy plus other anthropogenic activity, deforestation, etc., is shown in Figure 1.1. Both curves show a very strong linear relation between the atmospheric concentration and the energy emissions indicating that a fraction of the emitted CO_2 remains in the atmosphere. The CO_2 concentration data for these two curves is from the Mauna Loa Observatory, as reported in WRI (1989), and the emissions data are from the same report. It is not known precisely what happens to that fraction of CO_2 which leaves the atmosphere, but it is conjectured that most of it is absorbed in the oceans (Bolin, 1986). These data make an exceptionally strong case that anthropogenic carbon sources have upset the source-sink balance and that increased atmospheric concentrations are due to human activity. Similar data exist for the other greenhouse gases. A more detailed discussion of CO_2 and the other greenhouse gases are given in Appendix A.

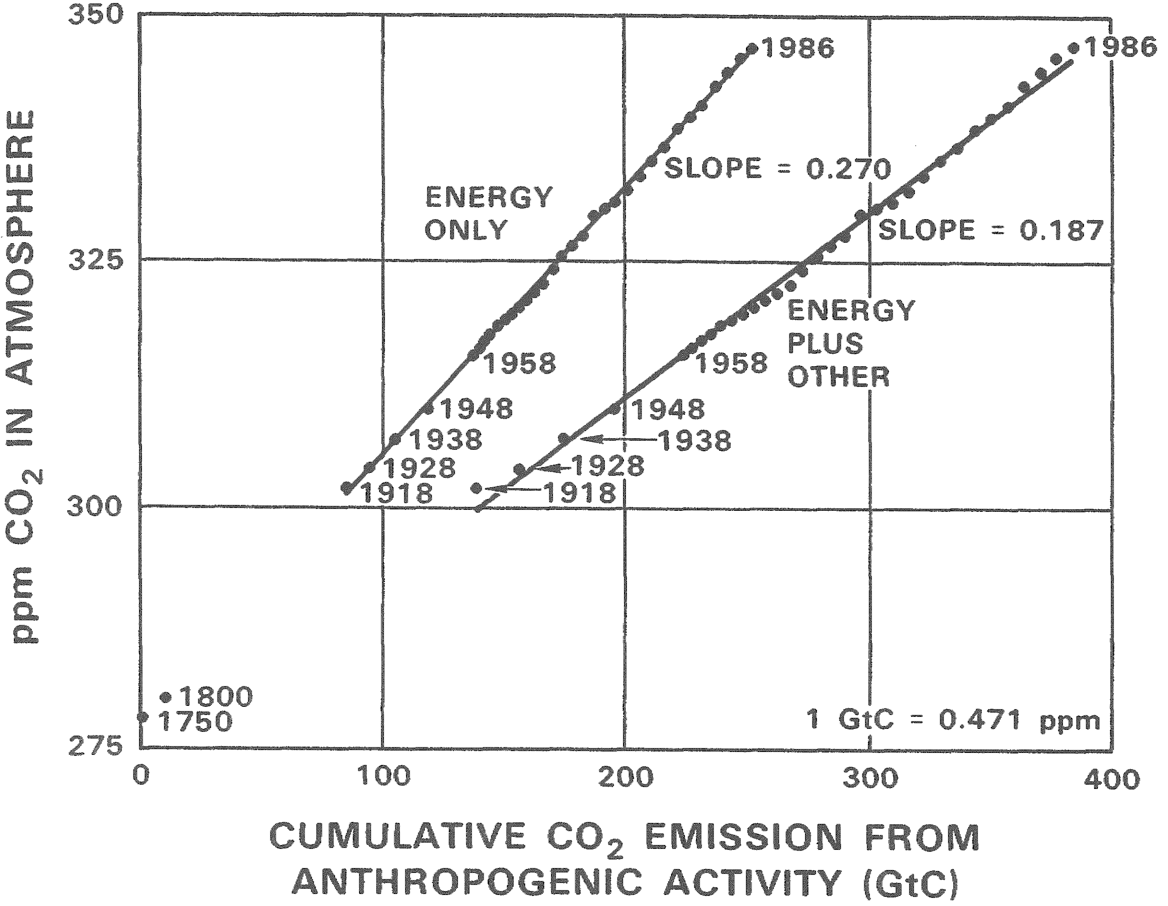


Figure 1.1 Atmospheric CO_2 Concentration vs. Cumulative Anthropogenic CO_2 Emissions

The contribution that each gas makes to the greenhouse effect depends on how strongly it absorbs infrared radiation and on its atmospheric concentration. Concentration, in turn, depends on the rate at which the gas is emitted, its distribution over time, and on the rate at which it decomposes or is absorbed by sinks. Data records indicate that greenhouse gas concentrations and average global temperature were fairly constant before the industrial revolution and that a very strong correlation exists between anthropogenic emissions and measured atmospheric greenhouse gas concentrations. Because the radiative properties of these gases are understood, it is almost certain that increasing greenhouse gas concentrations and a corresponding increased greenhouse effect are due to human activity.

Figure 1.2 is inserted here to put the relative importance of the various greenhouse gases and their anthropogenic sources (energy and nonenergy) into perspective. It was derived using the "Steady Scenario," described later in this report, which predicts a possible increase in average global temperature of 3.3 K from the year 1986 to 2050 due to the radiative effects (feedback effects are not included) of anthropogenically emitted greenhouse gases. The figure indicates that 57% of the increase is energy related, and the remaining 43% is caused by nonenergy, anthropogenic activity. Of the total anthropogenic emissions, about 10% of CO_2 emissions, 32% of N_2O emissions, 59% of methane emissions, and all of the CFC emissions are from nonenergy sources. The primary sources of nonenergy N_2O are from fertilizer use and the exposure of cultivated land (Bolin, 1986). Major nonenergy methane sources are rice production, enteric emissions from domestic animals, and land fills (Bolin, 1986). These figures illustrate that the greenhouse effect is not just an energy problem, and mitigation strategies should include both energy and nonenergy elements.

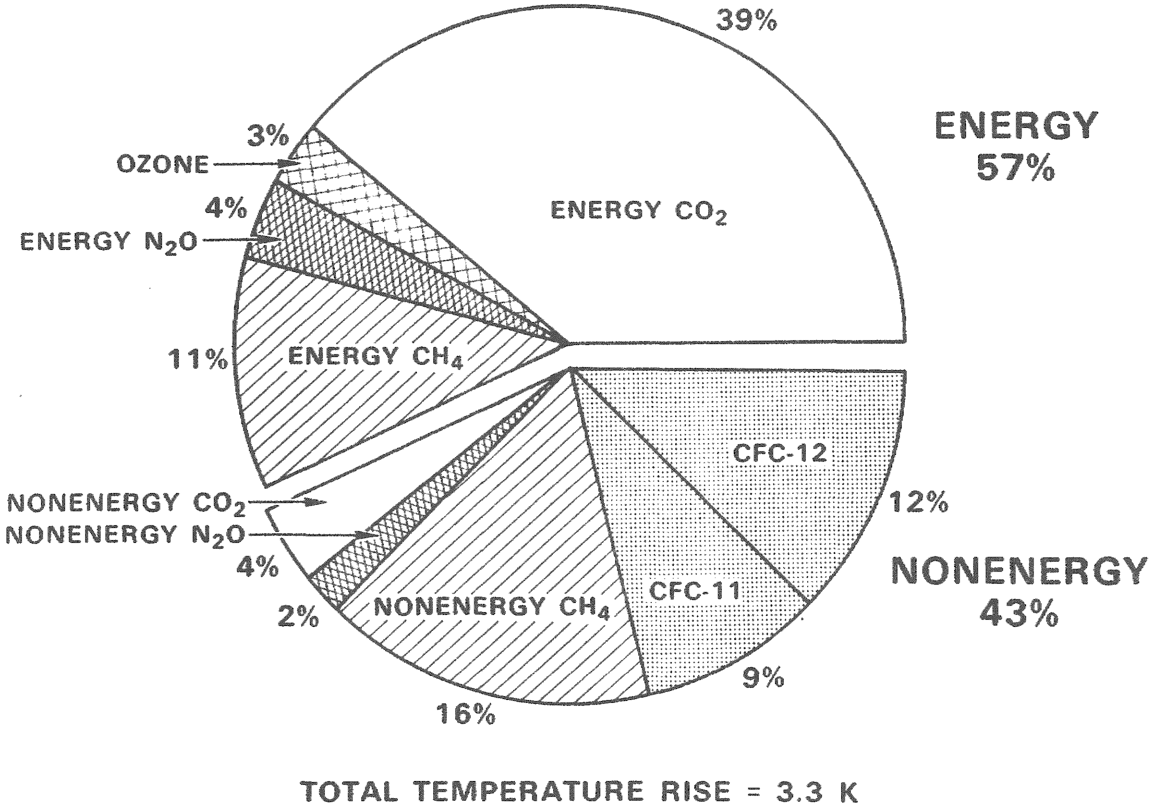


Figure 1.2 Relative Anthropogenic Contributions to an Increasing Greenhouse Effect Based on Changes in Temperature Between 1986 and 2050 from the Steady Scenario

Chapter II. Greenhouse Gas Emission Scenarios

The global use of energy, in particular the burning of fossil fuels, is the largest single contributor (see Figure 1.2) to the anthropogenic emission of greenhouse gases; thus, estimating the magnitude of the greenhouse effect requires projecting global energy use. With the year 1986 as a starting point, we projected two global energy consumption scenarios and estimated greenhouse gas emissions for each. Scenarios for nonenergy emissions were also projected (described later in this chapter) and added to energy emissions.

We constructed a 1986 energy flow chart for the world, Figure 2.1, using data from a World Resources Institute report (WRI, 1989). These data were used because they contain both aggregated global energy consumption and energy consumption broken down by world region and use sector. Our "agrescom" sector is the combination of agricultural, residential, and commercial energy use sectors. The differences between production and consumption in the WRI report are shown as "lost, reserved, etc." in the figure. Electrical transmission losses were not included in the reference. They are not shown in the figure and are not expected to be large enough to change our results significantly. The "other" fuel category refers to wood and other organic fuels. Appendix B gives a more detailed description of Figure 2.1. Energy consumption values are summarized in Table 2.1.

Our analysis explores two energy consumption scenarios: a steady emission trend scenario, "Steady Scenario," and a reduced emission trend scenario, "Reduced Scenario." Associated with each of the two energy consumption scenarios is a parallel scenario, described later in this chapter, for nonenergy, anthropogenic greenhouse gas emissions.

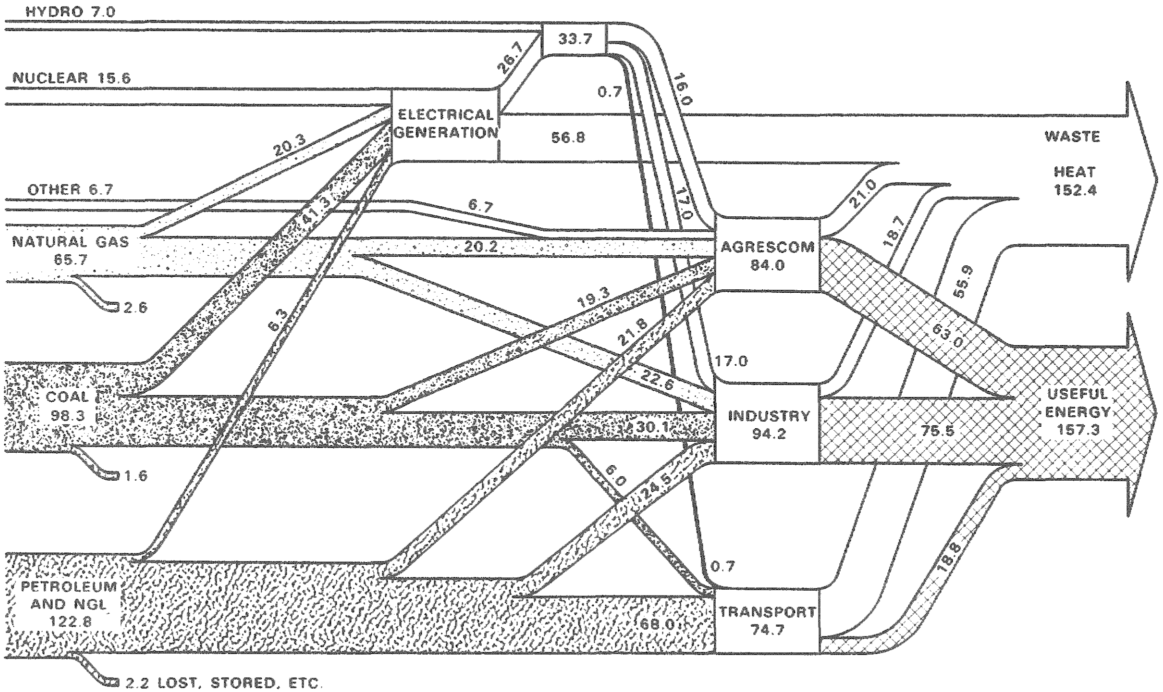


Figure 2.1 1986 World Energy Production and Consumption in EJ

Table 2.1
1986 World Energy Consumption in Exajoules, EJ.

Oil	120.6
Coal	96.7
Natural Gas	63.1
Nuclear	15.6
Hydroelectric	22.0*
Total	318.0

* The hydroelectric energy generated is 7.0 EJ_e, but WRI expressed it as an equivalent thermal energy input, 22.0 EJ_{th}.

Steady Emission Trend Energy Scenario--Figure 2.2 compares five energy projections. The one labeled "ORIEA" is from Edmonds (1985) and shows the highest growth rate projection of the five. The two projections labeled "IIASA High" and "IIASA Low" are from Hafele (1981). The other two projections are from Mintzer (1987) and are labeled "WRI High Emission" and "WRI Slow Buildup." Each of these projections was based on rather detailed population growth, economic growth, and supply-demand scenarios. Without judging the relative merits of these and other scenarios, we selected a 2% per year energy growth rate as our Steady Scenario, which is very close to the WRI High Emission case. We do not wish to imply that it is a "most likely" or a "worst case" scenario. It is simply one of many possible scenarios.

The Steady Scenario uses a 2% annual energy growth rate without conservation or efficiency improvements. It also assumes that the pattern of future energy use will be very much the same as it is now, except that, as oil and gas are depleted, they will be replaced by synthetic oil and gas made from coal. At the same time, the oil and gas used to generate electricity will be replaced by coal. This scenario, while not a "worst possible case", does not attempt to reduce the demand for fossil fuel, nor does it attempt to reduce emissions from CO_2 and the other greenhouse gases.

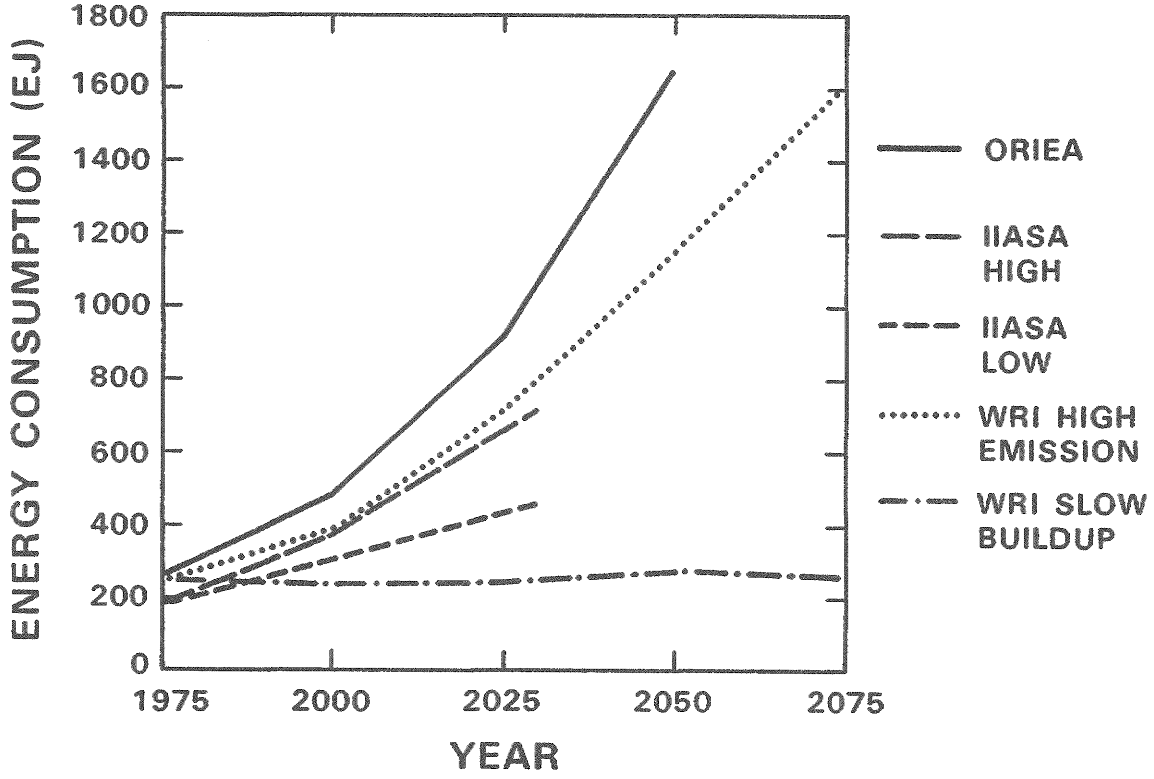


Figure 2.2 Global Energy Consumption Projection Comparison

Figures 2.3a through 2.3d show our assumptions about how the fractional mix of energy sources progresses with time for the Steady Scenario. These figures illustrate our assumption that little change is made to the energy mix and that synthetic oil and gas produced from coal will gradually displace fossil oil and gas beginning in the year 2000. This assumption was motivated by the fact that fossil oil and gas will be depleted during the 21st century. The Steady Scenario would deplete fossil oil by 2038 if synthetic oil is not substituted. This is based on the global fossil energy resources shown in Table 2.2. The information in Table 2.2 was derived using data from Hafele (1981) and represents what they call recoverable resources; for example, the oil figure is recoverable at $20 (1975 dollars) per barrel or less. The quantity of a recoverable resource will, of course, depend on the cost of competing resources.

