What are the Likely Roles of Fossil Fuels in the Next 15, 50, and 100 Years, With or Without Active Controls on Greenhouse Gas Emissions?*

CONF-901262--2

DE91 006768

R.L. Kane
Office of Fossil Energy
U.S. Department of Energy

D.W. South
Policy and Economic Analysis Group
Argonne National Laboratory

1 Introduction

Since the industrial revolution, the production and utilization of fossil fuels have been an engine driving economic and industrial development in many countries worldwide. This source of economic growth is expected to continue; most forecasts of future global economic activity in developed and developing countries are based on a continued reliance on fossil fuels. An extensive institutional infrastructure and fossil fuel resource base exist around the world to support the continued (and expanded) use of this fuel source. However, future reliance on fossil fuels has been questioned due to emerging concerns about greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), and its potential contribution to global climate change (GCC).

While substantial uncertainties exist regarding the ability to accurately predict climate change and the role of various greenhouse gases, some scientists and policymakers have called for immediate action. As a result, there have been many proposals and worldwide initiatives (e.g., Montreal Protocol, Intergovernmental Panel on Climate Change [IPCC]) to address the perceived problem. In many of these proposals, the premise is that CO_2 emissions constitute the principal problem, and, correspondingly, that fossil-fuel combustion must be curtailed to resolve this problem.

This paper demonstrates that the worldwide fossil fuel resource base and infrastructure are extensive and thus, will continue to be relied on in developed and developing countries. Furthermore, in the electric generating sector (the focus of this paper), numerous clean coal technologies (CCTs) are currently being demonstrated (or are under development) that have higher conversion efficiencies, and thus lower CO_2 emission rates than conventional coal-based technologies. As these technologies are deployed in new power plant or repowering applications to meet electrical load growth, CO_2 (and other GHG) emission levels per unit of electricity generated will be lower than that produced by conventional fossil-fuel technologies.

*Work supported by the U.S. Department of Energy, Assistant Secretary for Fossil Energy, under Contract W-31-109-ENG-38.

Thus deployment of advanced fossil fuel technologies will automatically reduce GHG emissions relative to conventional technologies while continuing to use the extensive worldwide resource base. In addition, if it is determined that CO_2 emission levels should be reduced, fossil fuels and fossil-fuel-based technologies can also play a role in the near- and long-term through various fuel substitution and CO_2 scrubbing options.

2 The Greenhouse Effect: Role of Fossil Fuel Emissions

The greenhouse effect is a popular term used to describe the roles of water vapor, CO_2, and other trace gases in keeping the earth's surface warmer than it would be without their presence. These "radiatively active" gases are relatively transparent to incoming shortwave radiation but relatively opaque to outgoing long-wave radiation. The long-wave radiation, which would otherwise escape to space, is trapped by these gases in the lower atmosphere. The subsequent "reradiation" of some energy back to the earth's surface produces surface temperatures higher than those that would occur if the gases were absent. It is the continued buildup of these higher surface temperatures over time that is postulated to produce climatic changes (Smith). While relatively easy to explain conceptually, there are numerous uncertainties in our ability to document the role of each GHG, model the current greenhouse and GCC effect, and accurately forecast potential climate change based on various energy scenarios.

There are four principal GHGs: CO_2, nitrous oxide (NO_x), methane (CH_4), and a group of chlorofluorocarbons (CFCs). The sources of each gas and their current contribution to global climate change vary substantially as illustrated in Fig. 1. While fossil fuel combustion

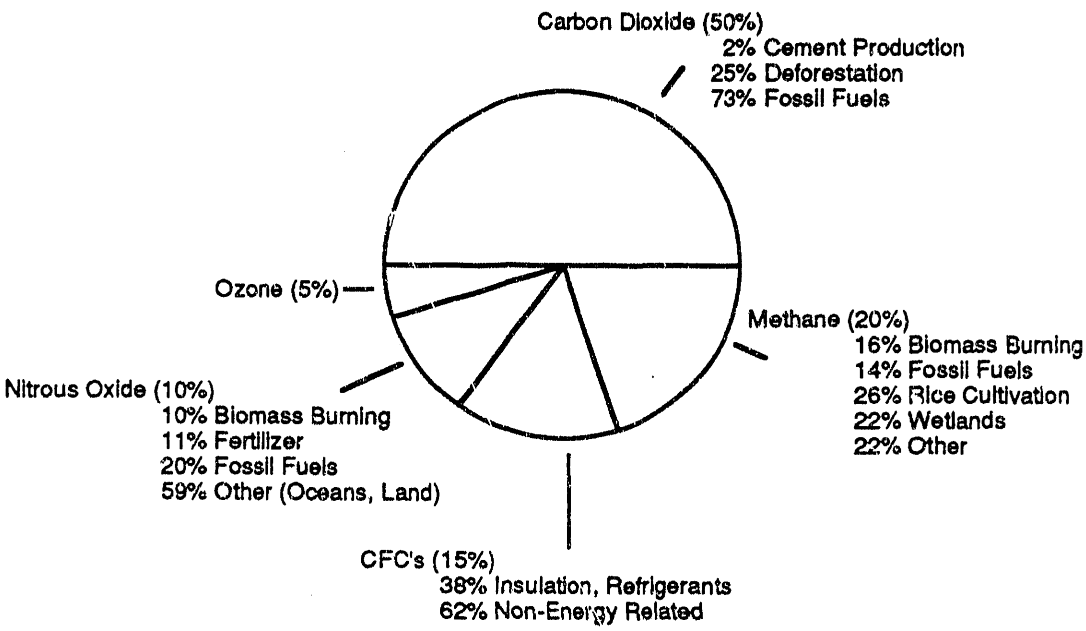

FIGURE 1 Current Greenhouse Gas Contribution to Increment in Global Climate Change (Source: U.S. EPA, 1988)

contributes to a substantial portion of the GCC increment due to CO_2, it contributes much smaller shares of CH_4 and NO_x; fossil fuel combustion does not contribute directly to CFC emissions.

The contribution of each gas to the greenhouse effect is based on its atmospheric concentration and lifetime, together with its radiative properties. Although CO_2 has the highest current atmospheric concentration among GHGs (358 parts per million), it is the least potent in terms of global warming potential on a molecule-for-molecule basis, since it is the least effective absorber of energy. Thus, the large quantity of CO_2 emitted annually is partially offset by its relatively low global warming potential. Figure 2 illustrates the global warming potential of each GHG on a molecule-for-molecule basis, relative to carbon dioxide; it demonstrates, for example, that a CFC molecule is approximately 20,000 times more potent than a molecule of CO_2 in terms of its potential contribution to GCC.

3 Global Climate Change: Principal Uncertainties

While the U.S. Congress has introduced a number of bills aimed at addressing climate change (see Hootman and South, 1990), and the IPCC and other groups have been discussing potential options to reduce GHG emissions (IPCC, 1990; U.S. EPA, 1989; Jaeger, 1988), substantial uncertainties remain about the potential magnitude and temporal dimensions of climate change due to GHG accumulation. Most of the uncertainty falls into three broad categories: determining future emissions and concentrations of GHGs; predicting the climate based on General Circulation Models (GCMs) and their associated scientific base; and detecting changes in the historical climate record. (See South, et al [1990] for a more detailed discussion of these uncertainties.) Given these uncertainties, actions to curtail fossil fuel usage may be premature due to the substantial economic and social costs that would arise.

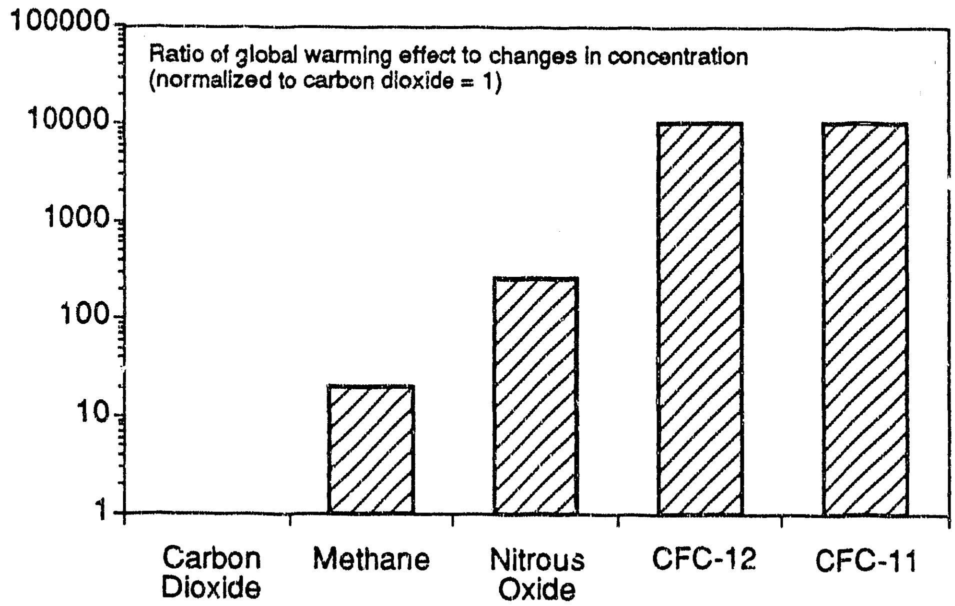

FIGURE 2 Global Warming Effect of Greenhouse Gases Relative to CO_2
(Source: Derived from Ramanathan, 1988)

One area of uncertainty requiring resolution is the future rate of fossil-fuel-based CO_2 emissions and other trace-gas emissions, together with their associated atmospheric concentrations. It is difficult to predict the technical developments, economic factors, and policy decisions on which future emission rates depend. There are uncertainties present in the projected data on both energy use and its determinants. There is also a spectrum of potentially available technologies and fuels, as well as a host of difficult to predict geopolitical, economic, social, and demographic factors that must be addressed. Included in these techno-economic uncertainties is the nature of any policy response to climate change, which is only dimly perceived at present.

The rate of global economic growth, which is only one determinant, will depend heavily on the rate of economic development in both developed and less developed countries (LDCs), and on the energy demands and choices of energy technologies associated with that development. Potential changes in both supply and demand technologies and the possibilities for interfuel substitution must also be considered, because such factors add to forecasting difficulties. End-use energy efficiency improvements also rank high on the list of important determinants. The remainder of this paper will focus on existing fossil fuel supply options for the electric generating sector. Demand technologies and end-use efficiency improvements to reduce CO_2 emissions are addressed in the Dahlem Workshop/Group 2 papers (Ashton and Secrest, 1990; Jenney, 1990; Jochem, 1990; Yamaji, 1990).

4 Fossil Fuel Combustion and CO_2 Emissions

Between 1950 and 1980, worldwide CO_2 emissions increased by almost 219%, an average growth rate of 7.3% per year (from 5.82 10^9 metric tons/yr of CO_2 in 1950 to 18.55 10^9 metric tons/yr in 1980). A further increase of 12.8% took place between 1980 and 1988, although the annual rate of change was substantially less, 1.6% per year. Current worldwide CO_2 emissions from fossil fuel and cement facilities total 20.9 10^9 metric tons.*

Figure 3 shows that the rate of growth in fossil-fuel-related CO_2 emissions has varied considerably by geographic region. (The top figure illustrates the CO_2 emissions pattern for developed or industrialized regions; the lower figure shows the pattern for developing regions.)

After exhibiting steady growth between 1963 and 1974 (4.5% per year), CO_2 emissions in North America (NAM) levelled off until 1986; however, the annual growth rate since then has returned to the 1963-74 rate. Centrally planned European countries (CPEURs) and centrally planned Asian countries (CPAs) have maintained rapid growth rates throughout the period 1950-1988. Since 1950, CO_2 emissions in CPEURs have grown 405.7%, or 10.7% per year. Despite a slight pause between 1978 and 1981, the growth rate in CO_2 emissions has returned to the long-term trend. While CO_2 emissions for CPAs has expanded rapidly since the 1960s, the increase has been the greatest since 1974; between 1974 and 1988 emissions increased by more than 116%,

*Carbon emissions increased from 1.59 10^9 metric tons in 1950 to 5.06 10^9 metric tons in 1980. As of 1988, carbon emissions were 5.7 10^9 metric tons.

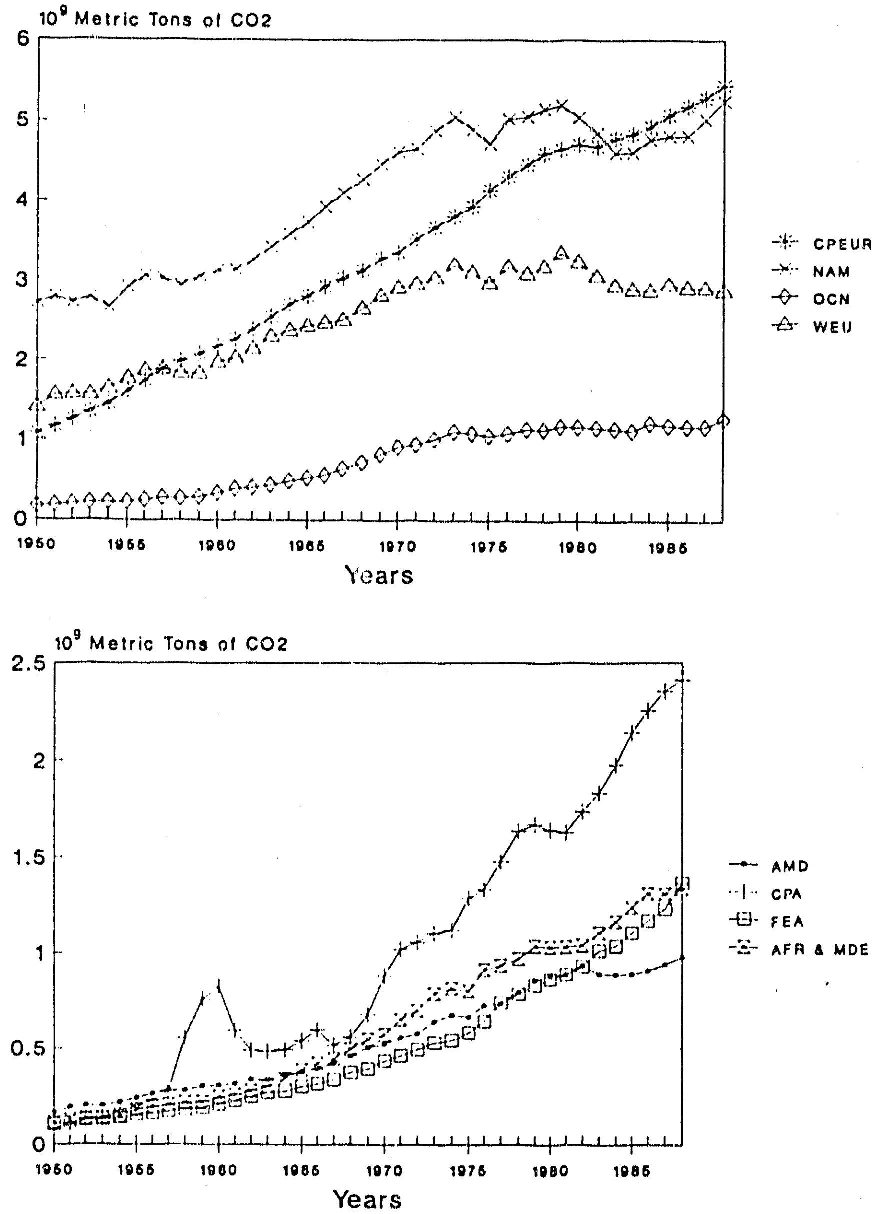

FIGURE 3 Trends in Fossil-Fuel-Related CO_2 Emissions by Major Geographic Area: Developed (Top) and Developing (Bottom) Regions (Source: Derived from Marland, et al., 1989)

AMD = South/Central America and islands; AFR = Africa; CPA = Centrally-Planned Asia; CPEUR = Centrally-Planned Europe; FEA = Far East; MDE = Middle East; NAM = North America; OCN = Oceania and Japan; WEU = Western Europe.

or 7.7% per year. After having grown by 75% between 1959 and 1973 (5.4% per year), Western Europe's (WEU) CO_2 emissions have fallen by 330 10^6 metric tons, or 10.3%, the only region to do so.

Carbon dioxide emissions in developing countries are expected to increase relatively rapidly because the energy consumption rate in these countries, both in aggregate and for fossil fuels, is increasing faster than in industrialized nations. Warrick and Jones (1988) found that energy consumption has grown by 6.2% per year in developing countries but by only 0.5% per year in industrialized nations. The higher growth rate is attributable to the fact that many developing countries, including China, have initiated plans for accelerated development and industrialization. In most cases, these policies entail a rapid expansion in the use of energy, and the most readily available, cost-effective, and practical source is coal. Based on energy consumption trends from 1973 to 1980 the largest increase in fossil fuel use in the next few decades is expected to be in the Third World (Warrick and Jones, 1988).

While developed countries have historically relied on fossil-fuel-generated electricity, centrally planned economies (CPEs) and LDCs are rapidly increasing their dependence on coal-fired units to develop their economic and industrial infrastructures. This dependency is likely to continue both for economic and political reasons; that is, fossil fuels, particularly coal, are indigenous or easily accessible.

Globally, the source of approximately one-third of the CO_2 emitted is from electricity generation. As of 1988, more than 60% of worldwide electricity generation is produced by fossil fuels, with approximately 45% being supplied by coal (World Energy Conference, 1989; U.S. DOE, 1989a). Table 1 illustrates that although the share of fossil-fuel-generated electricity varies by country, there is a predominant reliance in most countries on fossil fuels for the production of electricity, heat, and power. Fossil-fuel-generated electricity is greater than 60% in all regions except Central and South America and Western Europe, which have 30% and 45%, respectively.

TABLE 1 Electricity Generated by Region and Fuel Type, 1988 (10^9 kWh)

	Region							
Fuel Type	North America	Central and South America	Western Europe	Eastern Europe and USSR	Middle East	Africa	Far East	Total
Hydro	546.4 (0.16)[a]	314.2 (0.59)	512.3 (0.24)	251 (0.12)	8.6 (0.05)	43.5 (0.18)	377.1 (0.18)	2053.1 (0.20)
Nuclear	605.1 (0.18)	5.4 (0.01)	654.7 (0.31)	260 (0.12)	0 (0.00)	10.5 (0.04)	237.2 (0.12)	1772.9 (0.17)
Coal, Gas and Oil	2188.3 (0.66)	134.2 (0.30)	954.1 (0.45)	1585.1 (0.76)	169.2 (0.95)	194 (0.78)	1437.5 (0.70)	6662.4 (0.64)
Total	3339.8	453.8	2121.1	2096.1	177.8	248	2051.8	10488.4

[a]Fuel share of total electricity generated in region.

Source: U.S. DOE, 1989a.

It has been estimated that to replace all fossil-fueled power plants in the world with nuclear power would entail commissioning a new 1000 MW nuclear plant every one-to-three days until 2025; furthermore, even with this action CO_2 emissions would still continue to grow (Keepin and Kats, 1988). Since this is not a likely or feasible scenario, reliance on fossil fuels is likely to continue. Fossil fuels currently have the advantage of extensive worldwide recoverable reserves and an established international infrastructure for production, distribution, and consumption. In addition, alternative energy sources are not presently economically competitive or capable of directly replacing fossil-fuel-generated electricity.

5 Global Fossil Energy Resource Base

Fossil fuels presently constitute over 88% of the world's total primary energy sources and produce over 60% of the world's electricity (U.S. DOE, 1989a). This reliance on fossil fuels is based on extensive recoverable reserves; globally there is approximately 40 to 60 years worth of oil and gas remaining at present production rates, and more than 325 years worth of coal (see Fig. 4).

5.1 Oil

According to recent estimates of recoverable reserves, the world's supply of oil can last 40 to 50 years at current production/consumption rates. However, this lifetime is predicated on continued oil production from the Middle East, which has approximately 63% of the world's known recoverable oil reserves (see Fig. 5).

5.2 Natural Gas

World proven reserves of natural gas currently total 109 trillion cubic meters (m^3) and constitute approximately 60 years of supply at 1987 consumption rates. This reserve estimate is not static: proven recoverable reserves of gas have been doubling every 10 years. Some estimates indicate that the ultimate natural gas resources will be between 250 and 350 trillion m^3 (World Energy Conference, 1989).

Figure 6 indicates the regional concentrations of raw natural gas (excluding natural gas liquids); most of the recoverable reserves are located in centrally planned economies (CPE) or the Middle East. Figure 7 further delineates the distribution of these reserves by country. The U.S.S.R. has the largest single reserve, almost four times the second-ranked country, Iran. Unlike oil reserves that are more geographically concentrated, gas reserves are somewhat more globally dispersed; each continent has several countries with a significant level of proven gas reserves.

Increased availability of natural gas to the developed world, which also possesses the existing infrastructure to handle gas and the capital to expand that infrastructure, has led a number of

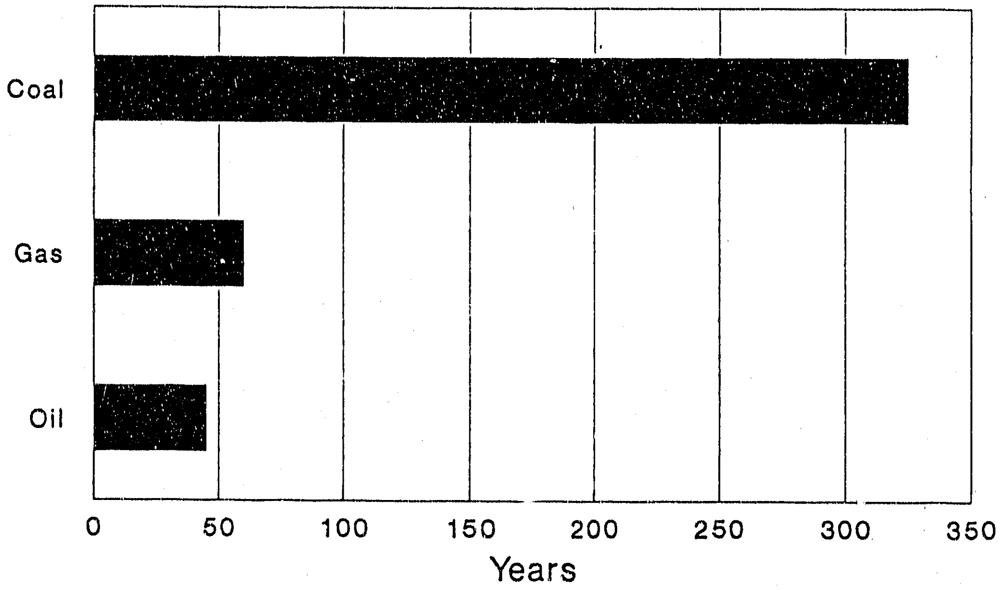

FIGURE 4 Duration of Recoverable Fossil Fuel Reserves at Current Production Rates (Source: Derived from U.S. DOE, 1989a; World Energy Conference, 1989)