Table 2.2
World Recoverable Fossil Fuel Resources, EJ

Oil	11,000
Natural Gas	8,900
Coal	250,000

To avoid a discontinuity in oil supply, we required a smooth transition from fossil to synthetic oil. The slopes of the synthetic oil and gas displacements were established by requiring that the fractions be linear with time and that the fractions of fossil oil and gas consumption reach zero at the same time the resource is depleted. With this transition from fossil to synthetic oil, fossil oil will be depleted in 2068 under the Steady Scenario. The real progression will be considerably more complicated and will be driven by economic and political considerations.

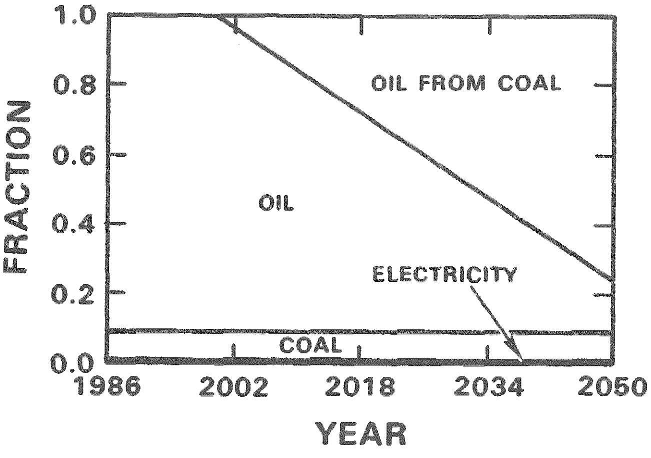


Figure 2.3a Steady Scenario Fractions for Transportation Energy Consumption

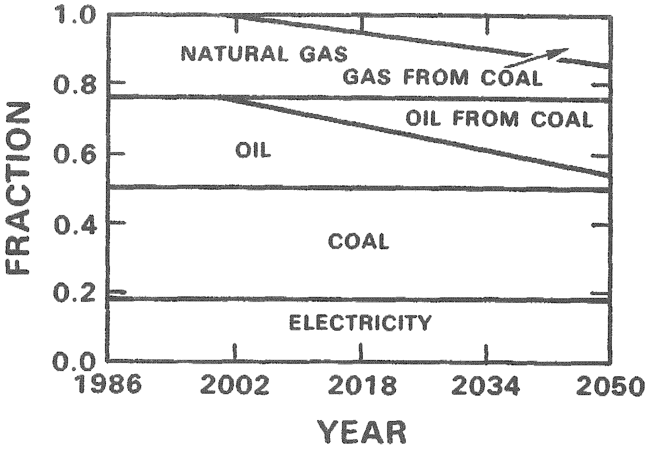


Figure 2.3b Steady Scenario Fractions for Industrial Energy Consumption

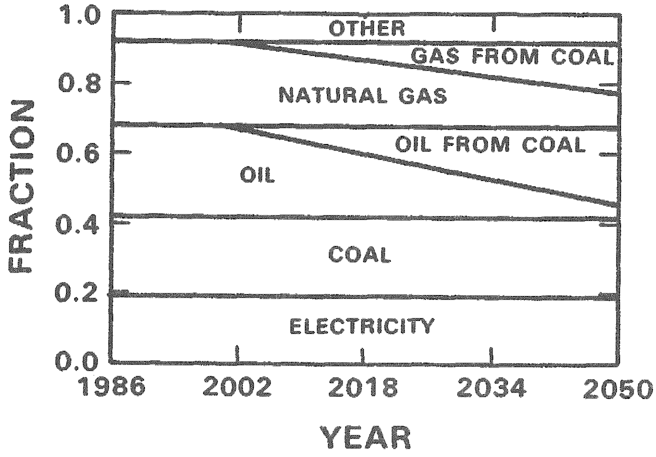


Figure 2.3c Steady Scenario Fractions for Agrescom Energy Consumption

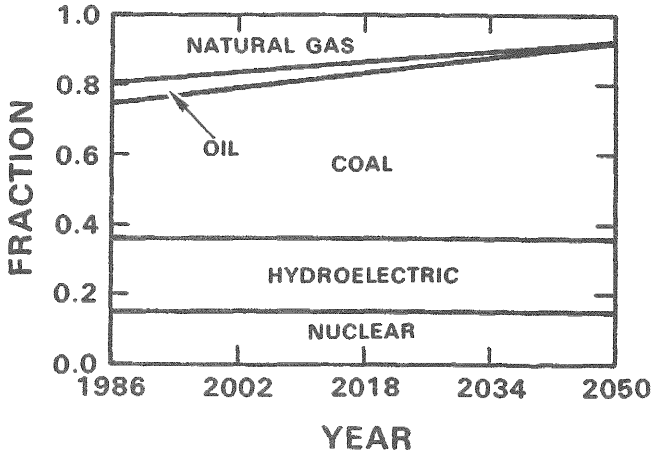


Figure 2.3d Steady Scenario Fractions for Electrical Generation Consumption

Our Steady Scenario assumption about replacing fossil oil and gas with synthetic oil and gas requires that the capacity to produce 1.2 million barrels of synthetic oil and 1.8 billion cubic feet of synthetic gas daily must be installed in the year 2000. The capacity added each year must increase to five times that rate by 2050. These synthetic fuel production capacity additions may seem overly ambitious; however, delaying additions or reducing additions, under the Steady Scenario, will require higher capacity additions at a later date if a discontinuity in the oil supply is to be avoided.

Oil shale is another potential source of synthetic oil, but we did not include it in our scenarios because its production and use emits more CO_2 per unit energy than oil produced from coal, as will be discussed later. This assumption may prove to be in error because shale oil is less expensive to produce than synthetic oil derived from coal (Edmonds, 1985), and its lower cost might outweigh its higher CO_2 emission.

<u>Reduced Emission Trend Energy Scenario</u>--Our Reduced Scenario, like the Steady Scenario, starts with the energy consumption pattern shown in Figure 2.1 and with an annual energy consumption growth rate of 2%; however, it allows energy conservation and efficiency improvements to reduce the baseline energy demand at the rates specified in Table 2.3.

Table 2.3
Reduced Scenario Conservation and Efficiency
Improvement Rates, Percent per Year

Transport	1.00
Industry	0.15
Agrescom	0.35

While more and less rapid improvement rates are quite possible, these values are our assessment of what may realistically be accomplished between 1986 and 2050. They are not based on specific technological, sociological, or political changes, nor are they limitations. If all technically possible improvements are realized and if they completely penetrate the world's economy (we believe this is unlikely), conservation and efficiency improvement rates would far exceed those we have assumed.

Transportation is the sector with the greatest conservation potential. Table 2.4 shows the fraction of U.S. energy currently used by each transportation subsector and estimates for potential reduction in energy use by 2050 (Cheng, 1986). The potential reduction estimates represent a combination of more efficient engines, lower weight, and better aerodynamic designs. The automobile figure is based on a 40 mpg fleet average. Even better fuel economy is possible but practicality is not clear. MacCready (1989) suggests that 200 to 300 mpg is possible using small, ultralight, extremely aerodynamic vehicles. The combination of current consumption fractions and potential reductions enumerated in the table result in an overall transportation energy reduction of 59% for the U.S. by 2050. This reduction should be interpreted as a per-passenger-mile or a per-freight-ton-mile reduction. Further reductions are possible if commuters switch from single passenger vehicles to carpools or mass transportation and if freight transportation switches from truck to rail which is considerably more efficient.

Table D.1
U.S. Transportation Energy Use and
Potential Reductions by 2050

Subsector	Current Consumption %	Potential Reduction %
Aircraft	12	50
Truck	27	60
Bus and Rail	5	30
Ship	5	40
Automobile	51	65

We have adopted a more moderate conservation and efficiency improvement scenario for reduced consumption for two reasons. The first is that the U.S. share of world transportation energy is roughly 30%, and other OECD countries presently have higher transportation efficiencies than the U.S. Thus, the world's reduction potential is not as great as that for the U.S. The second reason is that while a 59% or greater reduction is possible, the improvements mentioned above will not be completely adopted unless consumption patterns change. The present trend in the U.S. is toward lower transportation efficiency. For our Reduced Scenario, we use a 1% per year reduction in transportation energy due to conservation and efficiency improvements. This rate gives a 47% reduction (based on per-passenger-mile or per-freight-ton-mile) by 2050. Thus, instead of growing from 74.7 EJ in 1986 to 265 EJ in 2050 as in the Steady Scenario case, transportation energy consumption would grow to only 141 EJ.

Industry is presumed to have the least potential for conservation and efficiency improvements. Cheng (1986) estimates that conservation and efficiency can reduce U.S. industrial energy consumption (per unit of product) by 47 percent by 2050. This reduction is possible using a combination of more efficient thermal processes, more extensive use of heat exchangers to recover waste heat, and more efficient electric drives and motors.

We have assumed a more conservative reduction for two reasons. U.S. industry is less efficient than industry in other OECD countries; thus, their potential for improvement is lower. Also, most industrial growth is projected to be in developing countries, and we assume that these countries will not use the most efficient processes in the beginning. The most efficient processes are capital intensive and developing countries have limited capital. We assume an energy reduction rate of 0.15 percent per year, which gives an energy reduction (per unit of product) of 10% by 2050. Instead of growing from 94.2 EJ in 1986 to 335 EJ in 2050, as in the Steady Scenario, industrial energy consumption will grow to 304 EJ.

Energy consumption for the agrescom sector is assumed to have a lower conservation and efficiency improvement potential than transportation but a greater potential than industry. Cheng (1986) estimates a potential U.S. residential-commercial energy reduction of 58% by 2050. This is based on the use of building shells with reduced heat losses, more efficient heating and air conditioning units, more extensive use of heat pumps, and more efficient lighting. Changes will occur slowly because buildings have long lifetimes, but by 2050 most present buildings will be replaced.

We use a more conservative 0.35 percent per year reduction rate which reduces energy consumption by 20% by 2050. Larger reductions are certainly possible, but we are not convinced that the more energy efficient building methods will be used extensively in the near term unless they are dictated by building codes. Instead of increasing from 84 EJ in 1986 to 298 in 2050, as in the Steady Scenario case, agrescom's energy consumption will increase to only 239 EJ.

For the Reduced Scenario, we have also assumed that electrical generation efficiency will improve by 0.2% each year from 32% in 1986 to 36.4% in 2050. Some analysts look at today's most efficient electrical generation plants, which have efficiencies near 40%, and project that these efficiencies can be achieved for all generation systems in the future. This improvement will probably not be realized because electrical generation is a mix of base, intermediate, and peak load plants. Base plants tend to have the highest efficiencies because of the economic trade-off between capital cost and operating cost. We expect that future electrical generation will continue to use a mix of more and less efficient plants.

The above energy consumption, conservation, and efficiency growth rate scenarios allow us to make energy consumption projections, but they do not specify which energy sources will be used to meet the demand for energy. Our assumed mix of energy sources is shown in Figures 2.4a through 2.4d. The beginning mix is that shown in Figure 2.1. Like the conservation and efficiency improvement scenarios, these mixes are our estimates of how the world's consumption of energy may progress. The Reduced Scenario gradually replaces fossil fuels with geothermal, solar and other renewable, and nuclear sources. Again, this is not the most optimistic scenario imaginable, but it does project what we believe is an aggressive but realistic evolution to nonfossil energy forms.

This scenario projects that geothermal and solar/renewable (solar/renewable includes solar, wind, ocean, and biomass) energy sources will each satisfy roughly 10% of global energy needs by the year 2050. The estimated accessible energy resource from hydrothermal convection systems exceeds the oil resource in the U. S. (Muffler, 1979). If potentially accessible magma and hot-dry-rock geothermal sources are included, the world has a very

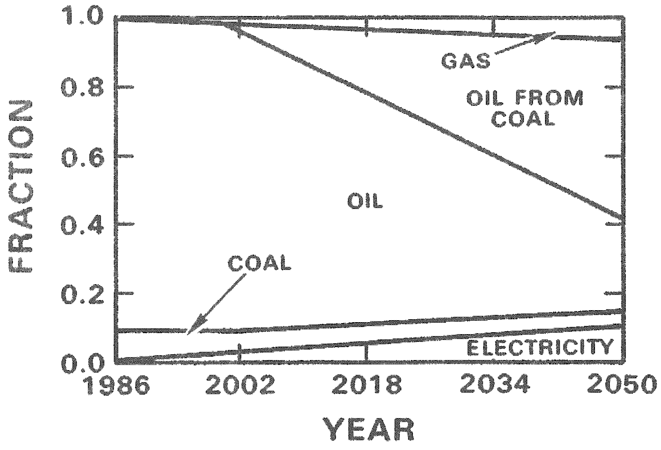


Figure 2.4a Reduced Scenario Fractions for Transportation Energy Consumption

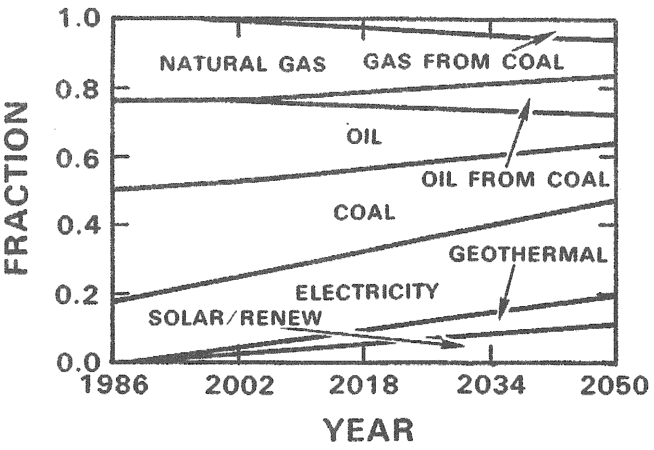


Figure 2.4b Reduced Scenario Fractions for Industrial Energy Consumption

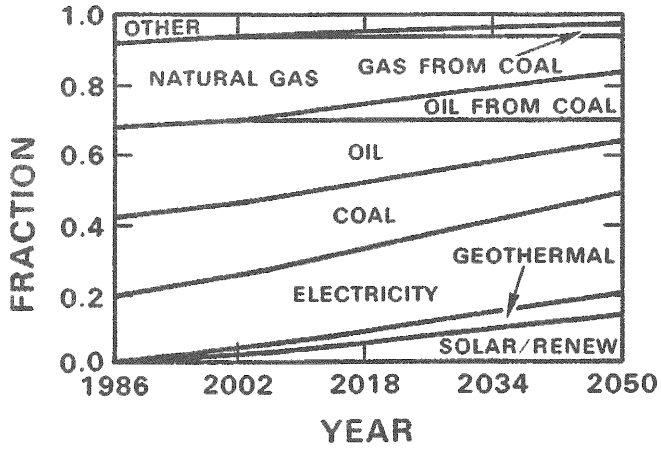


Figure 2.4c Reduced Scenario Fractions for Agrescom Energy Consumption

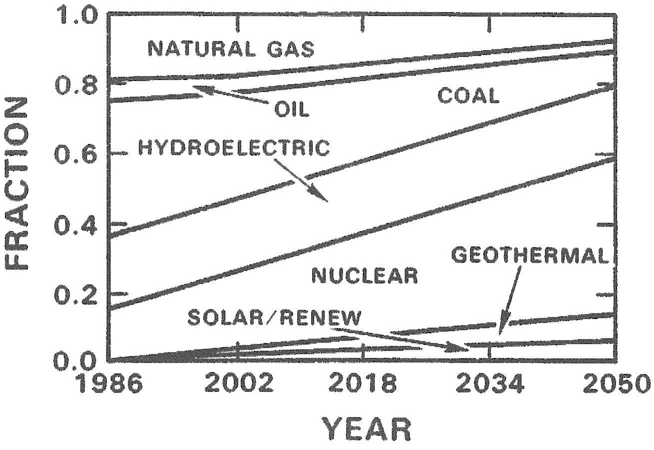


Figure 2.4d Reduced Scenario Fractions for Electrical Generation Consumption

large geothermal resource indeed. The potential for using solar/renewable energy sources is also huge; but, our assumption is that, while their potential is large, the expense of exploiting them will limit their use. They will make a significant, but not dominant, contribution.

We did not include the use of oxygenated fuels to displace oil. These fuels can be produced from biomass using renewable energy sources and their own bagasse, which would give them no net CO_2 emissions. We did not include them because of our uncertainty in their potential; however, they may prove to be important.

The Reduced Scenario assumes an increasing use of nuclear power and requires construction of 14 new 1 GW nuclear power plants somewhere in the world each year during the near term and 115 each year around 2050, assuming a capacity factor of 0.65 and a generation efficiency of 32% in the near term, increasing to 36.4% in 2050. To put this construction rate in perspective, 13 new plants came on line in 1986 (the number has decreased since then) and 44 came on line in 1979, the peak year. The number of new nuclear reactors required for the future is easily within the world's capacity, but the present trend would have to be reversed.

Again, the fractions in Figure 2.4, which indicate switching from one energy source to another, and the conservation and efficiency improvements projected for the Reduced Scenario assume making changes without indicating what mechanisms may motivate the changes. Significant changes will not occur without motivating mechanisms. Creating such a scenario is an interesting exercise, but the real challenge is to define mechanisms which will motivate the desired conservation and efficiency improvements and energy source switching.

Table 2.5 summarizes the energy consumption projections for the two energy scenarios.

Table 2.5
Energy Consumption Projection Assumptions
(Percent per Year Except Where Noted)

	Transport		Industry		Agrescom	
	Stdy	Redc	Stdy	Redc	Stdy	Redc
1986 Energy Consumption EJ	74.7	74.7	94.2	94.2	84.0	84.0
Consumption Growth Rate	2.0	2.0	2.0	2.0	2.0	2.0
Conservation And Efficiency Improvement Growth Rate	.00	1.00	.00	.15	.00	.35
Net Consumption Growth Rate	2.0	1.00	2.0	1.85	2.0	1.65
1986 Electrical Gen. Eff. %	32.0	32.0	32.0	32.0	32.0	32.0
Electrical Gen. Eff. Growth	.00	.20	.00	.20	.00	.20

The energy mix fractions directly consumed by each sector and from electrical generation are compared for the two scenarios in Table 2.6. They are assumed to change linearly between the dates shown.

The total energy consumption resulting from our two scenarios is shown in Figure 2.5. Figures 2.6 and 2.7 show the energy consumption breakdowns for the Steady and Reduced Scenarios, respectively. Less fossil fuel, coal in particular, is consumed in the Reduced Scenario.

Table 2.6
Assumed Energy Mix Fractions

	1986 Both	2000 Stdy	2050 Stdy	2000 Redc	2050 Redc
Transportation					
Oil	.91	.91	.15	.89	.27
Synthetic Oil	.00	.00	.76	.00	.52
Natural Gas	.00	.00	.00	.02	.06
Synthetic Gas	.00	.00	.00	.00	.00
Coal	.08	.08	.08	.06	.04
Electricity	.01	.01	.01	.03	.11
Industry					
Oil	.26	.26	.04	.24	.08
Synthetic Oil	.00	.00	.22	.00	.12
Natural Gas	.24	.24	.10	.24	.10
Synthetic Gas	.00	.00	.14	.00	.06
Coal	.32	.32	.32	.28	.16
Geothermal	.00	.00	.00	.02	.08
Solar/Renewable	.00	.00	.00	.02	.12
Electricity	.18	.18	.18	.20	.28
Agrescom					
Oil	.26	.26	.04	.24	.06
Synthetic Oil	.00	.00	.22	.00	.14
Natural Gas	.24	.24	.10	.24	.10
Synthetic Gas	.00	.00	.14	.00	.04
Coal	.23	.23	.23	.21	.15
Geothermal	.00	.00	.00	.02	.06
Solar/Renewable	.00	.00	.00	.02	.14
Other	.08	.08	.08	.06	.02
Electricity	.19	.19	.19	.21	.29
Electrical Generation					
Oil	.06	.05	.01	.05	.03
Natural Gas	.19	.16	.07	.18	.07
Coal	.39	.43	.56	.31	.10
Hydroelectricity	.21	.21	.21	.21	.21
Nuclear	.15	.15	.15	.21	.45
Geothermal	.00	.00	.00	.02	.08
Solar/Renewable	.00	.00	.00	.02	.06

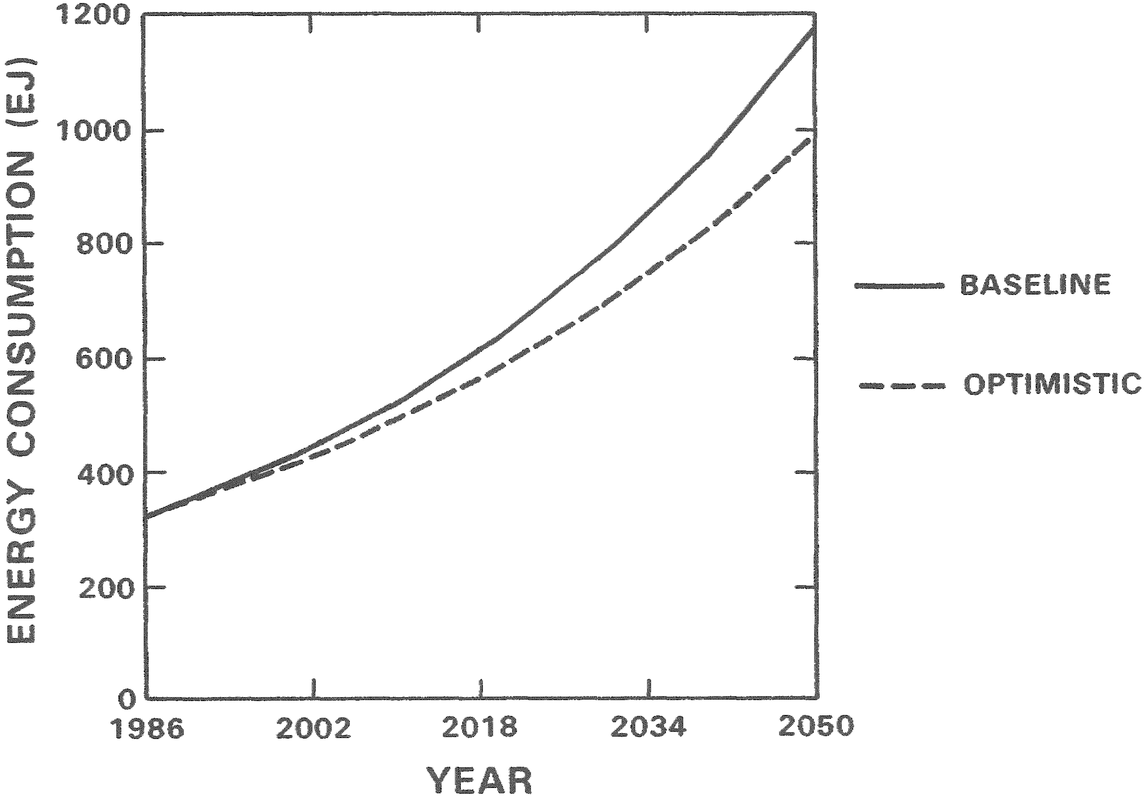


Figure 2.5 Energy Consumption Scenarios

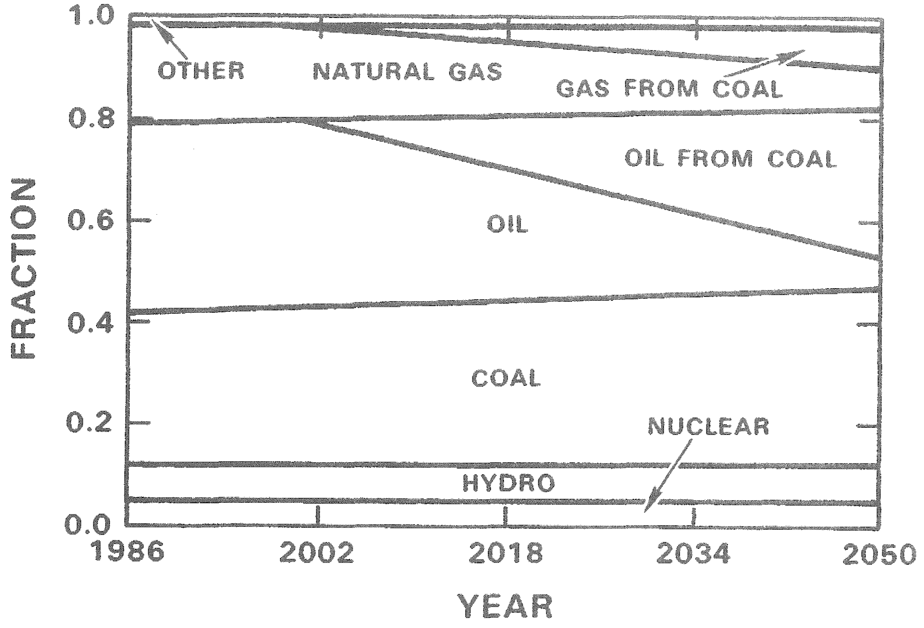


Figure 2.6 Total Energy Consumption, Steady Scenario Fractions

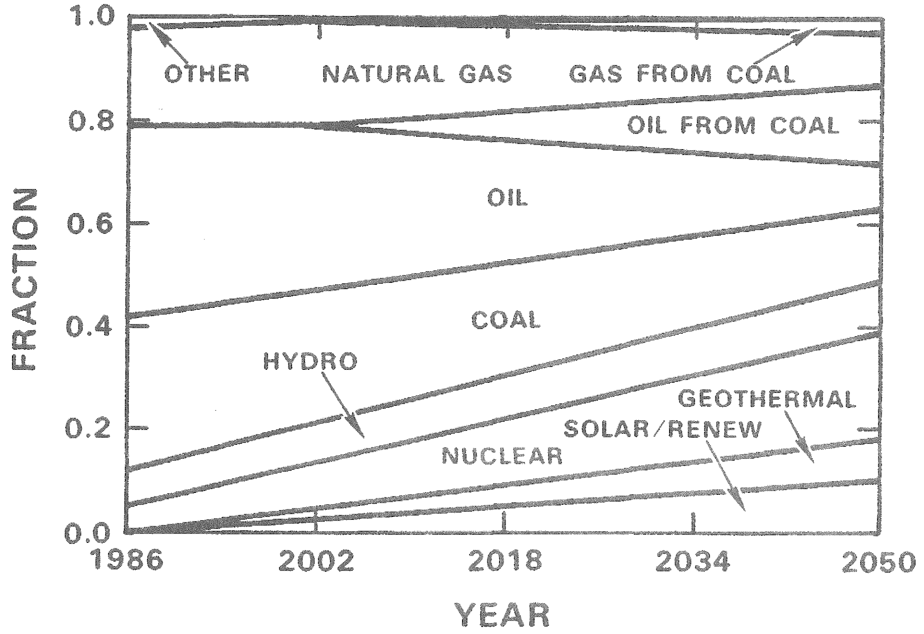


Figure 2.7 Total Energy Consumption, Reduced Scenario Fractions

Energy Related CO_2 Emissions--The carbon emissions per unit energy of coal, oil, and gas are shown in Table 2.7, along with emission estimates for synthetic oil and gas made from coal, shale, and tar sand (Mintzer, 1987). Of the natural fuels, coal produces the most carbon, with natural gas producing about half and oil about three-quarters the carbon that coal produces on a per unit energy basis. The synthetic fuels generate considerably more carbon emissions because of the substantial amount of energy required to produce them, in addition to the carbon emitted in their consumption. Figure 2.8 shows a CO_2 flow chart constructed using Table 2.6 and the 1986 energy consumption values form figure 2.1.

Table 2.7
Carbon Emissions of Fossil Fuels, MtC/EJ
(Megatonnes carbon per exajoule)

Natural Gas	13.8
Oil	19.7
Coal	26.9
Synthetic Oil	38.6
Synthetic Gas	40.7
Shale Oil	47.6

Geothermal energy can also emit CO_2, which is dissolved in the working fluid. The quantity of CO_2 being emitted depends on the geothermal field being used and the energy conversion mode. Figure 2.9 shows the relative carbon emissions for coal, oil, gas, and geothermal energy on the basis of MtC per EJ of generated electricity. This geothermal emission estimate is from the currently operating Geyser field in California (Randerson, 1984). For a geothermal plant operating in the "binary" mode, there should be essentially no carbon emissions.

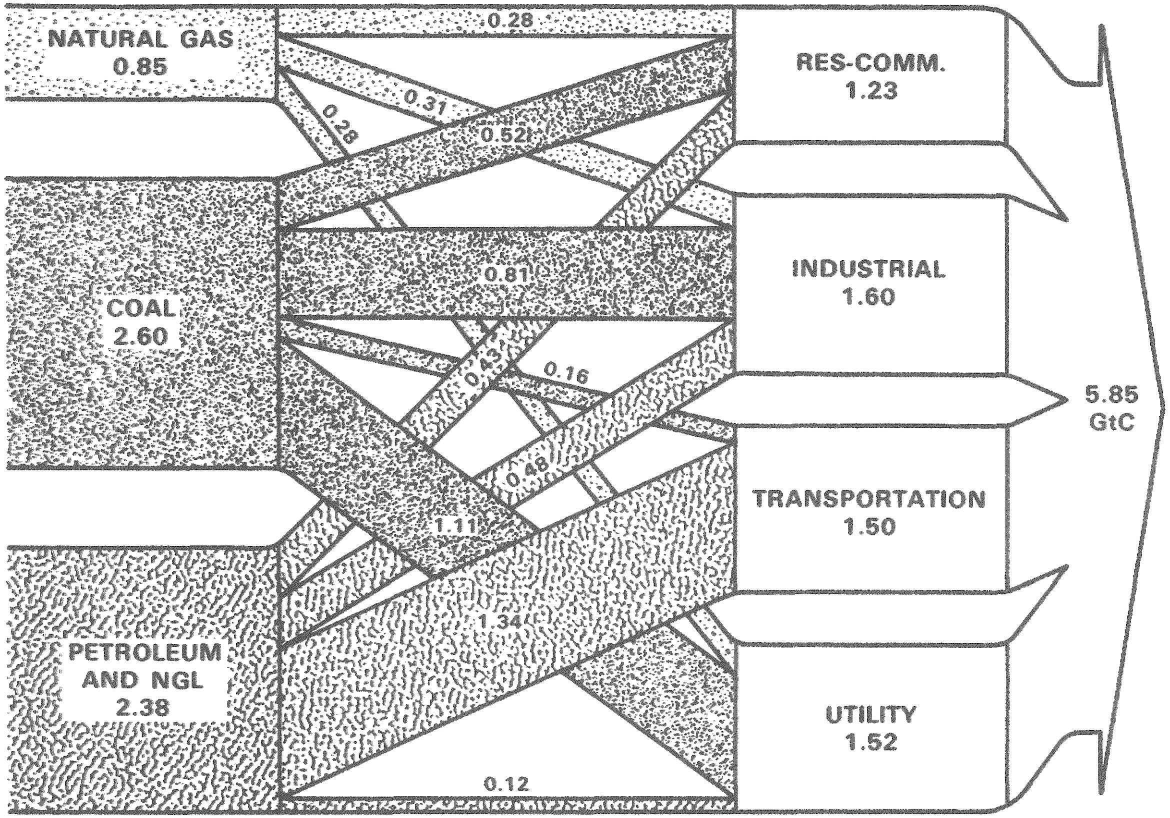


Figure 2.8 1986 Emission of CO_2 to the Atmosphere From Global Energy Use

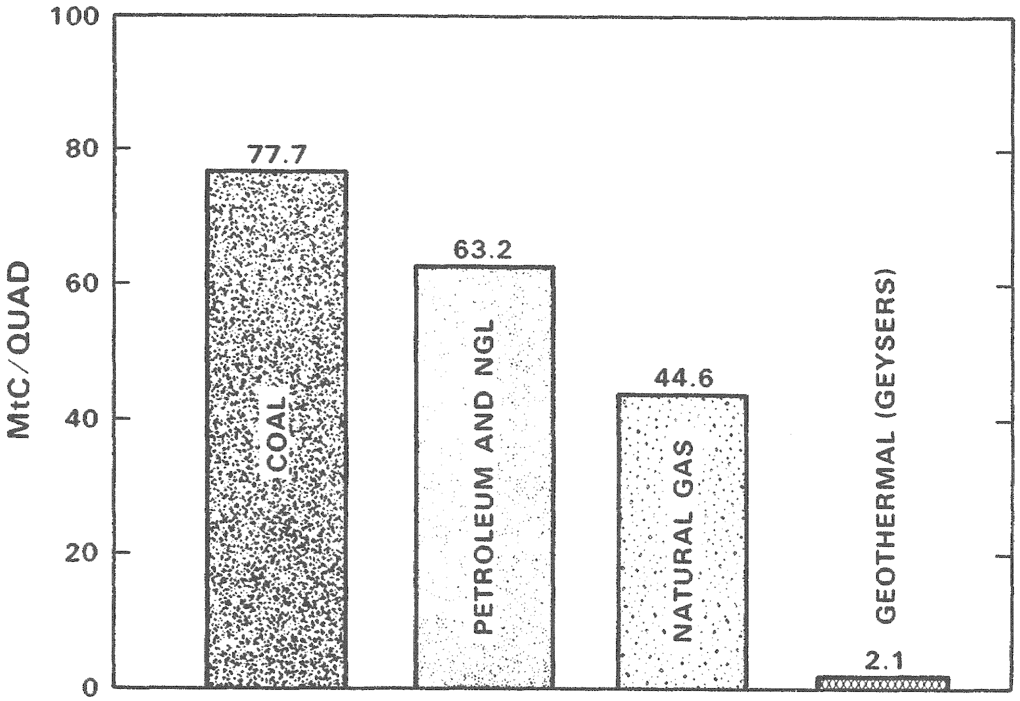


Figure 2.9 Carbon Dioxide Emissions in Megatonnes Carbon Per Quad of Distributed Electrical Energy

The emissions of CO_2 due to energy consumption are directly estimated from the previously described energy scenarios, with the use of Table 2.7.