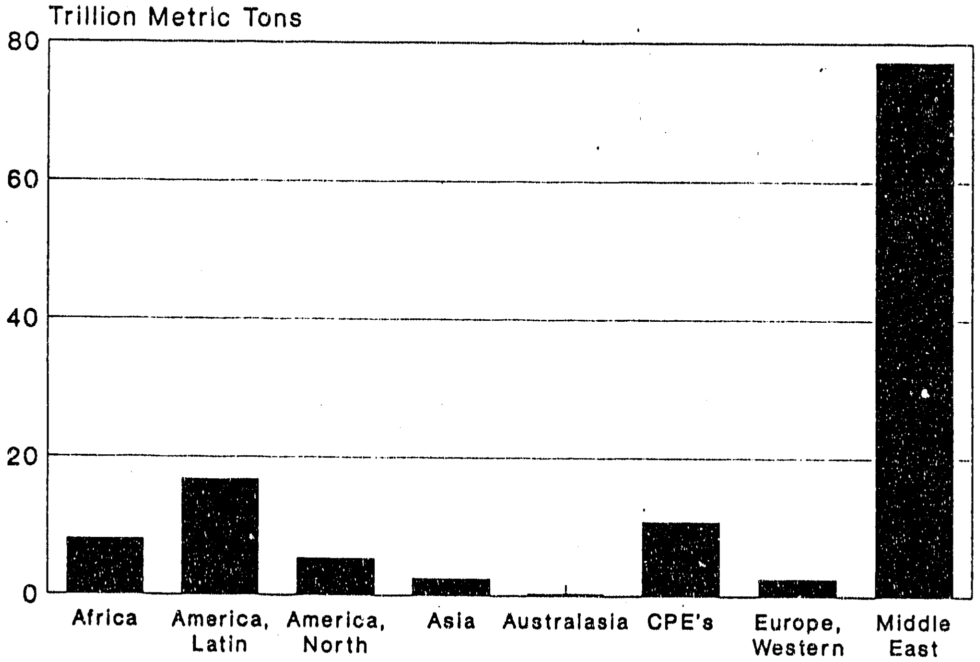

FIGURE 5 Proven Recoverable Reserves of Crude Oil and Natural Gas Liquids, 1987 (Source: World Energy Conference, 1989)

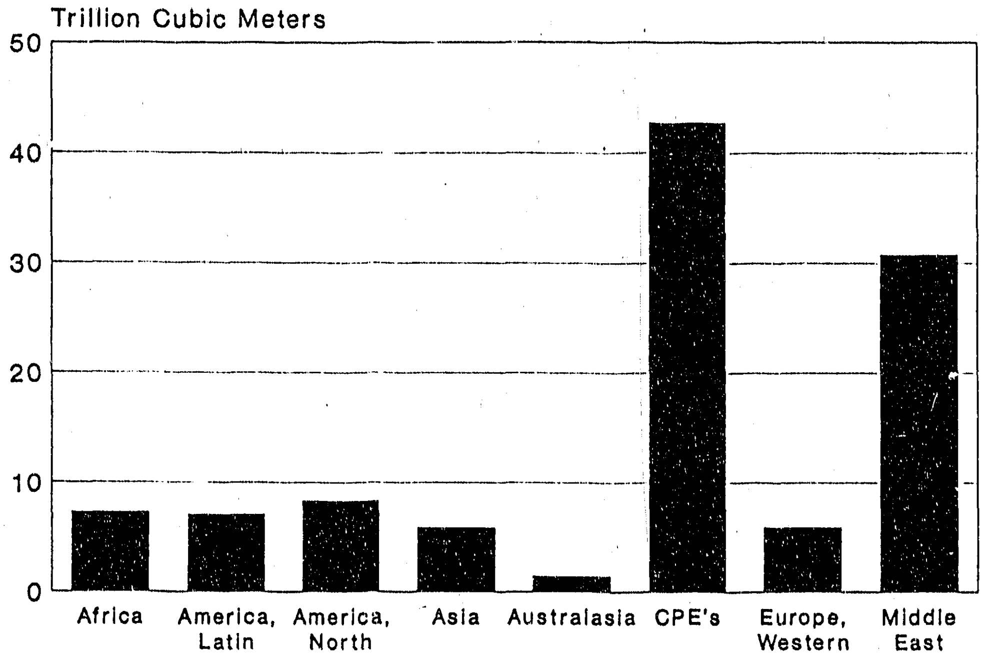

FIGURE 6 Proven Worldwide Recoverable Reserves of Natural Gas by Major Region, 1987 (Source: World Energy Conference, 1989)

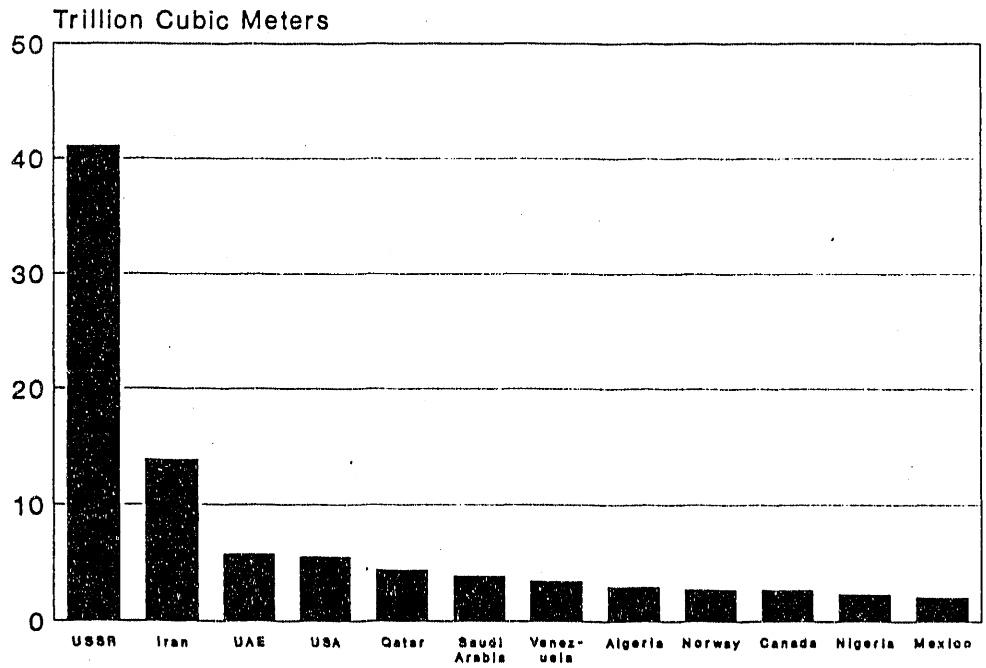

FIGURE 7 Proven Worldwide Recoverable Reserves of Natural Gas by Country, 1987 (Source: World Energy Conference, 1989)

DISCLAIMER

Organisation for Economic Co-operation and Development (OECD) countries to increase their use of gas instead of coal and nuclear energy. This has been primarily due to environmental concerns (IEA, 1989).

5.3 Coal

As shown in Fig. 8, most of the world's coal reserves are concentrated in eight countries. Three countries contain more than 75% of worldwide recoverable reserves: China, the United States, and the U.S.S.R. However, coal reserves exist or coal is generally available to all continents and nations.

Most of the world's coal reserves consist of anthracite, bituminous and subbituminous which are cleaner burning and more fuel efficient than lignite (see Fig. 9). While lignite reserves are found in most countries, Australia, China, Germany, and the U.S.S.R. have relatively large quantities. In Australia, Germany, and the U.S.S.R., lignite comprises 40% or more of the total coal reserve.

At current production rates, economically recoverable coal reserves are estimated to last roughly 325 years. Figure 10 illustrates the lifetimes of economically recoverable coal reserves by region, assuming 1987 production rates. Somewhat lower reserve lifetimes arise when projected demand growth is included or if coal trade with developing countries without reserves increases dramatically; even with these considerations, however, more than 100 years of recoverable reserves should be available in the year 2100.

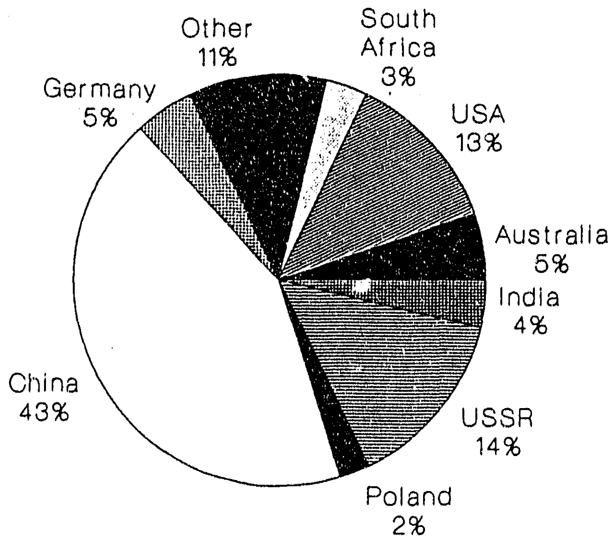

FIGURE 8 Proven Worldwide Recoverable Coal Reserves by Country, 1987 (Source: World Energy Conference, 1989)

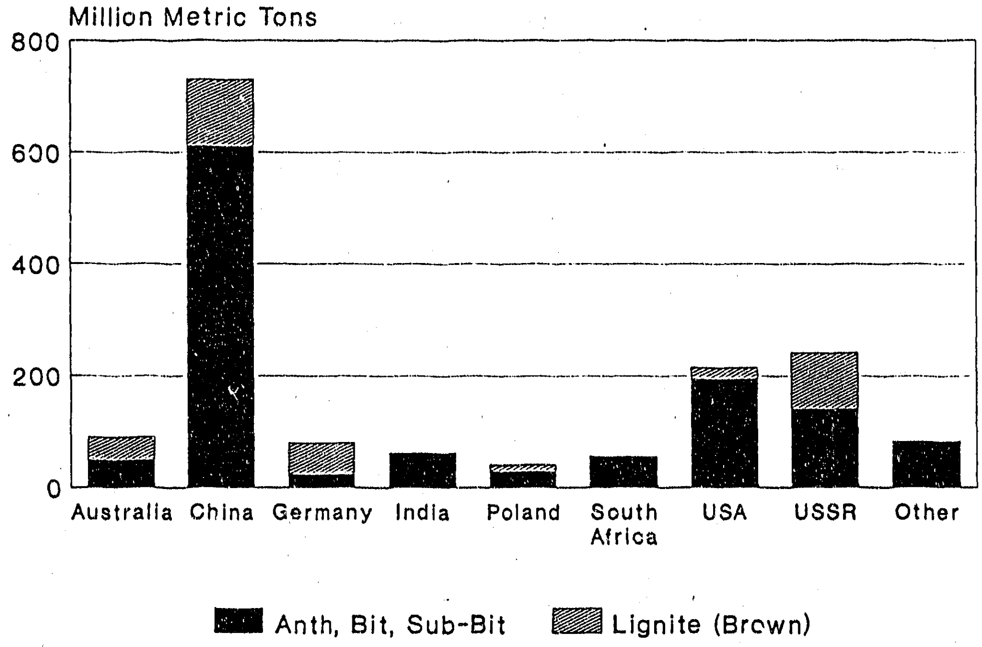

FIGURE 9 Estimated Global Recoverable Coal Reserves by Type and Country, 1987 (Source: World Energy Conference, 1989)