Greenhouse Gas Emission Scenarios--Associated with each of the two energy scenarios are parallel scenarios for the emissions of nonenergy, anthropogenic CO_2 and for the other greenhouse gases: N_2O, CH_4, O_3, CFC-11, and CFC-12. For consistency, the initial (1986) atmospheric concentrations and the Steady Scenario emissions are chosen similar to those in Mintzer (1987). Although the 1986 concentration of atmospheric methane has been measured, its emission history has only been very crudely estimated because of the large nonanthropogenic and significant nonenergy components of its emissions. Consequently, growth rates are applied directly to its concentration (see Chapter 3), and emission values are not used. Because of the extreme instability of tropospheric ozone--it is constantly being created and destroyed by various chemical and photo-sensitive processes--and the extreme variability of its temporal and local concentration, an initial concentration has not been selected. We specify its concentration rate of growth for each of the two scenarios and base its effect on its concentration relative to that in 1986 instead of on its absolute value (see Chapter 3). Table 2.8 shows the estimates of the initial concentrations and anthropogenic emissions of the greenhouse gases used in the two scenarios.

Our choice of 1600 MtC/yr for nonenergy anthropogenic CO_2 emission is consistent with Mintzer (1987). This choice also represents a compromise since estimates of these net emissions vary widely, from a high of 3200 MtC/yr to a low of virtually zero (USDOE, March 1988). The 1986 emissions of the CFC's are estimated from Hammitt (1986). The remaining estimates are from Mintzer (1987).

Table 2.8
Greenhouse Gas Atmospheric Concentrations and Emissions for 1986

	Concentration, ppbv	Emission, Mt/yr
Carbon Dioxide	346,800.0	1600.0*
Nitrous Oxide	304.0	5.0
Methane	1650.0	-
Ozone	-	-
CFC-11	0.240	0.353
CFC-12	0.409	0.454

* The CO_2 emission is for nonenergy, anthropogenic emissions only, in units of MtC/yr: emissions from energy are associated with the energy consumption scenarios.

The Steady and Reduced Scenarios are differentiated by the growth rates of the various emissions or concentrations given in Table 2.9. For consistency, we match our Steady Scenario for these phenomena to the WRI High Emissions case. Our Reduced Scenario represents our estimate of what may be accomplished in reducing emissions over the next 64 years. In keeping with the methodology of the WRI report, the emission growth of N_2O is set equal to the growth of coal use both as a source of synthetic oil and gas and as a primary fuel (see Chapter 3). The initial concentrations and emissions and emission and concentration growth rates given in this chapter are used to calculate time-dependent concentrations and the resulting global temperature increases using the algorithms presented in Chapter 3.

Table 2.9
Emission (or Concentration) Fractional Growth Rates per Year

	Steady Scenario	Reduced Scenario
Carbon Dioxide (Nonenergy)	0.00	-0.02
Nitrous Oxide	(Equal to growth of coal usage)	
Methane (Concentration)	0.024	0.010
Ozone (Concentration)	0.0023	0.0005
CFC-11	0.030	0.010
CFC-12	0.023	0.010

Chapter III. Atmospheric Concentration and Global Warming Models

Atmospheric Concentration Models--The following models (Mintzer, 1987) convert annual emissions into annual atmospheric concentration levels and implicitly include absorption and decomposition effects. All emissions are in Mt, except CO_2, which is in MtC (metric tons of carbon). We use the following notations:

y is a subscript denoting the year,
C_y is atmospheric concentration, ppbv, year y, and
E_y is the emission in year y.

Carbon Dioxide: $$C_y = C_{y-1} + A\ F_C\ E_y. \qquad (3\text{-}1)$$

F_C = CO_2 conversion factor = 0.471 ppbv/MtC.
A = Airborne fraction = 0.40.

The value of A is selected from the slope, adjusted by the conversion factor, of the least-squares line fit to CO_2 concentration growth vs. cumulative anthropogenic (energy plus nonenergy) emissions in Figure 1.1; A = 0.187/0.471 = 0.40. A physical interpretation of this model is that 40% of the anthropogenically emitted CO_2 remains in the atmosphere. Later in this chapter we will offer an alternative model which relates atmospheric concentrations to CO_2 emissions.

Nitrous Oxide: $$C_y = C_{y-1} + F_N\ E_y - (C_{y-1} - P_N)/L_N \qquad (3\text{-}2)$$

F_N = N_2O conversion factor = 0.127 ppbv/Mt.
P_N = Preindustrial concentration of N_2O = 282 ppbv.
L_N = "Apparent atmospheric life" of N_2O = 150 years.

The "apparent atmospheric life" used in these models is not necessarily the average atmospheric residence time of a molecule. We define its inverse to be the proportion of the difference between current concentration and preindustrial concentration which is removed from the atmosphere each year. See Stuiver (1980) or Weiss (1981).

Methane: $$C_y = C_o (1 + G_M)^y . \qquad (3\text{-}3)$$

C_o = Initial concentration (1986) = 1650 ppbv.
G_M = Methane concentration growth rate, scenario dependent, Table 2.8.
y = Years since 1986.

Ozone: $$C_y = 100 (1 + G_O)^y . \qquad (3\text{-}4)$$

C_y = Ozone concentration in percent, relative to 1986.
G_O = Ozone concentration growth rate, scenario dependent, Table 5.6
y = Years since 1986.

CFC-11: $$C_y = (1 - 1/L_{11})\, C_{y-1} + F_{11} E_y . \qquad (3\text{-}5)$$

L_{11} = Apparent atmospheric life of CFC-11 = 75 years.
F_{11} = CFC-11 conversion factor = 0.041 ppbv/Mt.

CFC-12: $$C_y = (1 - 1/L_{12})\, C_{y-1} + F_{12} E_y . \qquad (3\text{-}6)$$

L_{12} = Apparent atmospheric life of CFC-12 = 111 years.
F_{12} = CFC-12 conversion factor = 0.047 ppbv/Mt.

Alternative CO_2 Atmospheric Concentration Model--The model for atmospheric CO_2 concentration presented above (Eq.3-1) has the physical interpretation that 40% of the anthropogenically emitted CO_2 remains in the atmosphere and 60% is absorbed by some mechanism. Many researchers have used this simple airborne fraction model to project trends in CO_2 concentration. Much more comprehensive models are being studied which involve a treatment of individual mechanisms (USDOE, 1984), but they will not be discussed here. There is an excellent motivation for using the airborne fraction model. As can be seen in Figure 1.1, the linear correlation between cumulative anthropogenic CO_2 emissions and atmospheric concentration is extremely good over the time period of the data.

The identification of potential physical mechanisms underlying this model is troubling, however. The model predicts that if anthropogenic CO_2 emissions were to cease, the atmospheric concentration of CO_2 would remain constant at an elevated level and would not decrease over time. This result could be obtained if another CO_2 sink quickly comes into equilibrium with the atmospheric sink so that each sink holds a fraction of the emitted CO_2. The upper 75 m of ocean has been suggested as such a sink (Bolin, 1986). However, the upper ocean layer is gradually replaced by water from the deep ocean due to diffusion and circulation, and the ocean's capacity to absorb CO_2 is gradually renewed until a total ocean equilibrium is reached, which may take centuries. Thus, if anthropogenic emissions were to cease, the ocean would remove CO_2 from the atmosphere, decreasing its concentration, until a new equilibrium is reached. While the airborne fraction model does an excellent job of fitting past concentrations when CO_2 emissions were increasing, we are concerned that it may not accurately predict concentration if CO_2 emissions become level or decrease.

We suggest an alternative CO_2 atmospheric concentration model for estimating concentration trends It may be more compatible with realistic physical mechanisms than the airborne fraction model in that it allows CO_2 concentration to decrease if emissions cease. This model, which we will call the "concentration dependent" model, assumes that the rate of change of atmospheric CO_2 concentration is equal to the rate of CO_2 generation minus the rate of absorption, and that the rate of absorption contains a constant sink term and a concentration dependent term--gC(t):

$$dC(t)/dt = S_o + F_c\,E(t) - S_i - gC(t), \qquad (3-7)$$

where

$C(t)$ = time-dependent CO_2 concentration, ppbv,
t = time, years,
S_o = constant natural source rate of CO_2, ppbv/yr (This source is actually in MtC/yr, but is converted to ppbv using 0.471 ppbv/MtC.)
S_i = constant sink rate, ppbv/yr,
$E(t)$ = time dependent anthropogenic CO_2 emission rate, MtC/yr,
F_c = conversion factor, 0.471 ppbv/MtC.
g = an absorption constant, yr^{-1}.

This formulation assumes that the sink rate (excluding the constant sink rate) is directly proportional to atmospheric concentration. In reality the concentration dependent sink rate would almost certainly be more complicated than a simple linear proportion.

Preindustrial concentration, C_o, is found by setting dC/dt and E(t) to zero, yielding

$$S_i - S_o = gC_o. \qquad (3-8)$$

With this the model becomes:

$$dC/dt = g[C_o - C(t)] + F_C\, E(t). \qquad (3\text{-}9)$$

If we assume that E(t) is a step function with value E_y during the y^{th} year, then the solution of equation (3-9) is

$$C_y = C_{y-1} + g(C_o - C_{y-1}) + F_C\, E_y, \qquad (3\text{-}10)$$

if we use time steps of one year and note that $g << 1$. C_y and C_{y-1} are, respectively, the concentration in year y and y-1.

Equation 3-18 was used to model the relationship between anthropogenic CO_2 emission data and measured atmospheric concentration data by selecting values of g and C_o which best fit the data. The results are shown in Figure 3.1. The best-fit values are

$$g = 0.028\ yr^{-1},$$
$$C_o = 270\ ppmv.$$

The estimated value of C_o is well within typical estimates of the preindustrial concentration of CO_2. The fit shown in Figure 3.1 is excellent, as is the airborne fraction model fit in Figure 1.1.

While both models accurately correlate past emission data with measured concentration data, there are some important differences between the two.

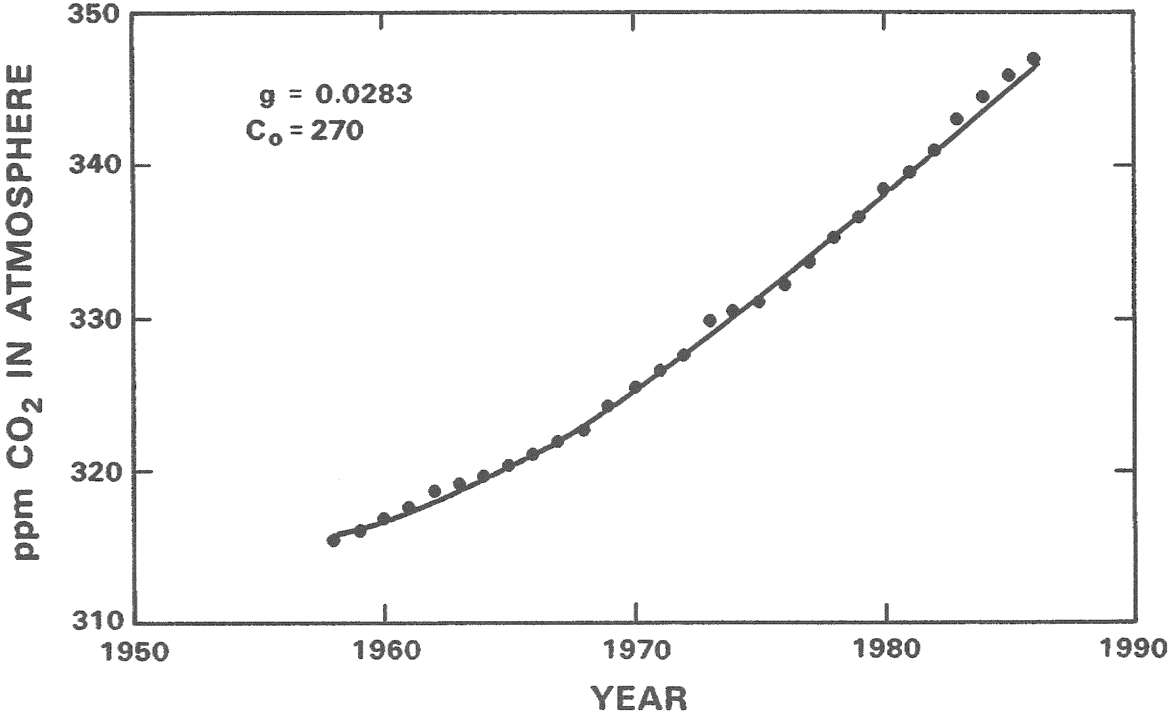


Figure 3.1 Comparison of the Atmospheric CO_2 Concentration Dependent Model with Historic Data

1. The airborne fraction model predicts that the CO_2 concentration increase is irreversible. Forty percent of the anthropogenically emitted CO_2 remains in the atmosphere forever. If anthropogenic emissions are reduced to zero, the CO_2 concentration will remain constant. The concentration dependent model predicts that the concentration increase is reversible. If anthropogenic emissions cease, the concentration will gradually return to preindustrial levels, as a consequence of the concentration dependent sink model.

2. The airborne fraction model predicts that if anthropogenic emissions reach a steady-state value, concentration will steadily increase. The alternative model predicts that if anthropogenic emissions reach a steady-state, concentration will achieve a new equilibrium level.

3. Atmospheric concentration of CO_2 is weighted equally on past and present anthropogenic emissions in the airborne fraction model, but recent emissions are weighted more heavily than past emissions in the concentration dependent model.

4. As will be illustrated in later sections of this report, the alternative model predicts more leverage in concentration reduction for measures which reduce CO_2 emissions than does the airborne fraction model. Rapidly increasing emissions will cause higher concentrations under the concentration dependent model but lower concentrations will be predicted if emissions decrease. Thus, policies and measures designed to reduce CO_2 emissions are predicted to be more effective by the concentration dependent model than by the airborne fraction model, as a consequence of item three above.

5. Because of the four items above, the concentration dependent model gives us more hope for being able to successfully limit the greenhouse effect than does the airborne fraction model.

One might believe that, because the concentration dependent model predicts reversibility, reducing CO_2 emissions is less critical. In fact, emissions reduction is more critical because the alternative model predicts worse consequences than the airborne fraction model if CO_2 emissions are not reduced, as will be seen later.

We must be cautious in adopting this or any other model because the true global sink mechanisms are not well understood and may contain some destabilizing factors such as reduced CO_2 solubility by the oceans due to increased global temperature and the erosion of other absorption mechanism caused by global climate changes.

Global Warming Models--The formulas for global temperature increase, in degrees K above 1986 temperature, associated with each of the greenhouse gases are given below. The symbol C_o denotes the concentration of the particular gas in question in 1986. These formulas were originally derived by Ramanathan, et al. (1985). They only include temperature increase due to the radiative effects from the increased atmospheric concentrations of the greenhouse gases. They do not include temperature feedback effects (positive or negative) caused by possible variations in ocean currents, atmospheric humidity, albedo due to cloud formation and ice and snow melting, temperature lag in ocean warming, etc.

Carbon Dioxide: $T_C(y) = 3.019\ [\mathrm{Ln}(C_y/C_{PI}) - \mathrm{Ln}(C_o/C_{PI})].$ (3-11)

C_{PI} = Preindustrial CO_2 concentration
= 275,000.0 ppbv.

Nitrous Oxide: $T_N(y) = 0.057\ [\sqrt{C_y} - \sqrt{C_o}].$ (3-12)

Methane: $T_M(y) = 0.019\ [\sqrt{C_y} - \sqrt{C_o}].$ (3-13)

Ozone: $T_O(y) = 0.1\ (C_y - 100)/15.$ (3-14)

Note: For ozone, C_y is the percent concentration relative to 1986.

CFC-11: $T_{11}(y) = 0.14\ (C_y - C_o).$ (3-15)

CFC-12: $T_{12}(y) = 0.16\ (C_y - C_o).$ (3-16)

The total temperature increase, from year 1986, in year y is

$$T(y) = T_C(y) + T_N(y) + T_M(y) + T_O(y) + T_{11}(y) + T_{12}(y). \quad (3\text{-}17)$$

On a per molecule basis, the radiative effect of methane is 20 times more severe than CO_2. The CFC effect is also very severe on a per molecule basis.

The algorithms given in this chapter allow us to calculate time-dependent atmospheric concentration and the associated contribution to global temperature rise for each of the greenhouse gases. Results based on the two scenarios are presented in Chapter 4.

Chapter IV. Results

Chapter II describes our two energy consumption scenarios, which are summarized in Tables 2.4 and 2.5 and in Figures 2.5 through 2.7. With these energy consumption scenarios and the emissions given in Table 2.6, we quantified energy related CO_2 emissions associated with each scenario. The CO_2 emissions for the Steady Scenario are shown in Figure 4.1, and those for the Reduced Scenario are shown in Figure 4.2. These figures do not include anthropogenic nonenergy emissions which will be included later in the chapter. Starting with the same CO_2 emission in 1986, the Reduced Scenario emits roughly half as much CO_2 as the Steady Scenario by the year 2050. Emissions are reduced by a combination of energy conservation, efficiency improvements, and switching among energy sources. In addition to reducing energy demand, conservation and efficiency improvements extend the use of oil and natural gas, thereby displacing synthetic (made from coal) oil and gas, which emit more CO_2 per unit energy than "natural" oil and gas. Increased use of hydroelectric, nuclear, geothermal, and solar/renewable energy also displace coal and synthetic fuels. Oil and natural gas are credited with some CO_2 displacement because they displace some coal. The relative contributions made to CO_2 emission reduction by conservation and efficiency improvements and by switching among energy sources are shown in Table 4.1. These percentages apply to the reduction of cumulative, energy related CO_2 emissions from 1986 to 2050. Conservation and efficiency improvements play the major role, but nuclear, geothermal, and solar/renewable energy are all also very important.

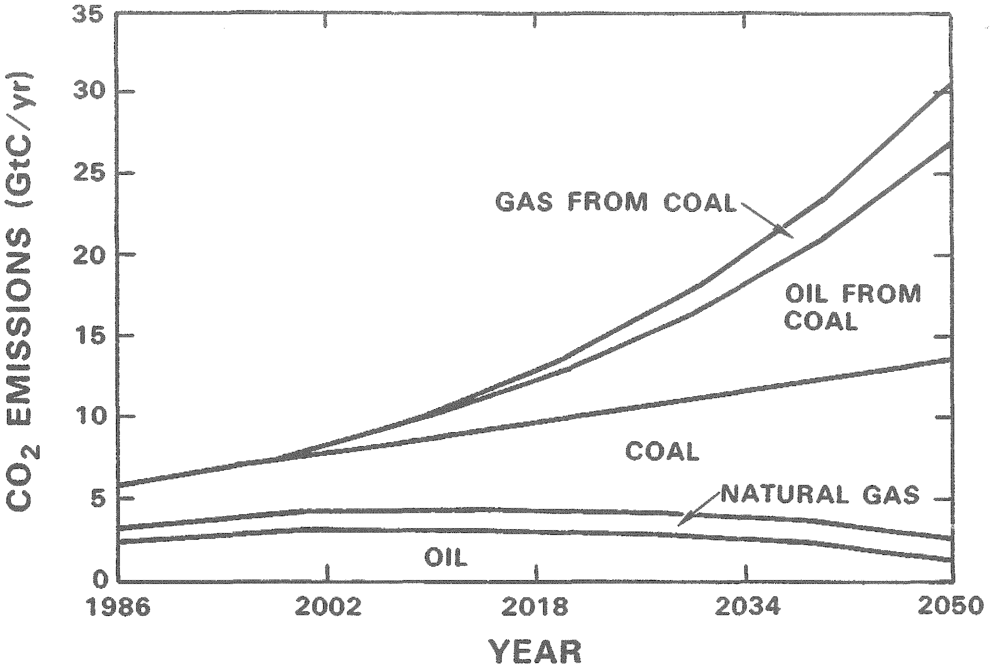


Figure 4.1 Steady Scenario CO_2 Emissions From Energy Consumption

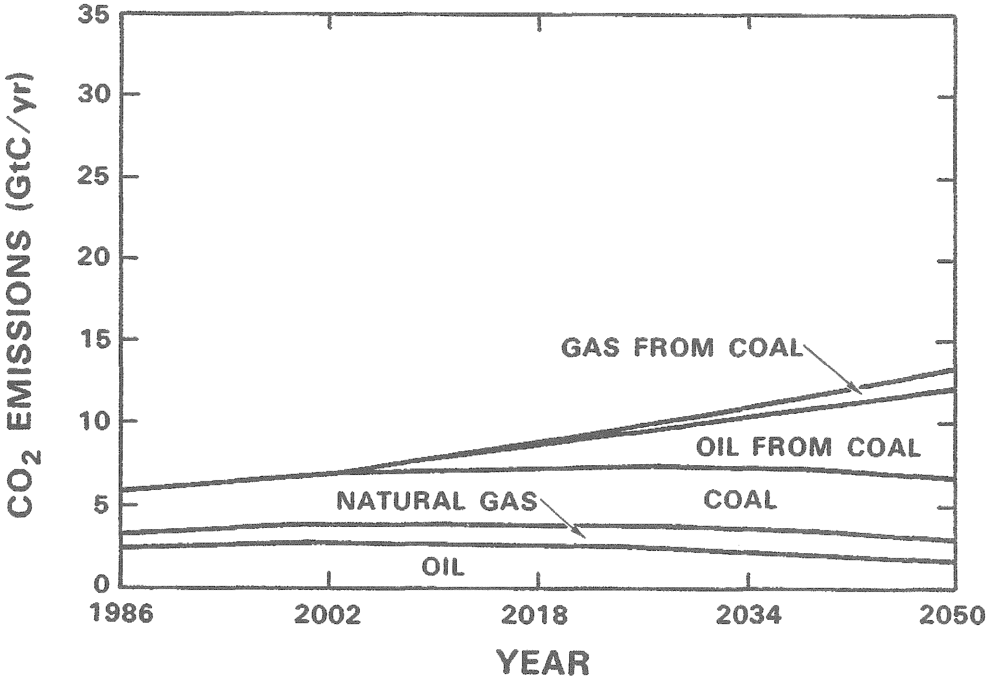


Figure 4.2 Reduced Scenario CO_2 Emissions From Energy Consumption

Table 4.1
Relative Contributions to the Reduction of CO_2 Emissions

Conservation and Efficiency	48%
Oil	2%
Natural Gas	3%
Hydroelectric	5%
Nuclear	20%
Geothermal	10%
Solar/Renewable	12%

We now consider both energy and nonenergy, anthropogenic emissions for both scenarios. The concentrations versus time of CO_2, N_2O, methane, and the CFCs are shown in Figures 4.3 through 4.6. The change in concentrations from 1986 to 2050 are summarized in Table 4.2.

Table 4.2
Atmospheric Concentrations in 1986 and 2050

	Concentration in ppbv			Percent Increase	
	1986	2050		2050	
		Steady	Reduced	Steady	Reduced
CO_2* (ppmv)	347	554	436	60	26
CO_2# (ppmv)	347	539	467	55	35
N_2O	304	448	370	47	22
Methane	1650	7530	3120	360	89
Ozone (%)	100	116	103	16	3
CFC-11	0.24	2.24	1.02	830	325
CFC-12	0.41	2.77	1.74	580	325

* Concentration dependent model, # airborne fraction model.

For the Steady Scenario, the percent increases in methane, and the CFCs are especially severe. In addition to the greenhouse temperature effect, the CFCs are a significant contributor to the destruction of stratospheric ozone, which helps protect global biota from UV radiation. Relative to the estimated preindustrial concentration of CO_2, 270 ppmv, the Steady Scenario shows the concentration doubling by 2050, while the Reduced Scenario indicates a 67% increase.

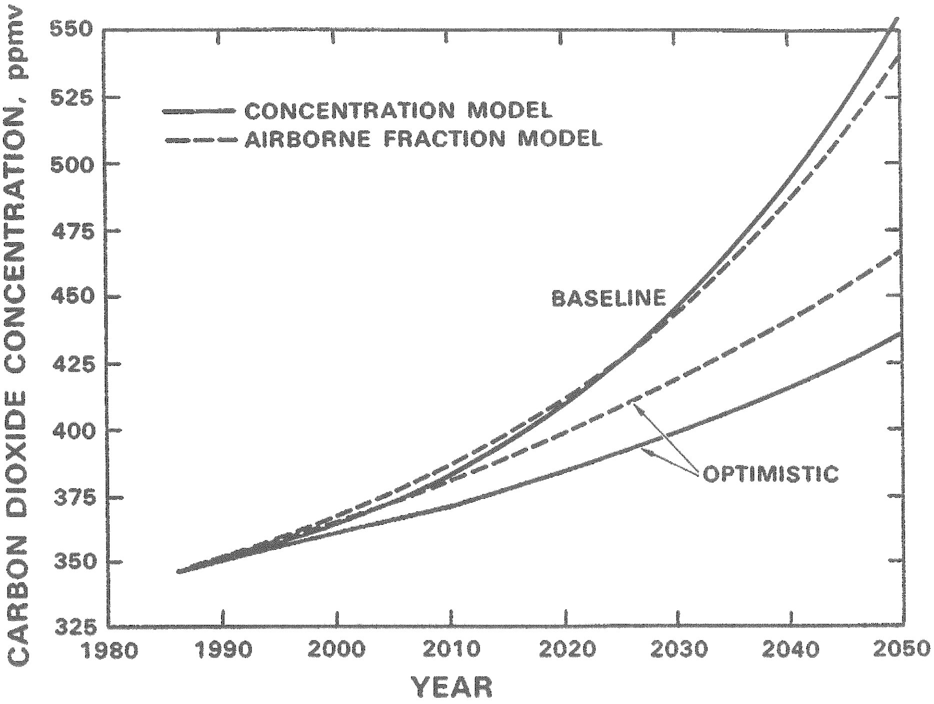


Figure 4.3 CO_2 Concentration

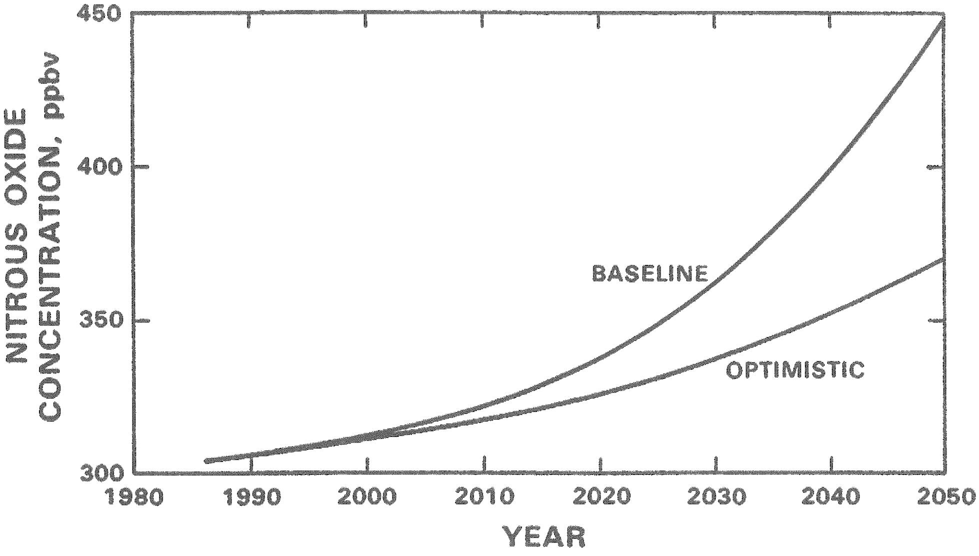


Figure 4.4 N_2O Concentration

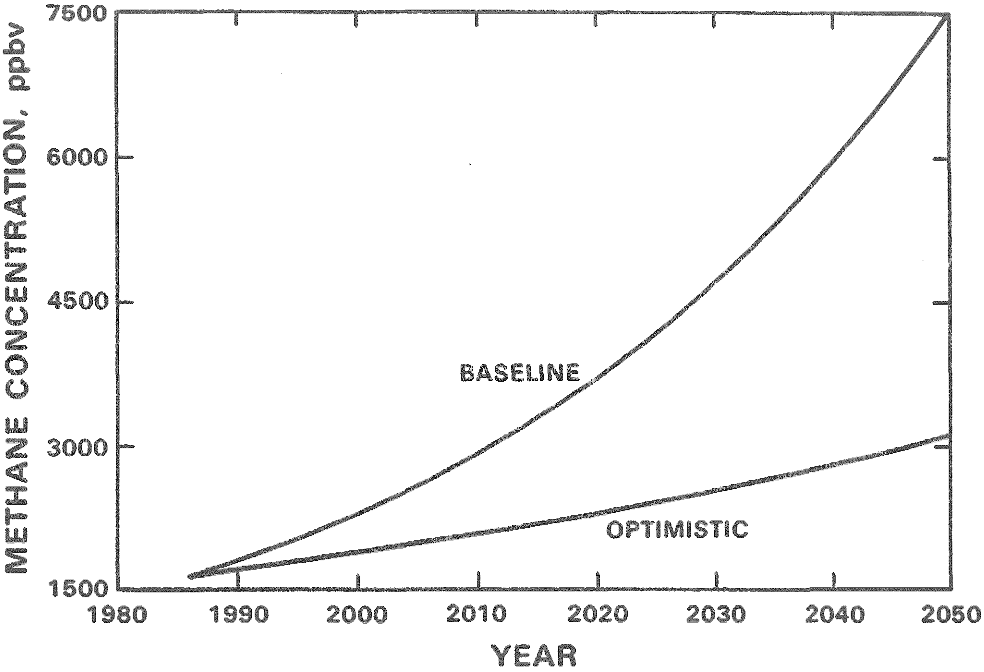


Figure 4.5 CH_4 Concentration

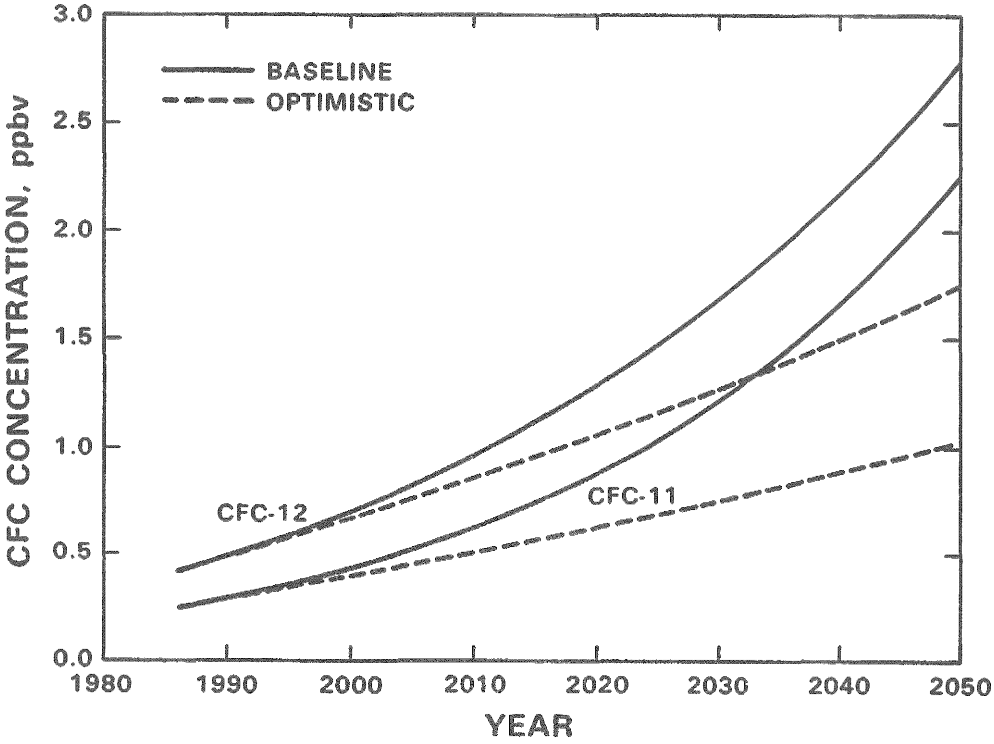


Figure 4.6 CFC Concentration

The average global temperature increase due to the greenhouse effect versus time is shown in Figures 4.7 and 4.8 for the Steady and Reduced Scenarios, respectively. The results for 2050 are tabulated in Table 4.3. For both scenarios, the major factor is CO_2, with methane and the CFCs also significant.

Table 4.3
Temperature Increase from 1986 to 2050

	Temperature Increase °K		Percent Contribution to Total Temperature Increase	
	Steady	Reduced	Steady	Reduced
CO_2*	1.4	0.7	43.3	48.3
CO_2#	1.3	0.9	-	-
N_2O	0.2	0.1	6.5	7.2
Methane	0.9	0.3	26.8	20.3
Ozone	0.1	0.02	3.2	1.5
CFC-11	0.3	0.1	8.6	7.7
CFC-12	0.4	0.2	11.6	15.0
Total*	3.3	1.4	100.0	100.0

* Concentration dependent model, # airborne fraction model.

These temperature increase estimates are the result of radiative effects only for the specified greenhouse gases. Feedback effects due to changes in atmospheric water vapor content, sea ice and surface albedo, and clouds are not considered. On average, they would tend to augment the temperature rise (Bolin, 1986). The temperature rise associated with each gas, shown in Figure 4.7 for the Steady Scenario, was decomposed into energy and nonenergy components, and the fractional contribution of each is shown in Figure 4.9.