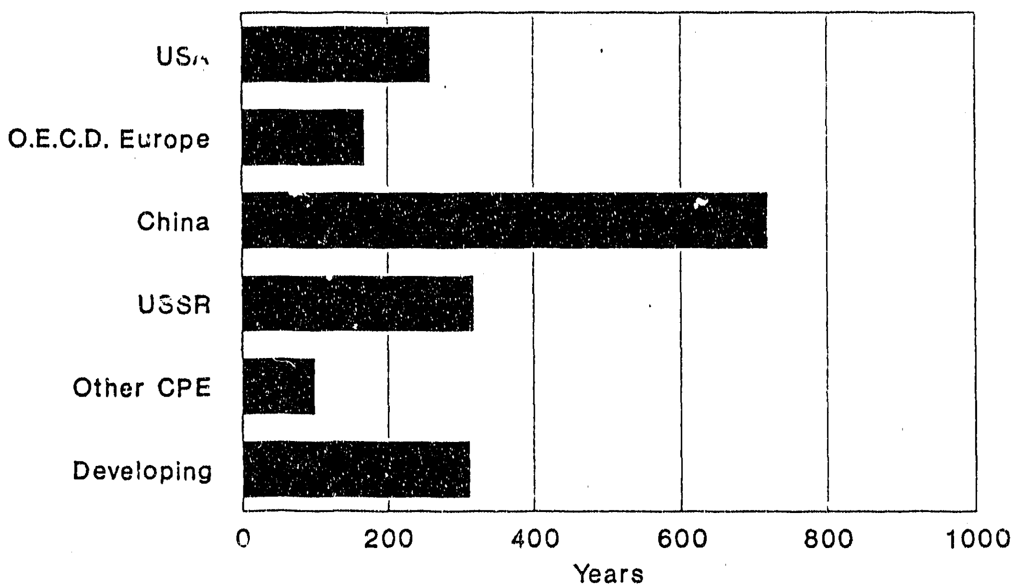

FIGURE 10 Remaining Lifetime of Recoverable Coal Reserves by Region, 1987 Production Rates (Source: World Energy Conference, 1989)

Because of extensive availability, assured supply and lower prices, coal will likely continue to play a major role in the world's energy picture. In the United States, 24% of all energy and approximately 57% of all electricity was produced from coal in 1988 (IEA, 1990a). Worldwide, 25% of all primary energy production, and 44% of all electricity, is produced from coal (World Energy Conference, 1989). For most countries, because of compelling economic and energy security reasons, it would be extremely difficult, if not impossible, to replace coal with another fossil fuel or a non-CO_2-emitting fuel source.

Looking into the future, reliance on fossil fuels is expected to expand worldwide, but the greatest growth is expected in developing countries. The recent history and projected usage of fossil fuels can be seen in projections produced by the Edmonds-Reilly Global CO_2 Model.* In a 1990 reference case forecast, the expected growth rate for fossil fuel consumption in the developed world between 1975 and 2025 is 65%; in comparison, the growth rate in developing countries is projected to be over 428% (see Table 2). In 1975, the developing world consumed only 28% of that by the developed world. By 2025, that percentage is expected to increase to 90%.

TABLE 2 Growth of Fossil Fuel Use by Developed and Developing Countries, 1975-2025

	Fossil Fuel Consumption (10^{18} Joules)			1975-2025 Growth Rate (%)	Average Annual Rate (%)
	1975	2000	2025		
Developed Countries					
Coal	37.55	76.98	77.27	105.8	2.12
Oil	60.33	86.37	80.73	33.8	0.68
Gas	63.76	72.87	109.13	71.2	1.42
	161.64	236.22	267.13	65.3	1.31
Developing Countries					
Coal	21.55	47.17	104.85	386.5	7.73
Oil	19.36	44.38	84.35	335.7	6.71
Gas	4.58	13.98	51.16	1017.0	20.34
	45.49	105.53	240.36	428.4	8.57

Source: Edmonds-Reilly Model, Reference Case (1990).

*The Edmonds-Reilly (ER) Model has been used to forecast worldwide energy patterns and CO_2 emissions, and examine alternative control policies, in a multitude of global climate change studies. For more information on the ER model and some of its applications see Edmonds and Reilly (1983a, 1983b, 1986 and 1987), and Edmonds et al. (1984 and 1986).

While the largest percentage increase in demand is for natural gas, the largest heat content expansion will be in coal: 123 10^{18} Joules for coal versus 86 10^{18} Joules for oil and 92 10^{18} Joules for gas. Table 3 shows the projected growth in fossil fuel utilization by developing nation/region. Coal and oil are projected to increase more than three-fold between 1975 and 2025, with natural gas increasing by more than ten-fold. Table 4 shows that if this pattern of fossil fuel demand in developed and developing countries is extended to the year 2100, current proven reserves of oil and natural gas will be essentially depleted and coal will remain the only fossil fuel of choice, capturing 95% of the market.

Table 5 illustrates the projected rapid growth in the utilization of coal in developing countries. By 2025, developing countries will constitute 57.8% of the world's coal demand. By 2100, that share is projected to increase to 67.2%.

TABLE 3 Projected Growth in Fossil Fuel Use by Developing Countries, 1975-2025

	10^{18} Joules			Growth Rate (%)	Average Annual
	1975	2000	2025	(1975-2025)	Rate (%)
Coal					
China	15.37	30.08	54.06	251.72	5.03
Middle East	0.08	0.31	3.03	368.75	7.38
S. and E. Asia	3.3	9.32	22.3	575.76	11.52
Africa	2.32	4.95	13.49	481.47	9.63
Latin America	0.48	2.51	11.97	2393.75	47.88
	21.55	47.17	104.85	386.54	7.73
Oil					
China	3.16	9.27	18.93	499.05	9.98
Middle East	2.63	6.86	13.44	411.03	8.22
S. and E. Asia	4.74	9.73	12.2	157.38	3.15
Africa	2.31	4.6	14.21	515.15	10.30
Latin America	6.52	13.92	25.57	292.18	5.84
	19.36	44.38	84.35	335.69	6.71
Natural Gas					
China	0.24	1.87	10.19	4145.83	82.92
Middle East	1.06	2.43	8.25	678.30	13.57
S. and E. Asia	0.75	1.64	8.53	1037.33	20.75
Africa	0.22	1.89	9.07	4022.73	80.45
Latin America	2.31	6.15	15.12	554.55	11.08
	4.58	13.98	51.16	1017.03	20.34

Source: Edmonds-Reilly Model, Reference Case (1990).

TABLE 4 Projected Demand for Fossil Fuels and Coal, Developed and Developing Regions

	10^18 Joules					
	1975	2000	2025	2050	2075	2100
Total Fossil Fuel	207.13	341.35	507.49	777.93	376.69	1229.23
Coal	59.1	124.15	182.12	334.38	697.68	1168.54
% Coal	28.53	36.32	35.89	42.98	79.58	95.06

Source: Edmonds-Reilly Model, Reference Case (1990).

TABLE 5 Projected Demand for Coal in Developing Countries, 1975-2100

	10^18 Joules					
	1975	2000	2025	2050	2075	2100
China	15.37	30.08	54.06	71.67	131.41	228.96
Middle East	0.08	0.31	3.03	13.5	24.74	46.77
Africa	2.32	4.95	13.49	46.01	63.05	120.5
Latin America	0.48	2.51	11.97	37.69	97.48	185.56
S. & E. Asia	3.3	9.32	22.3	50.98	114.78	203.84
Total LDC Usage	21.50	47.17	104.85	219.85	431.46	785.63
LDC %	36.38	37.99	57.57	65.75	61.84	67.23

Source: Edmonds-Reilly Model, Reference Case (1990).

Fossil fuel consumption for electricity generation follows a similar pattern to that exhibited for total energy, particularly for coal (see Table 6). However, when expressed in fossil fuel equivalent terms, there is also substantially increased use of 'other' sources of electricity, primarily nuclear and hydroelectric. Nonetheless, as stated above, the level of fossil fuel usage for production of electricity continues to increase in real terms, with oil increasing 11.54 10^{18} Joules, natural gas 29.22 10^{18} Joules, and coal 46.16 10^{18} Joules.

As indicated, fossil fuel consumption, and particularly coal, are projected to increase dramatically in both developed and developing countries. In developing countries, population growth and

TABLE 6 Projected Fuel Consumption for Electricity Generation in Developing and Developed Countries (10^{18} Joules)

	1975	% of Total	2025	% of Total
Developed Countries				
Coal	17.62	30.24	43.09	25.14
Oil	10.55	18.11	13.86	8.09
Gas	12.99	22.30	31.13	18.16
Other	17.10	29.35	83.33	48.61
Total	58.26	100.00	171.41	100.00
Developing Countries				
Coal	4.03	35.07	24.72	17.74
Oil	2.36	20.54	10.59	7.60
Gas	1.15	10.01	12.23	8.78
Other	3.95	34.38	91.81	65.88
Total	11.49	100.00	139.35	100.00

Source: Edmonds-Reilly Model, Reference Case (1990).

pressures for a higher standard of living are driving the need for more energy and electricity. With the extensive fossil fuel resource base and infrastructure, it would be extremely difficult, if not impossible to displace fossil fuel utilization in the near- and mid-term. As discussed in the next section, clean coal technologies offer a means to continue use of fossil fuels worldwide while minimizing CO_2 emissions.

6 Fossil Energy Options to Reduce CO_2 Emissions

Several options exist that could reduce the amount of CO_2 emitted from fossil fuel combustion. Conservation, conversion to lower-CO_2-emitting fuels, or substitution to non-CO_2-emitting fuels are three possible strategies. These potential solutions, however, would take time to have an effect due to 1) the maturity of the alternative technologies, 2) the limited availability of replacement fuels, and 3) the rate of replacement fuels and turnover for existing combustion systems in developing and industrializing economies that are heavily dependent on fossil fuels.

There are, however, three feasible options that involve the continued use of fossil fuels. The first is to combust more oil and natural gas in cases where this option is available and economical, since both of these fuels generate less CO_2 than coal.* Stated differently, more electricity could be generated per pound of CO_2 produced by burning natural gas or fuel oil, than by burning coal (see Table 7).

The second option involves the utilization of advanced fossil fuel technologies, such as CCTs being developed by the U.S. Department of Energy (U.S. DOE). These CCTs have lower CO_2 emission rates because of their higher thermodynamic conversion efficiencies: 40%-45% for near-term CCTs (50-60% for mid-term CCTs) versus 30%-35% for conventional technologies with SO_2 controls.

Figure 11 contrasts, for a single plant, the conversion efficiencies and CO_2 emissions of these advanced fossil energy technologies with those of a conventional pulverized coal (PC) power plant having a flue-gas desulfurization (FGD) unit. The data for each technology are based on a 500-megawatt (MW) power plant that burns coal with a sulfur content of 2.8% and a heating value of 11,600 Btu per pound, and that operates at a 65% capacity factor.

The advanced technologies include atmospheric fluidized-bed combustion (AFBC), pressurized fluidized-bed combustion (PFBC), integrated gasification combined cycle (IGCC) technology, fuel cell with natural gas technology, fuel cell with coal gasification technology, and magnetohydrodynamics (MHD) technology. The data in Fig. 11 clearly demonstrate that increased efficiency produces lower CO_2 emissions. Thus, deployment of these advanced fossil technologies in either greenfield (new) or repowering/retrofit applications would reduce current and future CO_2 emission levels below those achievable with conventional technologies.

Although commercial-scale CCTs are not currently operational in the United States, an aggressive demonstration program sponsored by the U.S. DOE is currently underway to make them available

TABLE 7 CO_2 Emitted by Fossil Fuel Combustion

Fuel	Heat Content (Btu/lb)	CO_2 Generated (lb $CO_2/10_6$ Btu)	Electricity Generated (kWh/lb CO_2)
Bituminous coal	12,700	204	0.56
Fuel oil/gasoline	17,600	178	0.70
Natural gas	24,000	115	1.01
Synthetic natural gas from coal	24,000	329	0.34

Source: Steinberg and Cheng, 1988

*Co-firing 10% to 20% natural gas with coal could reduce the amount of CO_2 emitted from coal-fired plants by the difference in CO_2 emission rates and share of gas co-fired.