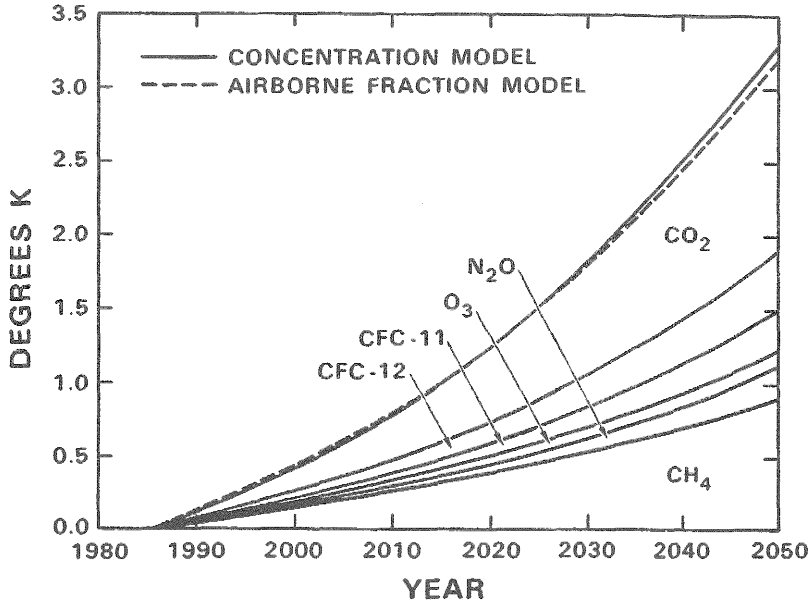


Figure 4.7 Global Temperature Rise for the Steady Scenario

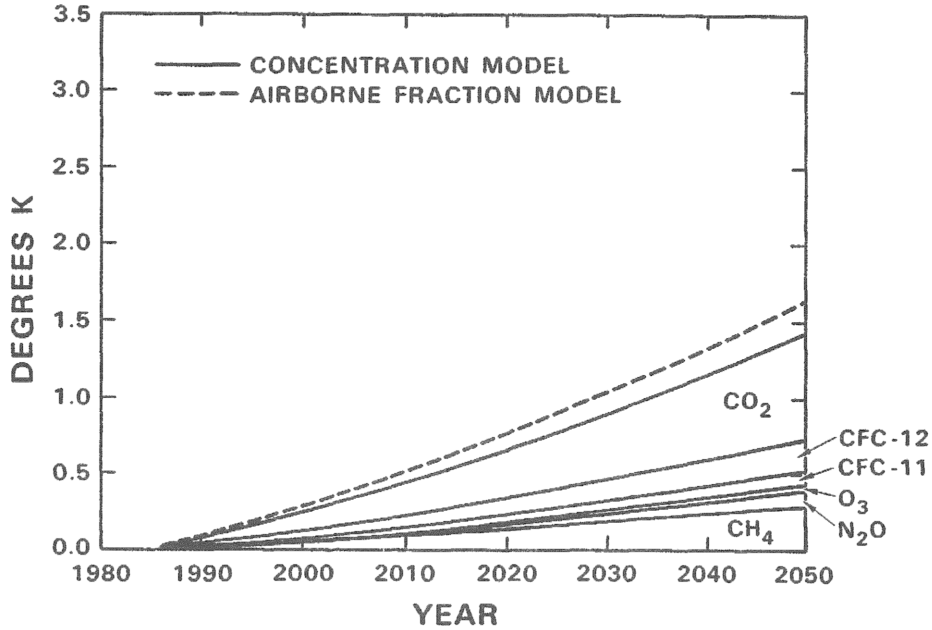
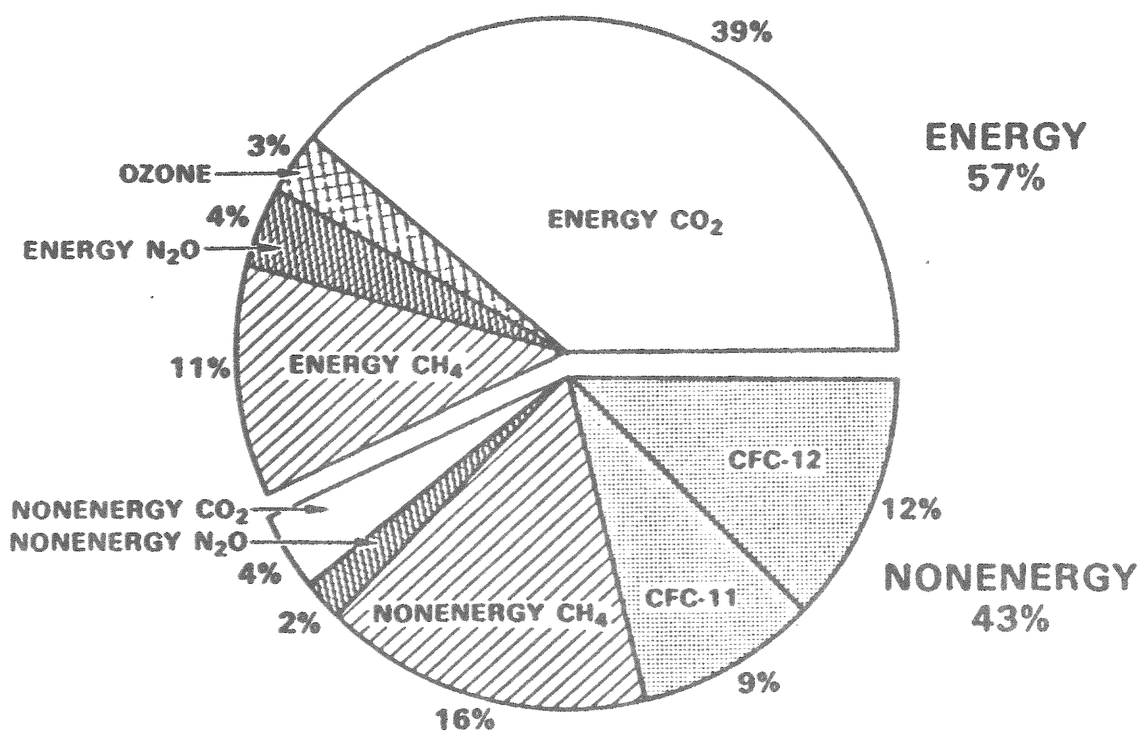


Figure 4.8 Global Temperature Rise for the Reduced Scenario



TOTAL TEMPERATURE RISE = 3.3 K

Figure 4.9 Relative Anthropogenic Contributions To an Increasing Greenhouse Effect Based on Steady Scenario, 1986 to 2050

Chapter V. Conclusions and Recommendations

Energy emissions, nearly all due to the consumption of fossil fuel, will contribute more than half (57% for the Steady Scenario) of the greenhouse effect. Mitigating global warming will require reducing energy related emissions; however, nonenergy anthropogenic emissions contribute nearly half and must also be reduced.

The results of this study illustrate that energy related emissions can be significantly reduced by a combination of conservation, efficiency improvements, and switching from fossil fuels to energy forms which release less CO_2 and other greenhouse gases. Based on our two scenarios, energy related CO_2 emissions were reduced by 38%. Of this, conservation and efficiency improvements contributed 48%, the increased use of nuclear contributed 20%, solar/renewable contributed 12%, and geothermal energy sources contributed 10%.

Our steady emission trend scenario, "Steady Scenario," predicts a 3.3 K average global temperature rise between 1986 and 2050 due to greenhouse radiative effects without feedbacks, while our reduced emission trend scenario, "Reduced Scenario," projects a temperature rise of only 1.4 K; thus, cutting global warming in half appears to be feasible by reducing both energy and anthropogenic, nonenergy greenhouse gas emissions.

Also of great importance is the fact that conservation, efficiency, and energy source switching can extend the availability of fossil oil and natural gas. Under the Steady Scenario, oil and natural gas would diminish rapidly between now and 2050. They would be replaced by synthetic oil and gas, made from coal, both of which are very rich sources of CO_2. Under the Reduced Scenario synthetic oil and gas are required, but in much smaller quantities than in the Steady Scenario.

We have suggested a concentration dependent model for estimating atmospheric CO_2 concentration. It is different than the airborne fraction model used by many researchers. The concentration dependent model does not predict an irreversible greenhouse effect as does the airborne fraction model. It predicts that CO_2 concentrations will decrease if CO_2 emissions cease; in contrast to the airborne fraction model, which predicts that CO_2 concentrations will remain constant if emissions cease. The effectiveness of measures (policies) taken to reduce emissions is projected to be greater by the concentration model than by the airborne fraction model; however, the consequences are also projected to be greater if the measures are not taken. While the concentration dependent model accurately relates past CO_2 emission data to atmospheric concentration data, it is not clear that it will adequately model the anticipated variety of feedback mechanisms which may be required to make satisfactory projections. An effort should be made to evaluate this model based on estimates from much more comprehensive models.

Under the Reduced Scenario, this study has assumed changes in the pattern of energy consumption--conservation, efficiency improvements, and energy source switching--without regard to the mechanisms which may motivate these changes. Some changes will be the result of natural market forces. As fossil fuel resources are depleted, they will become more expensive, motivating conservation and switching to less expensive alternatives. But, it is not clear that natural market forces will be sufficient to motivate the desired reduction of emissions which cause the greenhouse effect and global warming. We cannot assume that the desired pattern of energy consumption will be achieved spontaneously. Mechanisms which lead to the desired result must be identified, evaluated, and integrated into the world's economy. These mechanisms should include both domestic and international governmental policies. Careful market dynamics studies should be undertaken to find those policies that best motivate and achieve the desired changes in energy consumption patterns. These studies should include within them quantified estimates of the global costs associated with pollution and the greenhouse effect, costs which have previously been considered exogenous to energy economics.

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Appendix A. Contributors to the Greenhouse Effect

There are currently four major concerns in the area of atmospheric pollution: photochemical (classic) smog, acid rain, stratospheric ozone depletion, and the greenhouse effect. Among these four difficult problems, the greenhouse effect appears to be the most serious and fundamental because of its potential long-term effect on the earth. At the present time there is considerable, but inadequate, understanding of the basic chemistry and toxicity associated with photochemical smog and acid rain. Also, the long-term effects on plant and animal life due to increased UV radiation, caused by stratospheric ozone depletion, are not well understood. Although these three problem areas are by no means under control today, there is a good chance that they may yield to scientific research and technological solutions. The greenhouse effect, however, appears less tractable in that solutions are difficult to envision and implement on a global scale. Also, significant reversal of the effect is likely to be very difficult and expensive, if indeed possible. Furthermore, reducing its effect will require a change in world patterns of energy use and may have some detrimental impact on the global economy.

The most important greenhouse gases in the earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), tropospheric ozone (O_3), and the chlorofluorocarbons (CFCs): CFC-11 (trichlorofluoromethane, CCl_3F), and CFC-12 (dichlorodifluoromethane, CCl_2F_2). Significantly increased atmospheric concentrations of greenhouse gases since the preindustrial era have been measured (Neftel, 1985; Raynaud, 1985; Pearman, 1986; Khalil, 1987). This increase is mainly due to anthropogenic activity, in particular, increased fossil fuel consumption (Bolin, 1986). An extreme greenhouse example is the planet Venus, whose atmosphere is 96% CO_2, and whose surface temperature is about 450 K higher than it would be based on a radiative balance without CO_2. The earth's natural greenhouse effect is basic to the existence of life as we know it. Without the presence of greenhouse gases, instead of being a comfortable 288 K, the average temperature of the earth would be about 40 K lower, below the freezing point of water (Campbell, 1986).

Carbon dioxide is not toxic and is not usually considered as a pollutant. Indeed, its presence in the atmosphere is essential for life. However, it is the most serious of the greenhouse gases, due to its radiative effect and its atmospheric concentration, which may double in the next few decades. This gas is the natural product of burning carbon contained in all fossil fuels. In 1986 the atmospheric concentration of CO_2 was 346.8 ppmv, compared to about 285 ppmv in the preindustrial era, an increase of almost 22%. This increase is due largely to fossil fuel consumption, with additional contributions from other anthropogenic activity such as deforestation.

In 1986 about 5.8 GtC (metric gigatonnes-carbon) was emitted into the atmosphere due to world energy consumption (Rotty, 1987; WRI, 1989). It has been estimated that an additional 1.6 GtC was emitted from other anthropogenic activity, mostly deforestation (WRI, 1989). Independent of anthropogenic activity, the earth experiences a carbon cycle with a total flux of about 200 GtC in and out of the atmosphere each year. The oceans and plants are a net sink for atmospheric CO_2, while other biota and detritus decomposition are a net source. While the total nonanthropogenic flux of carbon is 35 times as great as the anthropogenic emissions, there has been a very close balance between nonanthropogenic sources and sinks; however, this "Carbon Cycle" process is not yet well-understood (Bolin, 1986; Trebalka, 1986). Anthropogenic carbon sources have upset its balance. Plots of the atmospheric concentration of CO_2 from year 1750 to year 1986 versus the cumulative emission of CO_2 from energy use alone and from energy plus other anthropogenic activity, deforestation, etc., is shown in Figure A.1. Both curves show a very strong linear relation between the atmospheric concentration and the energy emissions, with a slope of 0.270 ppmv/GtC for energy only and 0.187 ppmv/GtC for the total anthropogenic emissions. Since each GtC represents about 0.471 ppmv of atmospheric concentration, the plot indicates that if we consider only the CO_2 emitted from energy consumption about 57% (0.270/0.471 = 0.57) remains in the atmosphere. If we consider total anthropogenic CO_2 emissions about 40% (0.187/0.471 = 0.40) remains. The CO_2 concentration data is from the Mauna Loa Observatory (WRI, 1989; Keeling, 1987). The emissions data in Figure A.1 are from the same WRI report. There is general agreement on the energy emission data values as used here, but not on the nonenergy data. However, we will accept the nonenergy data as given as the basis for our scenarios. It is not known precisely what happens to the nonretained CO_2, but it is conjectured that most of it is reabsorbed in the oceans by marine biota near the surface and by the seawater itself. Carbon dioxide is chemically quite stable, and has a low stratospheric photodissociation rate.

Nitrous oxide is generated from "natural" as well as anthropogenic sources. Quantified details of the various sources are not well known. However, a trend of increasing atmospheric concentration with increasing anthropogenic activity has been measured. The most important anthropogenic sources are fossil fuel use, deforestation, and the use of nitrogen fertilizers. In addition to being a greenhouse gas, N_2O is an indirect cause of

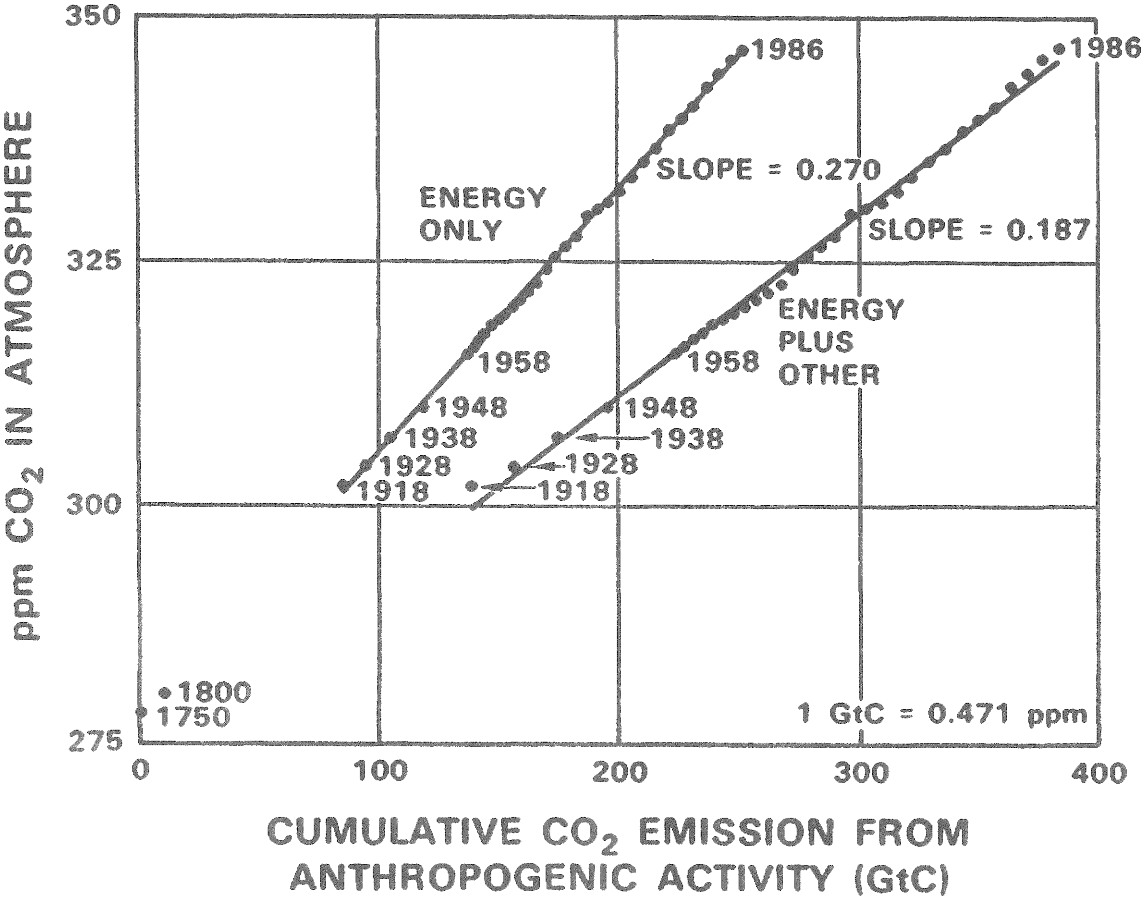

Figure A.1 Atmospheric CO_2 Concentration vs. Cumulative Anthropogenic CO_2 Emissions stratospheric ozone depletion. The average atmospheric residence time of an N_2O molecule is about 100 years (Campbell,1986; Bolin, 1986).

Atmospheric methane also has natural as well as anthropogenic sources. As with N_2O, there is considerable uncertainty in quantifying methane sources. The major anthropogenic sources are from enteric fermentation in cattle, rice paddies, solid waste, biomass burning, natural gas losses, and coal mining. There has been a significant increase in the methane atmospheric concentration in recent decades. Methane's average atmospheric residence time is about 11 years (Campbell,1986; Bolin, 1986).

The production of tropospheric ozone is an exceedingly complex phenomenon, which is also not well understood. It is produced indirectly by anthropogenic activity; by reactions with methane, carbon monoxide, hydrocarbons, and NOx, all anthropogenically, as well as naturally, generated gases. In addition to being a greenhouse gas, tropospheric ozone is an important factor in photochemical smog. In the stratosphere, ozone has the important function of shielding the earth from much of the UV solar radiation which is potentially dangerous to global plant and animal life. Because of its extreme chemical instability, ozone concentrations show considerable temporal and local spatial variation in the atmosphere (Campbell, 1986).

The CFCs are all anthropogenically generated. They are used for aerosol propellants (now banned in the U. S.), solvents, the production of rigid and flexible foams, refrigeration and air conditioning systems, and various other applications. Their indirect use with respect to energy is in refrigeration and air conditioning. They are not toxic and are very stable, with average atmospheric residence times of 75 and 111 years for CFC-11 and CFC-12, respectively. Their atmospheric concentration has increased dramatically in recent decades (Bolin, 1986; Campbell, 1986; Hammitt, 1986) They have been claimed as a major culprit in the depletion of stratospheric ozone, but this point is still being argued by various scientific factions (Miller, 1986). The Montreal Accords signed last year will reduce both the greenhouse effect and stratospheric ozone depletion by limiting the use of CFCs. A conference held in Helsinki has seriously considered a total global ban on CFCs by the year 2000. In addition to a CFC ban, there is discussion of banning certain halons, used in fire extinguishers, and methyl chloroform and carbon tetrachloride, used as cleaning agents and solvents. These latter chemicals also are greenhouse gases and stratospheric ozone depleters (Hammitt, 1986).

Some other major atmospheric pollutants are SOx, NOx, VOC (Volatile Organic Compounds), particulates, and lead. These emissions do not have a greenhouse effect in themselves, but have various indirect effects; for example, acid rain--mainly from SOx, NOx, and particulates--tends to kill trees and marine biota, thereby reducing the world's ability to absorb CO_2. We will discuss the current (1986) emissions of these substances in Appendix C.

The contribution that each gas makes to the greenhouse effect depends on its infrared absorption coefficient and on its atmospheric concentration. Concentration, in turn, depends on the quantity of gas emitted and its distribution over time.

Appendix B. 1986 Global Energy Consumption

The global use of energy, in particular the burning of fossil fuels, contributes a significant fraction to the anthropogenic emission of greenhouse gases. Therefore, predicting the magnitude of the greenhouse effect requires projecting global energy use. Using the year 1986 as a starting point for our projections, we have put together estimates of the magnitude and distribution of global energy consumption for that year. Figure B.1 is a 1986 energy flow diagram for the United States, constructed at Lawrence Livermore National Laboratory (Borg, 1987) which shows energy consumption for the three major sectors of our economy: residential-commercial, industrial, and transportation. The diagram also quantifies energy consumed directly by each sector, as well as the energy used to generate electricity. The LLL data is given in "quads." The basic energy unit used in this report is exajoules, EJ, which is 10^{18} Joules. Quads and EJ are very close in value. One quad equals 1.055 EJ.

We constructed a similar energy flow chart for the world, Figure B.2, using data from a World Resources Institute report (WRI, 1989). These data were used because they contain both aggregated global energy consumption and energy consumption broken down by world region and use sector. Data in the report are not always self-consistent but we were able to select a consistent subset in order to construct Figure B.2. Energy production (which does not include fuel wood and similar types of fuel) and consumption values were taken from WRI Table 7.1, and the differences between production and consumption are shown as "lost, reserved, etc." in Figure B.2. These energy consumption values are shown in Table B.1.

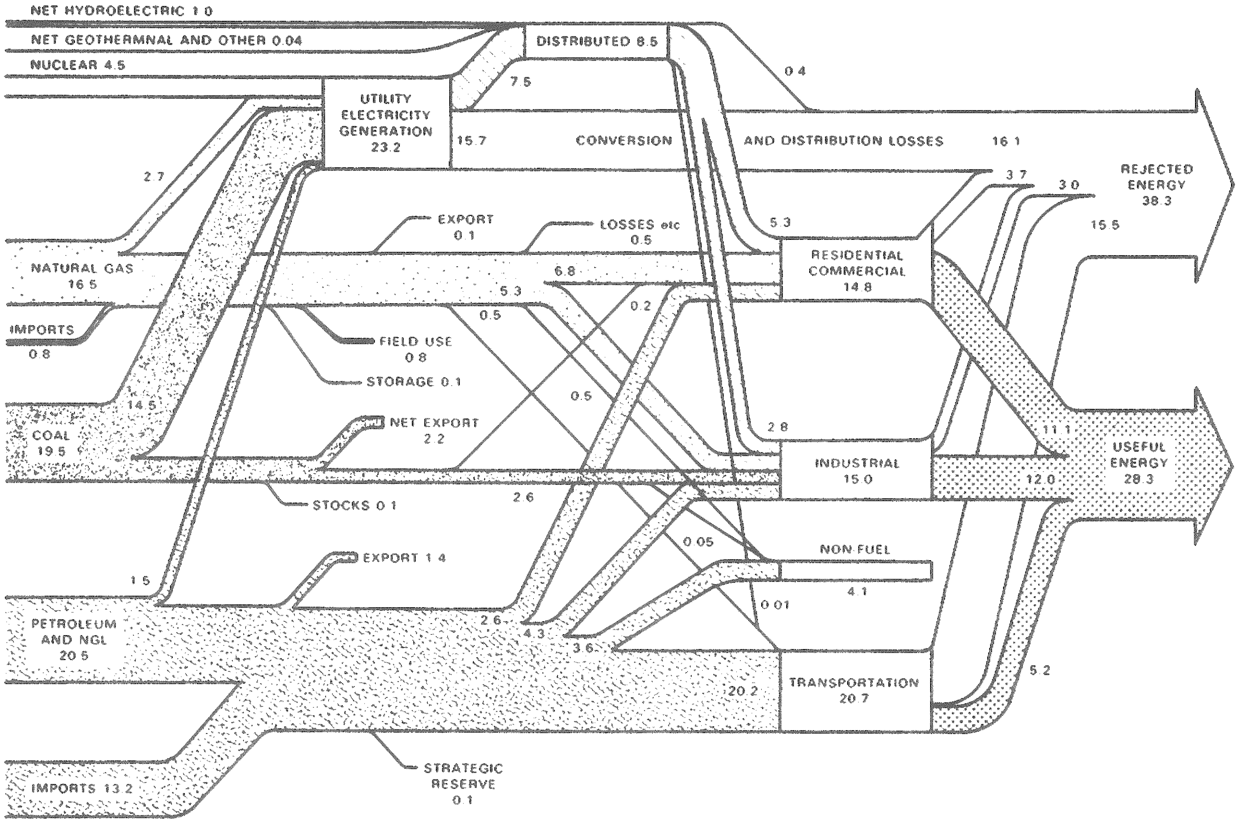

Figure B.1 1986 U.S. Energy Production and Consumption in EJ

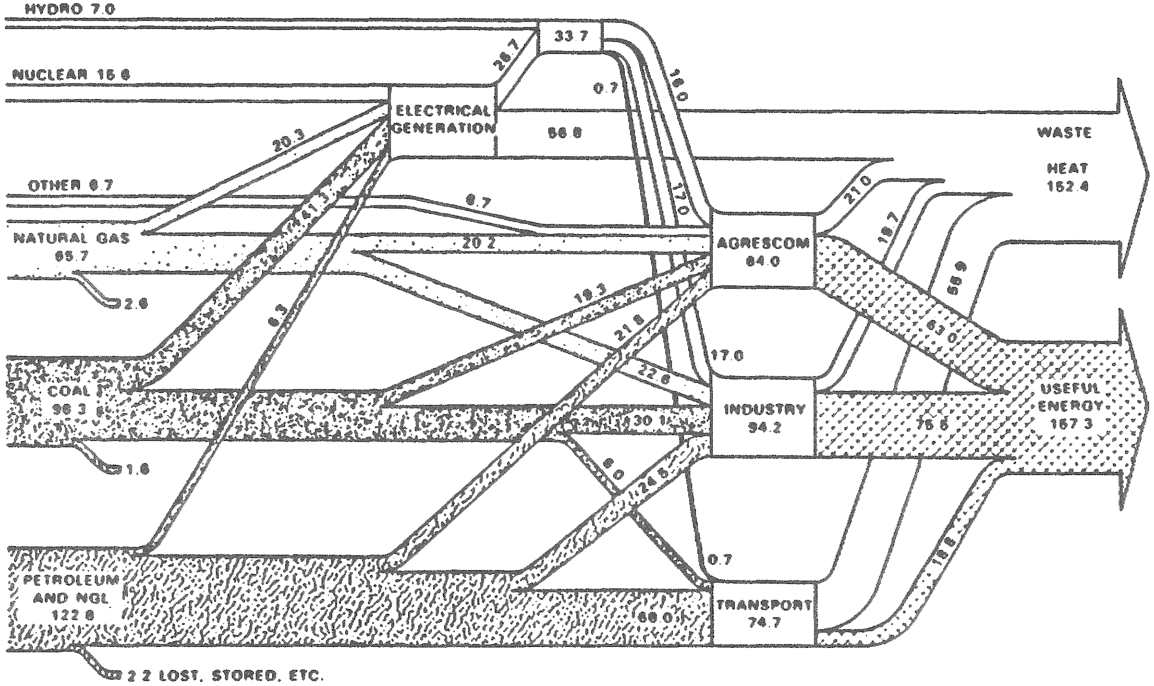

Figure B.2 1986 World Energy Production and Consumption in EJ

Table B.1
1986 World Energy Consumption in Exajoules, EJ.

Oil	120.6
Coal	96.7
Natural Gas	63.1
Nuclear	15.6
Hydroelectric	22.0*
Total	318.0

* WRI expressed hydroelectric energy as an equivalent thermal energy input. The electrical energy is 7.0 EJ.

The fractions of commercial primary energy consumed by each sector were calculated using the fraction of energy consumed by each sector in selected countries from WRI Table 20.3, weighted by the energy consumption in each country from WRI Table 20.1. Agriculture, residential, commercial, and "other" sectors were aggregated into a single sector which we call "agrescom." The results are shown in Table 3.2.

Table B.2
World Energy Consumption Fractions by Sector

Transportation	.24
Industry	.41
Agrescom	.35

The fraction of each sector's direct consumption contributed by each type of energy source (including electricity) was calculated using sectoral consumption data from WRI Table 7.4 and weights based on the energy consumed in each world region from WRI Table 7.1. We had to switch some countries from one region to another using data from WRI Table 20.1 because the regions in WRI Table 7.4 differed from the regions in WRI Table 7.1. The fraction of each sector's direct consumption contributed by each type of energy source is shown in Table B.3. Consumption of geothermal and solar/renewable energy is shown here as zero. There is in fact some consumption of geothermal and solar/renewable energy by industry and agrescom, but it is less than 0.5%.

Table B.3
World Energy Consumption Fractions

	Transportation	Industry	Agrescom
Oil	.91	.26	.26
Coal	.08	.32	.23
Natural Gas	.00	.24	.24
Other (wood, etc.)	.00	.00	.08
Geothermal	.00	.00	.00
Solar/Renewable	.00	.00	.00
Electricity	.01	.18	.19

The energy consumption values in Table B.1 and the fractions in Tables B.2 and B.3 were combined to create the values in Figure B.2. A global electrical conversion efficiency of 32% was assumed, which is slightly lower than the U. S. value of 32.3%, derived using Figure B.1. Table B.4 shows the fraction of electricity generated using each type of energy source. Again, the geothermal and solar/renewable fractions are greater than zero, but less than 0.5%.

Table B.4
World Energy Consumption Fractions
for Electrical Generation

Oil	.06
Coal	.39
Natural Gas	.19
Nuclear	.15
Hydroelectric	.21
Geothermal	.00
Solar/Renewable	.00

There are some very interesting differences between U. S. and global energy consumption patterns as shown in Figures B.1 and B.2. The U. S. uses much more energy for transportation compared to industry and agrescom than does the rest of the world. The U. S. also uses relatively less coal for industry. Figure B.2 does not show global nonenergy uses of fossil fuel as does Figure B.1, nor does it show electrical transmission losses. These data were not available in the WRI report, nor have they been found elsewhere. Figure B.2 is the starting point for our global energy projections in the Chapter II.

Appendix C. Energy Related Emissions

Using 1986 data described in Chapter II, we made estimates of atmospheric emissions of various pollutants from both energy and nonenergy uses. Figure C.1 shows the estimated global anthropogenic atmospheric emissions of CO_2 from the three major sources of fossil fuel (coal, oil, and natural gas), plus an estimate of the nonenergy emissions for the year 1986. Figure C.2 gives a more detailed breakdown of 1986 CO_2 global emissions by energy consumption as well as by energy source. Figure C.3 shows a comparable source and consumption breakdown of the CO_2 emissions for the U. S. in 1986.

Comparison of global and U. S. CO_2 sources indicates that, on a relative basis, the U. S. tends to use less coal, more gas, and considerably more oil than the rest of the world. The greater relative oil use by the U. S. is primarily in transportation consumption, and the greater global coal use is in the agrescom and industrial areas. The smaller global and U. S. natural gas emissions are due to the fact that, on an energy basis, less gas is consumed than either coal or oil, and that, on a per unit energy basis, gas produces less CO_2.

The carbon emissions per unit energy of coal, oil, and gas are shown in Table C.1, along with emission estimates for synthetic oil and gas and shale oil (Mintzer, 1987).

Table C.1 Carbon Emissions of Fossil Fuels, MtC/EJ
(Megatonnes carbon per exajoule)

Natural Gas	13.8
Oil	19.7
Coal	26.9
Synthetic Oil	38.6
Synthetic Gas	40.7
Shale Oil	47.6