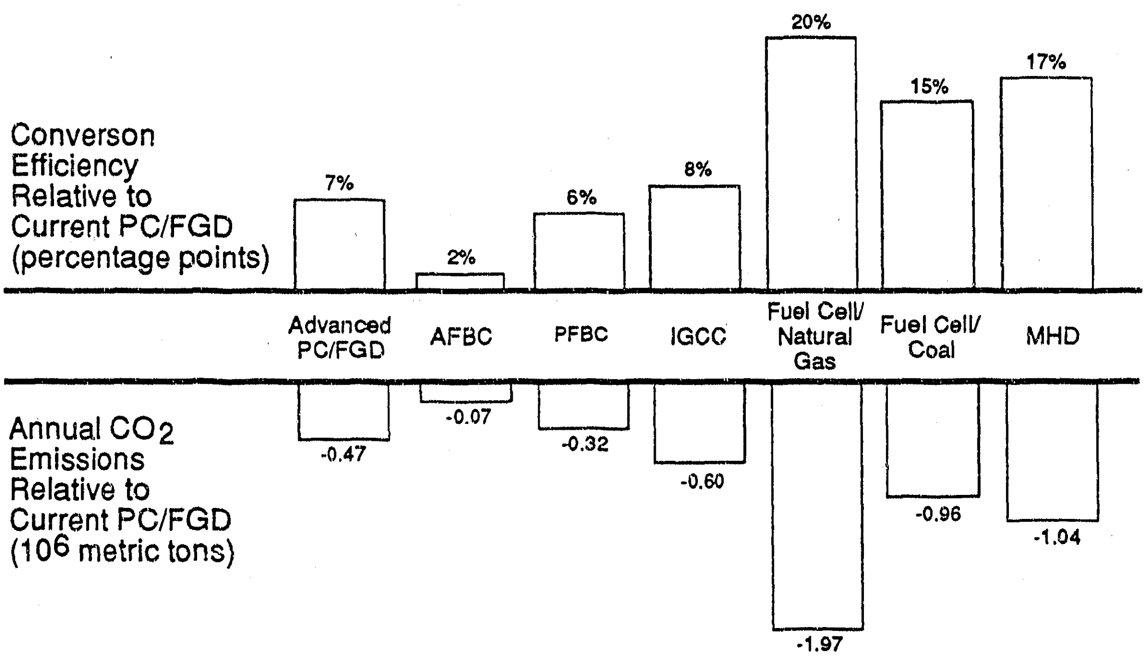

FIGURE 11 Comparison of Conversion Efficiencies and CO_2 Emissions from Advanced and Conventional Fossil Fuel Technologies

at the earliest possible date.* Table 8 indicates the CCT demonstration projects that have been selected as part of the CCT Program; approximately 40 alternative CCTs are currently being demonstrated. In addition, a number of U.S. electric utilities are considering construction of CCTs to meet future electric load growth requirements; the Electric Power Research Institute (EPRI) has conducted 10 integrated coal gasification/combined cycle (IGCC) studies for utilities needing new capacity (Gluckman, Wolk and Touchton, 1989).

Through the CCT demonstration program and subsequent initial deployment, these technologies should be available some time after the year 2000. After the year 2020, fossil-fuel-based fuel cell technologies and MHD technologies with conversion efficiencies of 45%-60% will probably become available. The adoption of these technologies will provide an even greater reduction in CO_2 emissions, yet will allow fossil fuel use to be maintained.

*The Clean Coal Technology Demonstration Program is a $5 billion industry and government initiative to commercially demonstrate and deploy innovative, low-emission, coal-based technologies. The program is a result of former U.S. President Reagan's commitment to Canadian Prime Minister Mulroney to address the transboundary acid rain problem and comply with the recommendations of the joint report of the special envoys on acid rain (U.S. DOE, 1986).

TABLE 8 Classification of Demonstration Projects into Characteristic Technology Categories

Technology Category	Demonstration Project	Selected CCT-I	Selected CCT-II	Selected CCT-III	Total Projects
Advanced Combustion	Advanced Cyclone Combustor	✓			4
	Advanced Slagging Coal Combustor	✓			
	LNS Burner for Cyclone-Fired Boilers		✓		
	Healy Power Project			✓	
Coal Preparation	Advanced Coal Conversion Process	✓			3
	Coal Quality Expert Project	✓			
	OTISCA Fuel		✓		
Flue Gas Cleanup: Combined SO_2/NO_x Control	Gas Reburning/Sorbent Injection	✓			6
	Limestone Extension and Coolside Demonstration Project	✓			
	SOX-NO_x-ROX Box Flue Gas Cleanup		✓		
	WSA-SNO_x Flue Gas Cleaning		✓		
	NO_xSO SO_2/NO_x Removal Flue Gas Cleanup			✓	
	Confined Zone Dispersion Flue Gas Desulfurization			✓	
Flue Gas Cleanup: NO_x Control	Advanced Tangentially Fired Combustion		✓		7
	Advanced Wall-Fired Combustion		✓		
	Coal Reburning in Cyclone-Fired Boilers		✓		
	Selective Catalytic Reduction		✓		
	Low NO_x Cell Burner Retrofit			✓	
	Wall-Fired Boiler Gas Reburning and Low NO_x Burner			✓	
	Integrated Dry NO_x/SO_2 Emission Control System			✓	
Flue Gas Cleanup: Sulfur Control	Advanced Flue Gas Desulfurization (AFGD)		✓		4
	CT-121 FGD		✓		
	Gas Suspension Absorption Flue Gas Desulfurization			✓	
	LIFAC Flue Gas Desulfurization			✓	

TABLE 8 (Cont'd)

Technology Category	Demonstration Project	Selected CCT-I	Selected CCT-II	Selected CCT-III	Total Projects
Fluidized-Bed Combustion: Circulating Fluidized-Bed	Nichols CFB Repowering		✓		4
	Nucla CFB	✓			
	Alma PCFB Repowering			✓	
	CFB (Tallahassee)	✓			
Fluidized-Bed Combustion: Pressurized Bubbling-Bed	PFBC Utility Demonstration		✓		2
	Tidd PFBC	✓			
Integrated Gasification Combined-Cycle	Clean Energy IGCC	✓			3
	IGCC Repowering		✓		
	IGCC Demonstration			✓	
Industrial Processes	Cement Kiln Gas Cleaning		✓		4
	Coke Oven Gas Cleaning		✓		
	Prototype Commercial Coal/Oil Coprocessing	✓			
	Blast Furnace Granulated Coal Injection			✓	
New Fuel Forms	Liquid Phase Methanol			✓	2
	Mild Gasification			✓	

Source: USDOE, 1990.

The U.S. DOE is also actively involved in pursuing the international transfer of CCTs. Cooperative agreements have recently been signed with Costa Rica and Chile. The objective is to enhance energy security through the use of coal and CCTs; other benefits include fuel diversity, increased economic cooperation, and expanded trade opportunities. It is also recognized that deployment of these advanced technologies will have environmental benefits, such as reduced CO_2 emissions.

The third option to reduce CO_2 emissions is CO_2 scrubbing via tail-gas cleanup technologies. To apply this technique in the electric power industry would involve the adaption of acid-gas removal technologies that are currently used by the petroleum and petrochemical industries to remove sulfur dioxide. While several techniques are possible, they are presently not cost effective and have disposal problems.

6.1 Substitution Between Fossil Fuels

One strategy to reduce CO_2 emissions from power plants without displacing fossil fuels is to alter the fuel mix. This can be accomplished by switching to less-CO_2-intensive fossil fuels, such as natural gas.

Utilities typically decide on a fuel mix on the basis of long-term and short-term considerations. A long-term choice is made when a utility decides whether to fill its need for new capacity by building a coal, oil, gas, nuclear, or hydroelectric power plant. In many cases, once a plant has been built for a particular fuel type, there is little opportunity to switch to an alternate fuel without incurring significant costs. Generally speaking, it is easier (i.e., less costly) to switch from coal to oil or gas, than to switch in the opposite direction.

In some cases, fuel flexibility is inherent in the technology at the plant. For example, some boilers are designed to burn both oil and gas (the selection at any given time depends on local fuel availability and price), and some are designed to burn both coal and oil. Table 9 indicates the number and share of multi-fired boilers that exist in North America, OECD Europe and OECD Pacific. Multi-fired boilers comprise between 18% and 24% of total 1988 worldwide capacity, with the majority of the boiler capacity designed to burn oil and natural gas or coal and oil. Only a small proportion (1.2-3.4%) of the existing boilers can switch from coal to natural gas. In the short-term, a utility decides which units and fuels in an existing mix will be used to meet a given level of demand. These short-term decisions are primarily based on fuel costs, operating costs, and maintenance requirements.

Every fuel has advantages and disadvantages, depending on the issue of concern. Oil is the most versatile fuel and natural gas is the cleanest. Coal has continued to be the cheapest fossil fuel option for meeting base-load demand, but it emits significantly more CO_2 (and other pollutants) than oil and gas. It does have the largest resource base of the fossil fuels, however, as pointed out in Sec. 5.

TABLE 9 Share of Multi-Fired Capable Boilers in Selected Regions, 1988

Classification by Fuel	North America			OECD Europe			OECD Pacific		
	Capacity (MW)	% of Total Capacity	% of Total Conventional Thermal	Capacity (MW)	% of Total Capacity	% of Total Conventional Capacity	Capacity (MW)	% of Total Capacity	% of Total Conventional Thermal
Total Capacity	772510			498045			207023		
Total Conventional Thermal Capacity	519929	67.30		245215	49.24		129949	62.77	
Multi-Fired									
Solids/Liquids	26608	3.44	5.12	39493	7.93	16.11	11296	5.46	8.69
Solids/Natural Gas	26412	3.42	5.08	6007	1.21	2.45	1885	0.91	1.45
Liquids/Natural Gas	124434	16.11	23.93	32697	6.57	13.33	16053	7.75	12.35
Solids/Liquids/Nat. Gas	3542	0.46	0.68	11965	2.40	4.88	880	0.43	0.68
Total	180996	23.43	34.81	90162	18.10	36.77	30114	14.55	23.17

Source: IEA, 1990b.

As illustrated in Table 7, coal has the highest carbon content per unit of energy produced of any of the widely used fossil fuels (with the exception of synfuels, which are really synthesized coal). Natural gas has the lowest carbon content, and thus can generate the most electricity per pound of CO_2. Thus, if it were feasible to switch from coal to natural gas, the rate of CO_2 emissions from energy generation could be decreased significantly.

Implementation of any fuel-switching strategy would not be easy, especially in developing countries. Whereas coal is relatively easy to transport and requires only a minimal amount of specialized equipment, natural gas and oil require more sophisticated transportation systems and equipment. In the United States, the locations of many power plants were chosen to be near a coal transportation network, and an oil or gas network may not be accessible. Oil and gas networks cannot be readily adapted to rural populations in the Third World. Furthermore, many parts of the Third World and China have abundant supplies of coal, whereas natural gas and oil have to be imported.

Switching from coal to natural gas and oil is not a feasible long-term means to reduce GHG emissions. The reservoirs of gas and oil are relatively small when compared with those of coal; approximately 90% of the recoverable reserves of fossil fuel are in the form of coal. Moreover, at current production rates, these oil and gas reserves may last only a few decades, and any substitution that would increase their rate of utilization could reduce their reserve life unless supplemented with new discoveries.

In addition, a vast infrastructure already exists (especially in the United States and other developed countries) for using natural gas and oil in other applications such as for transportation and residential cooking and heating. Demand can be expected to continue to grow, thus putting additional pressure on the use of all energy resources, including coal. In addition, any increased demand for oil and gas via substitution would increase their price, thereby raising electricity costs.