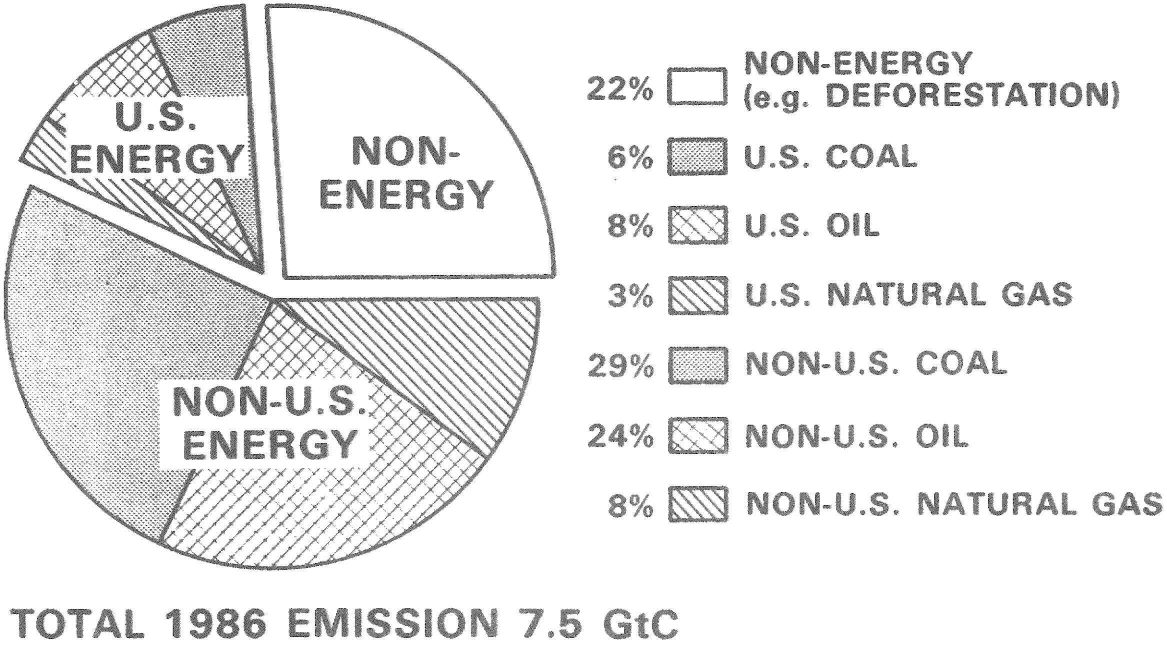

Figure C.1 Global Anthropogenic CO_2 Emissions

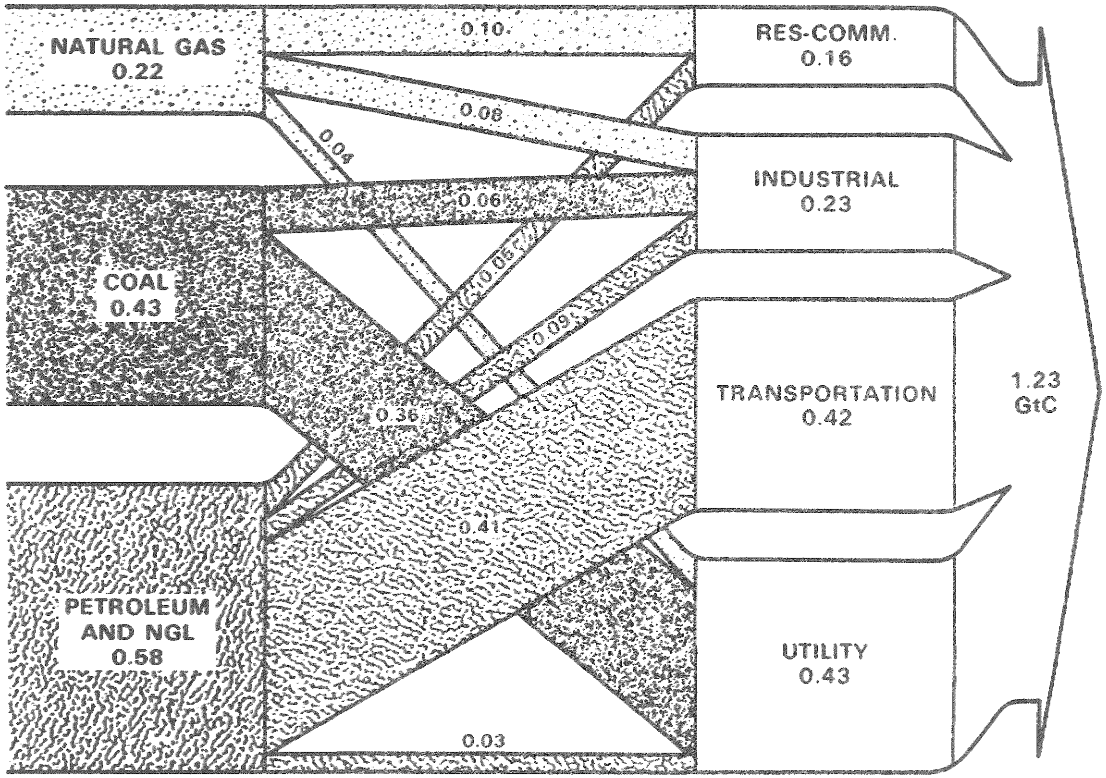

Figure C.2 1986 CO_2 Emissions From Global Energy Use

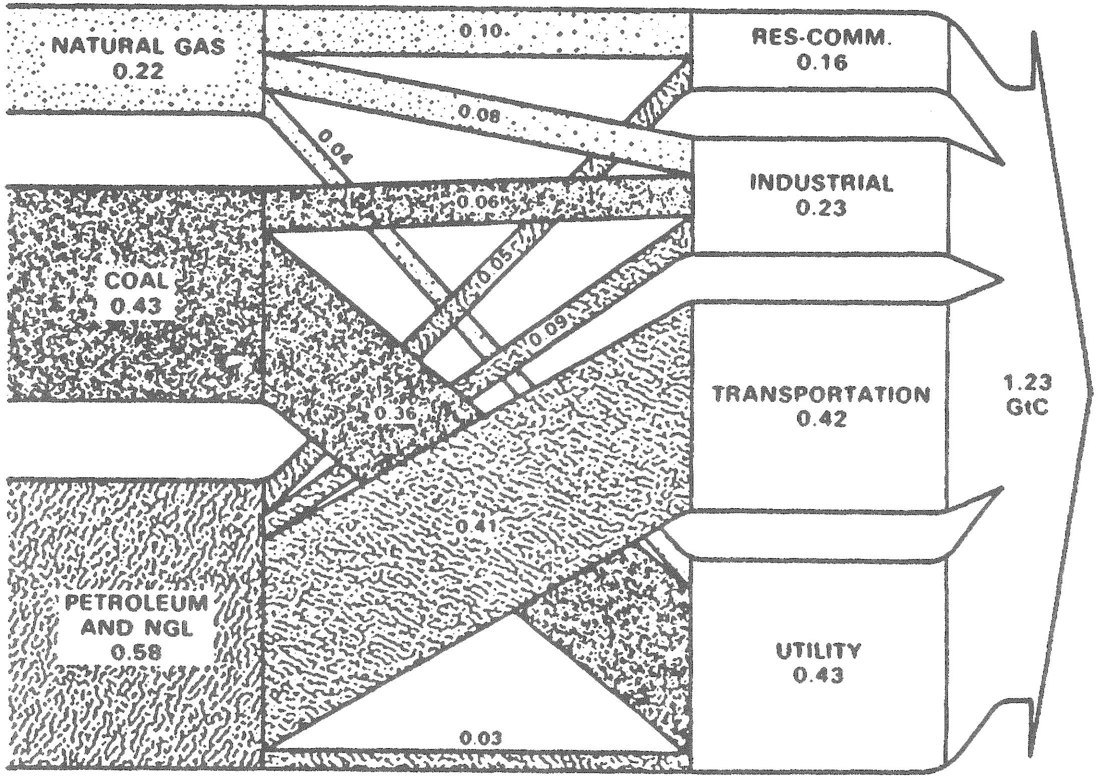

Figure C.3 1986 CO_2 Emissions From U.S. Energy Use

On a per unit energy basis, coal produces the most carbon, with natural gas producing about half and oil about three-quarters the carbon that coal produces. The synthetic fuels generate considerably more carbon emissions because of the substantial amount of energy required to produce them, in addition to the carbon emitted in their consumption.

Figures C.4 through C.9 show the 1986 U. S. emissions of other atmospheric pollutants; namely, oxides of sulfur, SOx, oxides of nitrogen, NOx, carbon monoxide, CO, volatile organic compounds, VOC, particulates, and lead. These chemicals have little direct greenhouse effect, but are important in the creation of acid rain, photochemical smog, and general atmospheric toxicity. In addition, NOx, CO, and VOC have an indirect greenhouse effect in the creation of tropospheric ozone, a very effective greenhouse gas. Thus, there is a significant relationship between energy use and all types of atmospheric pollution. For more information on these pollutants see, for example, (Campbell, 1986; USEPA, 1988; USDOE, December 1988).

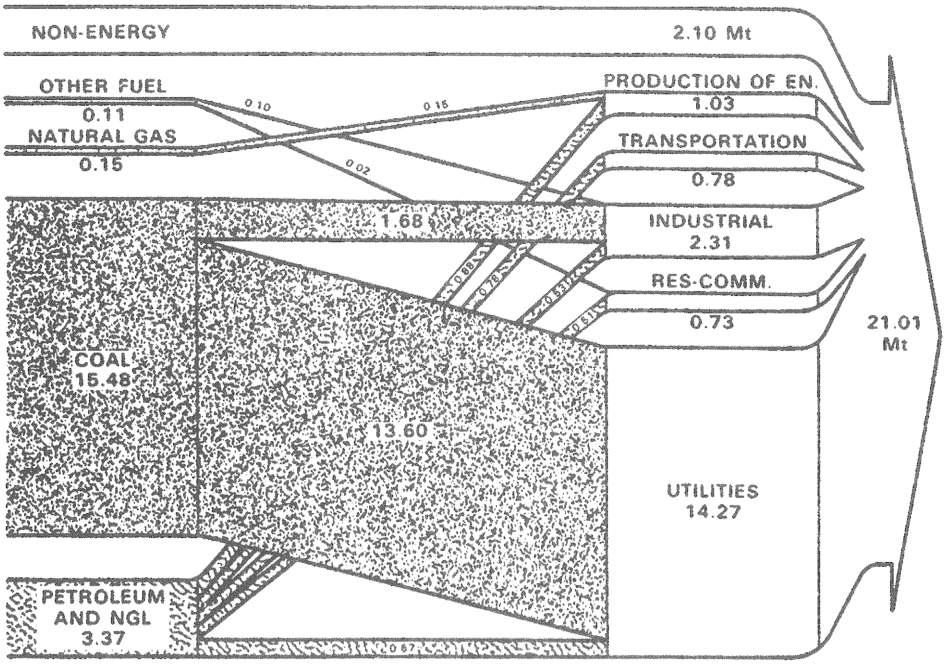

Figure C.4 1986 U.S. Anthropogenic SO_x Emissions

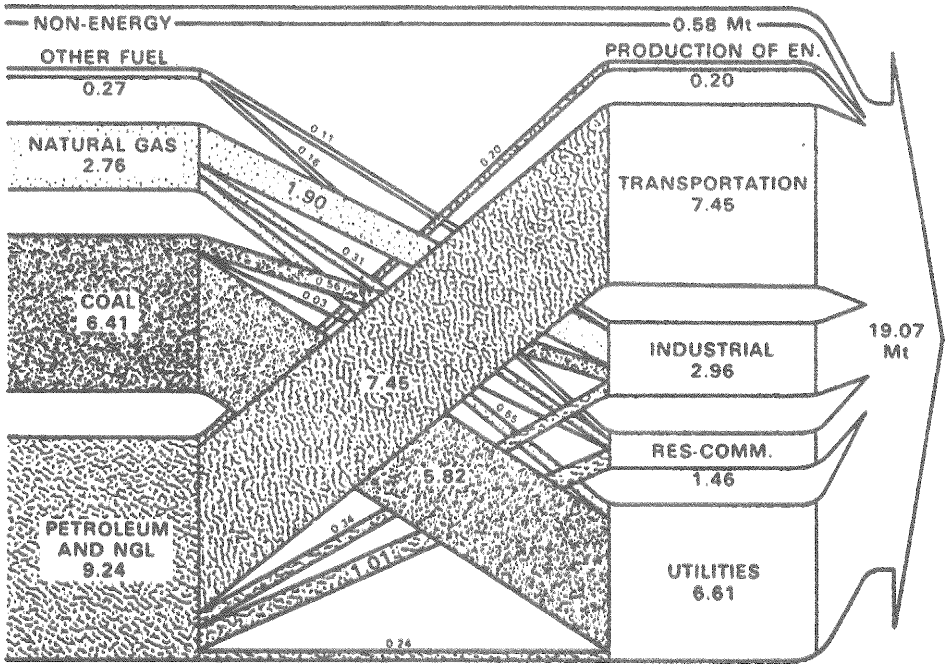

Figure C.5 1986 U.S. Anthropogenic NO_x Emissions

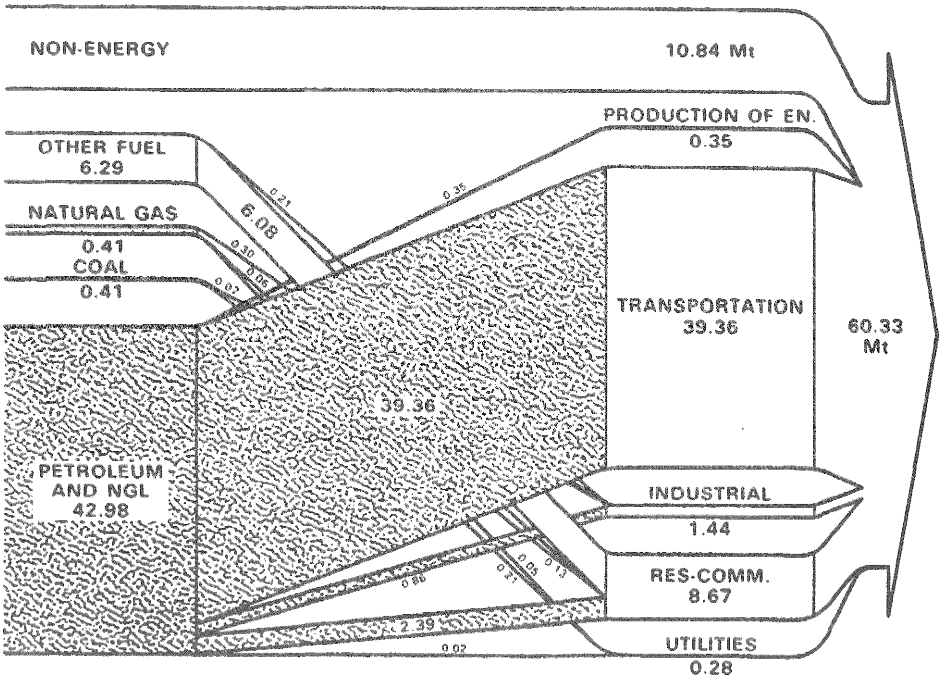

Figure C.6 1986 U.S. Anthropogenic CO Emissions

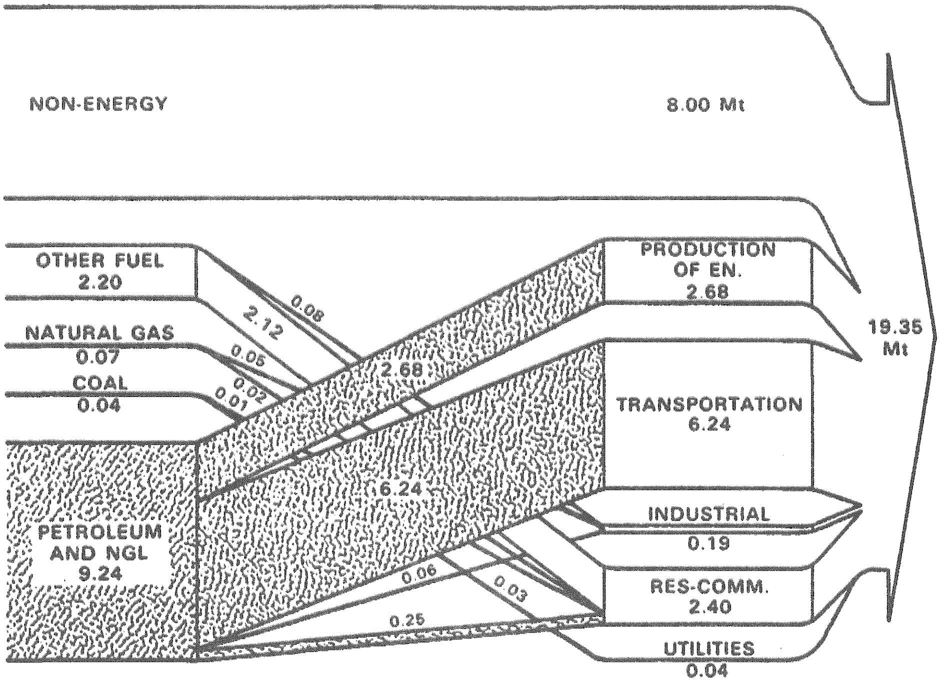

Figure C.7 1986 U.S. Anthropogenic VOC Emissions

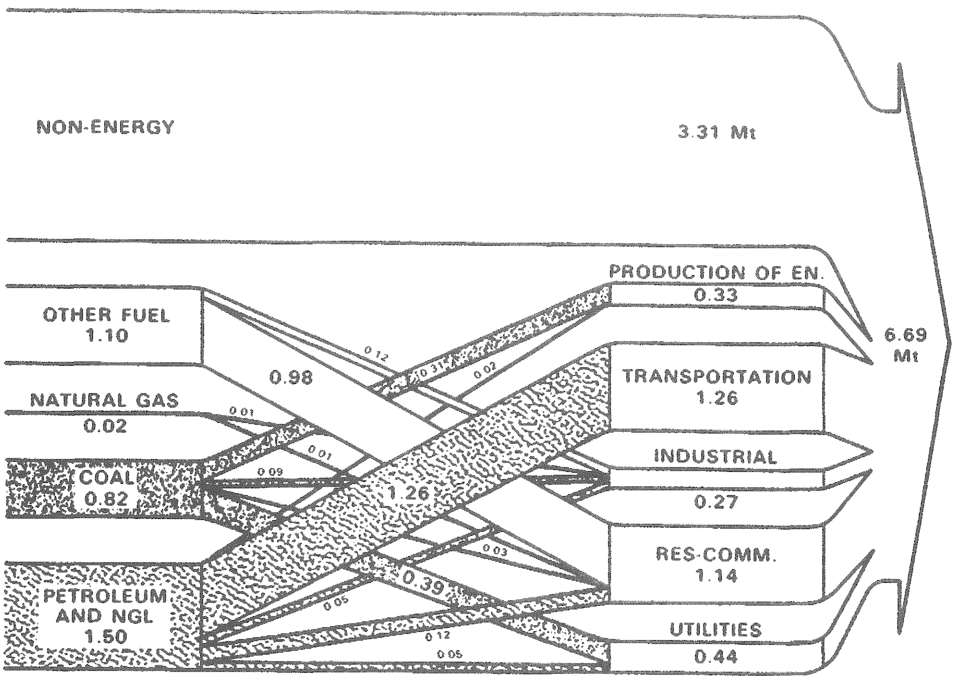

Figure C.8 1986 U.S. Anthropogenic Particulate Emissions

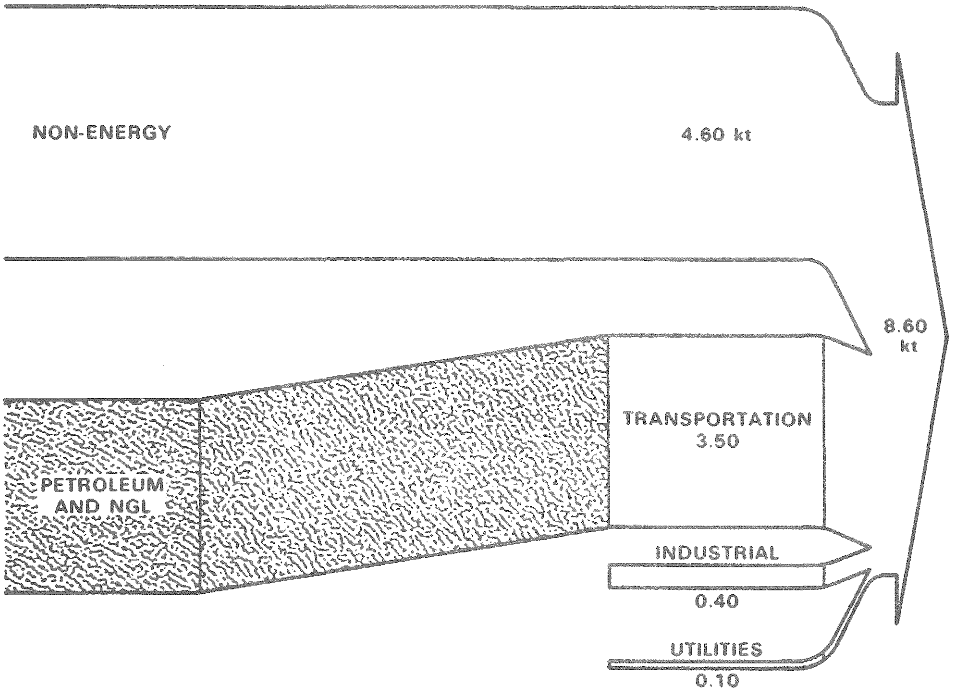

Figure C.9 1986 U.S. Anthropogenic Lead Emissions

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6250	R. K. Traeger
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