Another problem associated with natural gas and oil is that these fuels are concentrated in a few areas and are subject to political and economic manipulation. Finally, any reduction in the use of coal (unless carried out on a global basis) would increase the supply of this fuel, thereby decreasing its price and making it even more attractive to countries not participating in the switch to oil or gas. The increased use of coal would then add to CO_2 emissions, offsetting any potential decrease in CO_2 emissions resulting from the countries that might have switched to less-carbon rich fuels.

Given the economic importance and vast deposits of coal in many nations, coupled with the limited reserves of natural gas and oil, coal will undoubtedly play a major role in the energy future of the world. Other nonfossil fuel options could play a role in the energy sector while producing little or no CO_2 at the power plant. The material, transportation, and land requirements and other needs of these technologies must be examined to ascertain their overall CO_2 (and other GHG) impact. Combinations of technologies, such as the gasification of coal via nuclear power, also offer some potential for reduced CO_2 emissions; many technical, economic, and societal considerations, however, must be addressed and resolved before such combinations can be expected to make a significant impact on CO_2 emissions (Green, 1988).

6.2 Advanced Fossil Energy Technologies

Many advanced fossil fuel technologies that are currently under development in the United States by the government (principally the U.S. DOE) and private sector (in some cases, through EPRI) could reduce CO_2 emissions. Several of these technologies are based on the continued use of fossil fuels, principally coal. The reduction in CO_2 emissions is accomplished by increasing the efficiency of the coal-to-electricity (or other marketable output) conversion over that typically attained in current, commercial fossil fuel technologies. Although more technologies are under development, six representative options are summarized in the following paragraphs. Figure 11 provides a comparison of conversion efficiencies, and total CO_2 emissions of advanced fossil fuel technologies relative to a conventional fossil fuel technology.

In the following sections, GHG emissions from each of these options are compared with those from a reference 500-MW power plant operating at an annual capacity factor of 65%. This reference plant uses a wet limestone FGD system to remove 90% of the SO_2 generated, by burning a coal with 3.5% sulfur and a higher heating value of 11,600 Btu/lb.

6.2.1 Reference Case, Conventional Coal Combustion with Wet Limestone Flue-Gas Desulfurization

Coal-fired plants using the conventional, commercial technology burn pulverized coal and use a wet limestone FGD system to remove the SO_2 from the flue gas before releasing it to the atmosphere. The net efficiency for this type of power plant is approximately 30%-35% (a value of 33% will be used for comparative purposes). Based on the above assumptions and on the assumption of 100% combustion efficiency, 0.89 pound (lb) of coal would be burned for every kilowatt-hour (kWh) of saleable electricity. The corresponding CO_2 emission rate from the coal is approximately 204 lb of CO_2 per million Btu of energy released, or approximately 2.07 lb/kWh of saleable electricity.

As noted above, conventional pulverized-coal-fired units typically use a wet-limestone-based FGD system to control SO_2 emissions. Because limestone ($CaCO_3$) is a carbonate, some additional CO_2 is released when the limestone is calcined into lime (CaO). Based on typical values of calcium-to-sulfur ratios used in this type of system, the amount of CO_2 released in this process is approximately 0.05 lb/kWh. The total CO_2 released from the power plant boiler is thus about 2.12 lb/kWh. The annual amount of CO_2 released from the reference plant would be approximately 3.02 million metric tons. This estimate is only for releases that result from coal combustion and does not include releases that occur during the mining of coal or limestone, transportation, waste disposal, or any other phase of the total cycle. Small quantities of other

GHGs are also released as a consequence of coal combustion. Table 10 delineates the emission rates for these other gases.

6.2.2 Advanced Coal Combustion and Flue-Gas Desulfurization

A considerable amount of R&D is being done to improve the operating characteristics of conventional power plants such as the one described above. With respect to CO_2 emissions, improvements could be realized through an increase in the efficiency of the plant and through greater utilization of sorbent materials in the FGD system. Efficiency improvements could be realized by using supercritical steam, higher initial steam temperatures, or multiple reheat. It has been estimated that the efficiency of an advanced pulverized-coal-fired power plant could be increased to about 40% in the near-term (EPRI, 1989). This degree of efficiency represents a substantial improvement over the reference-case efficiency of 33% for conventional plants.

Improvements in the FGD system could be achieved through regenerating the sorbent, using noncarbonate sorbents, or changing the temperature, humidity, and other parameters that influence the use of sorbent in the FGD system. Figure 12 shows a schematic of an advanced pulverized-coal plant with an advanced FGD system. Although the use of lime in place of limestone would reduce CO_2 emissions at the power plant, an equal amount of CO_2 would be released in the production of commercial lime, since lime is produced by calcining limestone.

The rate of CO_2 emitted from coal combustion in the advanced plant would be approximately 1.75 lb/kWh from the carbon content of the coal and approximately 0.04 lb/kWh from the

TABLE 10 Approximate GHG Emissions for Selected Advanced Fossil-Fuel Technologies (lb/kWh)

	CO_2	NO_x	N_2O	CH_4
PC/FGD	2.12	0.006	0.00014	0.0020
ABC/FGD	1.79	0.004[a]	0.00011[a]	0.0016[a]
AFBC	2.07	0.0024	0.0015	0.0022
PFBC	1.90	0.0021[a]	0.0013[a]	0.0019[a]
IGCC	1.70	0.0009	0.00014	0.0020

[a]Estimate based strictly on efficiency improvements.

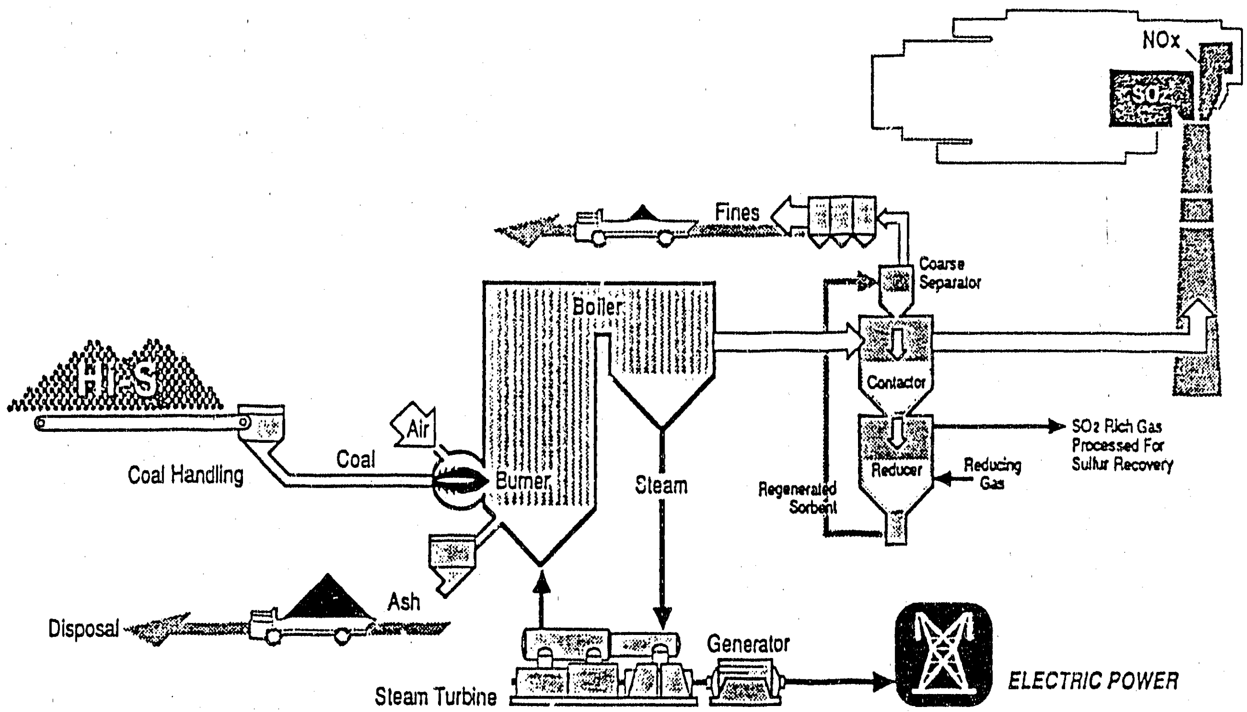

FIGURE 12 Power Plant with Advanced Flue-Gas Cleanup (Source: U.S. DOE, 1987)

limestone. The latter number was estimated based on the assumption that near-term applications of advanced FGD systems would be based on improved sorbent utilization rather than wide-scale sorbent regeneration. The total rate of CO_2 emissions from this advanced coal-fired plant would thus be approximately 1.79 lb/kWh, and the annual emissions would be about 2.55 million metric tons based on the same assumptions for plant size and annual capacity factor. Emissions of other GHGs are shown in Table 10.

6.2.3 Atmospheric Fluidized-Bed Combustion

One of the technologies being developed as part of the U.S. DOE Clean Coal Technology program uses atmospheric fluidized-bed combustion (AFBC). In this technology, pulverized coal (or some other fuel), an inert bed material such as sand or ash, and a sorbent such as limestone are suspended (fluidized) by an upward flow of combustion gases and air. This process provides a high level of combustion efficiency while keeping temperatures low enough to minimize NO_x formation and to provide for near-optimal SO_2 capture by the sorbent. Heat is removed from the combustion zone by producing steam in water-filled tubes passing through the fluidized bed and/or the hot gas stream. The steam is sent to a conventional steam turbine to generate electricity. Particulates (consisting of ash, spent sorbent, and unreacted sorbent) are removed from the gas stream with conventional cleanup devices such as baghouses, cyclones, or electrostatic precipitators.

The AFBC technology can be used both for new generating facilities or as a repowering option in refurbishing old power plants. When used in new facilities, the efficiency of an AFBC power plant is expected to be approximately 35%, which represents an improvement of about two percentage points over the conventional pulverized-coal plant with FGD (EPRI, 1989).

Based on the earlier assumptions about coal characteristics, approximately 1.99 lb of CO_2 would be created per kWh of electricity generated. Because limestone is used as the SO_2 sorbent in AFBC units, additional CO_2 is released during this process. An additional 0.08 lb of CO_2 is released from the limestone per kWh of electricity generated. The total CO_2 release from a new AFBC facility is thus estimated at 2.07 lb/kWh, or about 2.95 million metric tons per year. It must be emphasized that this value, which is 0.07 million tons per year less than that of the reference case, is dependent on the calcium-to-sulfur value needed for the required level of SO_2 control. The other GHG gases emitted are comparable to those of the reference plant (see Table 10).

6.2.4 Pressurized Fluidized-Bed Combustion

Another version of the fluidized-bed concept uses pressurized fluidized-bed combustion (PFBC). In this technology, the combustor is maintained at a pressure of 8-16 atmospheres as opposed to the near-atmospheric pressure maintained in AFBC units. Particulates are removed from the pressurized gases exiting the combustor in a hot-gas cleanup system. The cleaned gases are then expanded in a gas turbine to produce electricity. Steam that is generated by cooling the combustor and in waste-heat steam generators at the exit of the gas turbines is expanded in a conventional steam turbine to produce additional electricity. This combined-cycle aspect of PFBC units yields an overall efficiency of approximately 39% (EPRI, 1989). The amount of CO_2 created in a PFBC is about 1.79 lb/kWh.

As in AFBCs, SO_2 control in PFBC units is accomplished in the fluidized bed through the addition of a calcium-based sorbent. For many years, it has been believed that dolomitic limestone (a mixture of approximately equal molar quantities of $CaCO_3$ and magnesium carbonate or $MgCO_3$) rather than regular limestone ($CaCO_3$) must be used in PFBCs. Therefore, even though some recent evidence suggests that the necessary SO_2 removal rates can be achieved with regular limestone, the following estimates are based on the use of dolomitic limestone.

A calcium-to-sulfur ratio of about 1.5 is believed necessary to achieve 90% SO_2 removal from a high-sulfur coal. Because both the calcium and the magnesium are in the form of a carbonate, twice the amount of CO_2 will be released from dolomitic limestone as from an equal number of moles of regular limestone. Based on a calcium-to-sulfur ratio of 1.5, approximately 0.11 lb of CO_2 are released per kWh of electricity generated. The total rate of CO_2 emissions from a PFBC unit is thus 1.90 lb/kWh. An annual CO_2 release of about 2.70 million tons, or 0.32 million metric tons less than that of the reference case, is estimated. This estimate is dependent on the required calcium-to-sulfur ratio and whether dolomitic or regular limestone is used. Other GHGs released from PFBC units are similar to those from AFBC units but are reduced by the plant efficiency ratio (see Table 10).

6.2.5 Integrated Gasification Combined-Cycle Technology

Integrated coal-gasification combined-cycle (IGCC) technology is under development for use in new power plants and for repowering old ones. In this technology, coal is partially combusted under substoichiometric conditions so that it is gasified. The gas is then cleaned and burned in a combustion turbine, where it produces electricity. Although there are several concepts based on different gasification processes and gas cleanup systems, steam can be produced in waste-heat steam generators, the gasification chamber, and the gas cooling system. This steam is then sent to a conventional steam turbine, where it is expanded to produce additional electricity. A schematic of an IGCC power plant is shown in Fig. 13.

The combined-cycle aspect, when combined with advances in combustion turbines, yields an expected efficiency of approximately 41% for some systems (EPRI, 1989; South et al. 1990). Based on the assumption that all the carbon in the coal is eventually oxidized to CO_2, this efficiency is equivalent to the release of 1.70 lb of CO_2 per kWh of saleable electricity. For most IGCC units, the annual release of CO_2 would be approximately 2.42 million metric tons, or about 0.60 million tons less than that of the reference case. The other GHG emissions are shown in Table 10.

Unlike the technologies described thus far, most IGCC units do not use a carbonate sorbent to control SO_2. Instead, they use special solvents that selectively absorb the hydrogen sulfide (H2S) and carbonyl sulfide (COS) along with some CO_2 and H_2O. The sulfur is then recovered and can be sold if an appropriate market exists. As a result, no significant additional CO_2 releases are associated with SO_2 control as they are with the technologies described previously. Such hot-gas cleanup systems are undergoing extensive R&D with the objective of being commercially available within the next few years. An exception to this type of gas treatment exists with a fluidized-bed gasifier, in which in-bed SO_2 con. .l is accomplished with limestone in a way similar to that used in AFBCs.

6.2.6 Fuel Cells with Natural Gas

One of the advanced technologies currently undergoing R&D is the fuel cell. An advantage of this technology is that it produces electricity directly from the combustion of fuel, thus eliminating the need for the intermediate steps of conventional technologies (fuel combustion with the subsequent conversion of the heat to steam, to mechanical energy, and then to electricity). As a consequence, the efficiency of fuel-cell power plants can be quite high. Several types of fuel cells are under development; phosphoric acid and molten carbonate fuel cells have been receiving a great deal of attention.

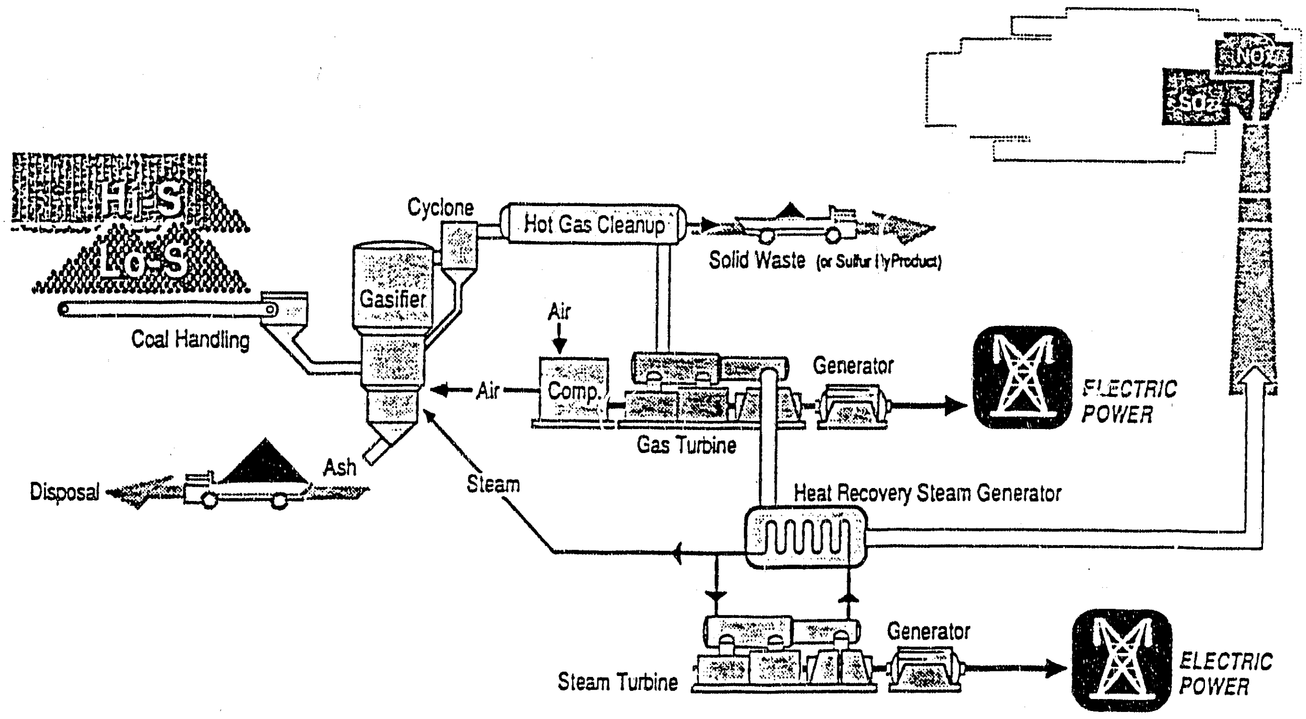

FIGURE 13 Power Plant with Integrated Gasification Combined-Cycle Technology (Source: U.S. DOE, 1987)

Early versions of fuel cells to be used in the production of electricity will probably be based on the use of a light distillate oil or natural gas as the basic fuel. Efficiencies for this type of fuel cell are estimated to be as high as 53% (U.S. DOE, 1988). When natural gas is the base fuel, the CO_2 released from this power plant would be about 0.74 lb/kWh, based on the assumption that the natural gas releases 115 lb $CO_2/10^6$ Btu of energy released. The annual release from a power plant using this concept, based on the reference case assumptions, would be about 1.05 million metric tons. No estimates of non-CO_2 GHG emissions are available, but the use of natural gas would result in some increase in CH_4 losses with respect to the reference technologies.

6.2.7 Fuel Cells with Coal Gasification

As an alternative to the use of relatively scarce (when compared with coal) natural gas and light distillate fuels, a technology that combines coal gasification with fuel cells is undergoing R&D. In this concept, coal is gasified in a manner similar to that used in IGCC units to produce a hydrogen-rich synthesis fuel. Because fuel cells have an extremely low tolerance to sulfur, the synthesis gas is subjected to a gas cleanup system, where almost all the sulfur compounds are removed. Depending on the type of fuel cell, other impurities such as carbon monoxide are also removed before the synthesis gas enters the fuel cell.

Due to its coal gasification and gas cleanup steps, the fuel cell/coal gasification technology would probably be slightly less efficient than fuel cell technologies based on natural gas or light distillate. An efficiency of about 48% has been estimated for a fuel cell/coal gasification concept using the Texaco gasification process (EPRI, 1989). Based on this efficiency, it is estimated that the CO_2 released from this power plant would be about 1.45 lb/kWh, or about 2.06 million metric tons per year. Estimates for the release of other GHGs have not been made.

6.2.8 Magnetohydrodynamics

The final technology considered here is that of MHD. In this process, coal is burned at temperatures high enough (about 5,000°F) to dissociate the resulting combustion gases into highly charged particles. This flow of charged particles, called a plasma, is then passed through a magnetic field, which results in the production of electricity. The hot gases exiting the magnetic field are sent to a heat recovery steam generator to produce steam, which is expanded in a conventional steam turbine to produce additional electricity. This combined-cycle type configuration is expected to yield overall efficiencies of 50% or more (U.S. DOE, 1989b).

Based on the assumption of 50% efficiency, the rate of CO_2 released from an MHD power plant would be about 1.39 lb/kWh. Annual releases would be about 1.98 million tons. This value is 1.04 million metric tons per year less than that released by a conventional pulverized-coal plant with wet limestone FGD. Estimates for emissions of other GHGs are not available.

6.2.9 Summary

The technologies discussed above are representative of the advanced fossil fuel options being demonstrated or under development for use in electric utilities. These options are the subjects of significant R&D efforts in both the public and private sectors. The anticipated conversion efficiencies and the corresponding CO_2 emissions reductions are summarized in Fig. 11, where the values for the advanced technologies are compared with those of a conventional pulverized-coal-fired power plant equipped with a wet limestone FGD system for SO_2 control. For a rough approximation, the estimates are presented in order of anticipated commercialization (see Fig. 14). Those technologies on the left-hand side of Fig. 11 are those believed to be currently available or those that could reasonably penetrate the electric utility sector by the year 2000. Those technologies on the right-hand side of the figure are not anticipated to play a large role until after the turn of the century, at the earliest.

6.3 Removal, Recovery, and Disposal of CO_2

The concentration of CO_2 in the atmosphere can, in theory, be controlled by removing it either before or after it has been released from a power plant to the atmosphere. Removal mechanisms

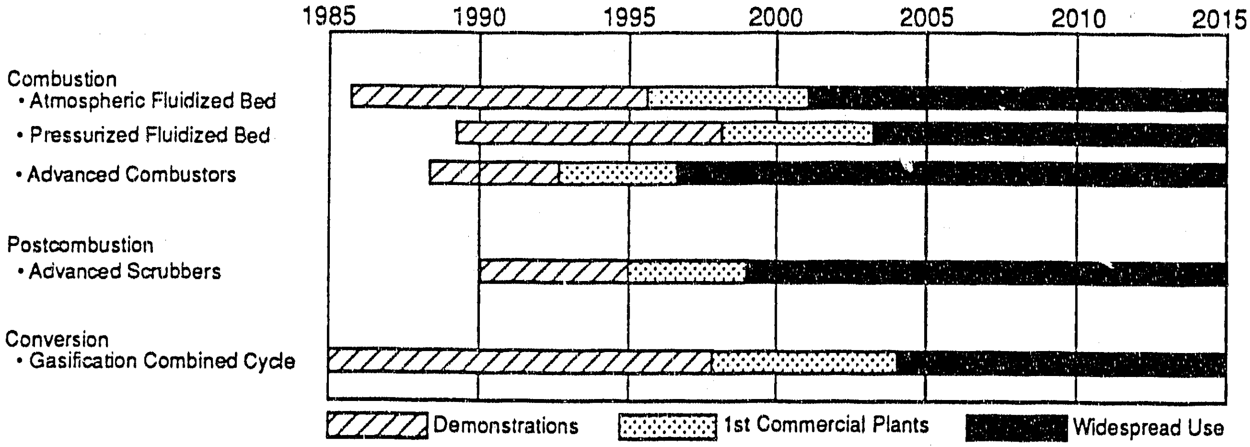

FIGURE 14 Commercial Readiness of Clean Coal Technologies (Source: U.S. DOE, 1989b)

designed to extract CO_2 directly from the atmosphere have been proposed but are usually considered to be too energy consuming, expensive, and generally impractical. Furthermore, the additional energy consumed by these processes would, if generated from fossil fuels, release additional CO_2 and other GHGs into the atmosphere, thereby offsetting their positive results. The control of CO_2 releases before they are released to the atmosphere appears to be a somewhat more feasible option, and several techniques have been proposed. Some of the basic features of some of these techniques are discussed below.

At the present time, the only option available for CO_2 control would involve a tail-gas cleanup (i.e., CO_2 scrubbing) system that could be adapted from the acid-gas removal technologies used in the petroleum and petrochemical industries. In general, this type of control technology consists of four steps: recovery, concentration, liquefaction, and disposal or reuse of the CO_2. The various CO_2 scrubbing concepts (discussed below) emphasize one step over another, but most involve some version of each of the four steps.

The most advanced CO_2 scrubbing techniques are based on CO_2 absorption. This general process is widely used by the petroleum industry in acid-gas cleanup systems. It is based on the concept that certain liquid solvents (e.g., amines or seawater) can be used to selectively absorb gases in a stream consisting of several different gases. It has been projected that 90% of the CO_2 in a gas stream can be absorbed in this way, but also that the net electrical output from a typical power plant would be reduced by 30%. Work is underway to develop more concentrated solutions that would improve the efficiency of the removal process so that the net power reduction would be about 20%.

A second general technique makes use of the adsorption properties of materials such as clay. In this process, the CO_2 would be adsorbed in the clay until it became saturated, at which time the material would be removed for storage in clay pits. Removal efficiencies of up to 90% have been estimated, but a severe power penalty of up to 50% has also been estimated for this level of removal.

A third technique is based on chemical and biochemical processes. Plankton or algae are exposed to CO_2 in a controlled environment, where photosynthesis techniques are used to capture CO_2 and convert it to a useable form such as cellulose. This technique is still being developed and is not expected to be available until after the turn of the century.

The fourth general technique is expected to be capable of removing 90% of the CO_2 by condensing the gases. Power requirements are currently estimated to be 20%-30% of the plant output. This is the least mature of all the generic type of scrubbing, options discussed, and, as such, has very high levels of uncertainty associated with it.

There are at least three fundamental difficulties with each of these scrubbing options. First, the cost are anticipated to be quite high. Flour Daniel, Inc., under contract to EPRI, recently completed a detailed engineering and economic evaluation of CO_2 removal, recovery and disposal from a 500 MW pulverized coal-fired power plant with FGD (PC/FGD) and from a 400 MW integrated coal gasification combined cycle (IGCC) power plant (Smelser and Booras, 1990).* The evaluation assessed the incremental impact of reducing CO_2 emissions (nominally 90%) on the design, thermal efficiency, capital and O&M cost for both plants.

As depicted in Table 11, the study found that net power plant output of the PC/FGD plant will be reduced by approximately 35%, with a net heat rate of 14,965 Btu/kWh. In comparison, the net power output from the IGCC plant would be reduced by only 12%, with a net heat rate of 11,975 Btu/kWh. Incremental plant capital costs, including the cost of replacement power,** are \$1660/kW and \$1226/kW for CO_2 controls on a greenfield PC/FGD and IGCC, respectively. Corresponding CO_2 control costs for a retrofit PC/FGD plant would be \$1876/kW. Incremental plant cost for IGCC/CO_2 control are much lower than costs for PC/FGD plants because CO_2 removal from high pressure syngas requires less energy and uses lower cost processes than CO_2 recovery from low pressure flue gas (Smelser and Booras, 1990).

---

*It was assumed that ocean disposal would be used; the disposal costs reflect a 400 mile pipeline (300 miles overland and 100 miles offshore for disposal at 1500 feet), the typical distance from most power plants in the eastern United States.

**Replacement power was prorated by multiplying the lost power by \$1475/kW, the capital cost of a new nuclear power plant (EPRI, 1990).

TABLE 11 Capacity, Performance and Cost Impact of CO_2 Controls on PC/FGD and IGCC Power Plants

	Net Electrical Output (MW)	Heat Rate (Btu/kWh)	Coal-to-Power Effic. (%)	In-Plant Power Consump. (MW)	Total Plant Cost (1990 $ x10^6)	$/kW	Incremental Cost ($/kW)[a]
PC/FGD							
Base Case	513	9,800	34.8	41	580	1,129	-
Retrofit w/CO_2 control	336	15,000	22.8	111	1,282	3,830	1,876
Greenfield w/CO_2 control	338	14,900	22.9	109	1,173	3,469	1,660
IGCC							
Base Case	432	9,640	35.4	70	691	1,600	-
Greenfield w/CO_2 control	389 (Net)[a]	12,000	28.5	117	1,142	3,015	1,226

[a]Total incremental capital requirements are the difference between the cost of the CO_2 removal plant and the cost of the base case plant, plus the replacement power costs, divided by the net power produced by the original base case plant.

Source: Smelser and Booras, 1990.

The second general problem is that of efficiency. Again, depending on the specific process and level of removal, up to 50% of a plant's electrical output could be consumed by the CO_2 control system.

The final problem is that of the disposal or use of the concentrated CO_2. The vast quantities of CO_2 to be removed would require very large markets for reuse and/or have special storage techniques. Several disposal options have been considered, but they have limited applications and, in some cases, very high costs. One example of a disposal technique is the storage of the CO_2 in depleted gas wells. This option is constrained by how close the depleted wells are to the coal-fired power plants and by how much capacity is available in the wells. It has been estimated that the current U.S. well capacity is 48 gigatons (10^9 tons) or approximately 25 years of CO_2 production at current CO_2 emission rates (Steinberg and Cheng 1988). Yet even this estimate is based on the assumption that there are no constraints that would result from the relative locations of the CO_2 sources and the well storage sites.

Another storage option that has been suggested is to pipe the CO_2 to ocean depths of 500 to 3000 meters, where the natural absorptive characteristics of the sea could be used for the long-term storage of the CO_2. The application of this option appears to be limited to power plants near the sea, and there is a great deal of technical uncertainty about the process itself.

A process that can use the CO_2 removed from power plants is enhanced oil recovery (EOR). In this process, pressurized CO_2 is pumped into those oil wells in which little or no oil can be recovered through conventional techniques. The high-pressure CO_2 mixes with the oil, thereby decreasing its viscosity so that it can flow and be pumped out of the well. Information compiled by Wolsky and Brooks (1988) suggests there is a potential market for 1-3 trillion cubic feet per year of CO_2 in the EOR area. However, this quantity of CO_2 is equivalent to the amount that could be recovered from about 50,000 MW of fossil fuel capacity, which is only about 10% of the equivalent U.S. capacity. The respective locations of the power plants and the oil wells could also limit the practicality of using recovered CO_2 for this purpose.

7 Summary and Conclusions

Energy forecasts indicate a large increase in worldwide energy consumption as population growth and industrialization expands, particularly in developing countries. One model, the Edmonds-Reilly Global CO_2 Model, projects an expanded role for fossil fuels in the next century. Substantial increases in fossil fuel consumption are projected for developing countries. Any projected growth in fossil fuel consumption could be readily accomodated, especially for coal. Up to 325 years of proven coal reserves remain worldwide, and 40-50 years of oil and gas, at current production rates.

While concerns about GHG emissions, particularly CO_2, are emerging, it may be premature to take any immediate actions to curtail fossil fuel consumption given the large uncertainties that remain unresolved. Regardless of the outcome, fossil fuels can continue to fuel economic growth and development worldwide by reliance on CCTs. Clean coal technologies reduce CO_2 emissions per kilowatt-hour of electricity generated due to their improved efficiencies. If it is determined that GHG emissions should be reduced, fossil fuels and fossil-fuel-based technologies can continue to play a role. Fuel substitution to lower carbon-content fossil fuels or CO_2 scrubbing of power plant flue gases are feasible options. At 90% control the incremental cost of CO_2 scrubbing is currently estimated to be very expensive ($1200-$1800/kW), however, lower incremental capital costs are expected if only a 20% reduction (for example) is required. Any alternative fuel source or mitigation strategy to reduce CO_2 emissions should be carefully compared with the fossil fuel options to ensure that all aspects and costs of supplying energy and power are appropriately considered.

Acknowledgements

The authors wish to recognize the research and production support provided by B. Kinzey (Battelle/Pacific Northwest Laboratory), and T. Rogers, J. Gillette and L. Kickels (Argonne National Laboratory).

References

Ashton W.B. and T.J. Secrest, 1990, *Options for Reducing Greenhouse Gas Emissions form Building and Community Systems*, presented at Dahlem Workshop on Limiting the Greenhouse Effect: Options for Controlling Atmospheric CO_2 Accumulation, Berlin, December 9-14.

Edmonds, J.A., and J.M. Reilly, 1983a, *A Long Term Global, Energy Economic Model of Carbon Dioxide Release from Fossil Fuel Use*, Energy Economics, *5*(2).

Edmonds, J.A., and J.M. Reilly, 1983b, *Global Energy Production and Use to 2050*, The Energy J., *4*(3).

Edmonds, J.A and J.M. Reilly, 1986, *The IEA/ORAU Long-Term Global Energy-CO_2 Model: Personal Computer Version A84PC*, Institute for Energy Analysis, Oak Ridge Associated Universities, ORNL/CDIC-16 (CMP-002/PC), Washington DC, December.

Edmonds, J.A., and J.M. Reilly, 1987, *Uncertainty Analysis of the IEA/ORAU CO_2 Emissions Model*, The Energy J., *8*(3).

Edmonds, J.A., et al., 1984, *An Analysis of Possible Future Atmospheric Retention of Fossil Fuel CO_2*, U.S. Department of Energy, Office of Energy Research Report DOE/OR/21400-1, September.

Edmonds, J.A., et al., 1986, *Uncertainty in Future Global Energy Use and Fossil Fuel CO_2 Emissions 1975 to 2075*, U.S. Department of Energy, Office of Energy Research Report DOE/NBB-0081.

EPRI, 1989, *TAG™ -- Technical Assessment Guide -- Electricity Supply*, Electric Power Research Institute Report P-6587, Vol. 1, Palo Alto, September.

Gluckman, M., R. Wolk, and G. Touchton, 1989, *Power Generation to Meet the Competitive Challenge*, AEIC Meeting, Palo Alto, April 6.

Green, L., 1988, *Alternatives to Coal Combustion*, presented at the American Association for the Advancement of Science, Annual Meeting, Boston, February 11-15.

Hootman, H.A., and D.W. South, 1989, *A Comparison of Global Climate Change Initiatives in the 101st Congress*, Argonne National Laboratory Report ANL/EAIS/TM-1, Sept.

IEA, 1989, *Energy and the Environment: Policy Overview*, International Energy Agency, Organisation for Economic Co-operation and Development, Paris.

IEA, 1990a, *Coal Information 1990*, International Energy Agency, Organisation for Co-operation and Economic Development, Paris.

IEA, 1990b, *Energy Statistics of OECD Countries, 1987-1988*, IEA Statistics, International Energy Agency, Organisation for Economic Co-operation and Development, Paris.

IPCC, 1990, *Policymakers Summary of the Formulation of Response Strategies*, Report Prepared for the Intergovernmental Panel on Climate Change by Working Group III, June.

Jaeger, J., 1988, *Developing Policies for Responding to Climatic Change, A Summary of the Discussions and Recommendations of the Workshops held in Villach (28 September-2 October 1987) and Bellagio (9-13 November 1987), Under the Auspices of the Beijer Institute, Stockholm*, World Meteorological Organization and United Nations Environment Programme Report WMO/TD-No. 225, April.

Jenney, L., 1990, *What Are the Prospects for Reducing the Contribution to the Greenhouse Effect from the Transportation Sector in the Next 15, 50, 100 Years?*, presented at the Dahlem Workshop on Limiting the Greenhouse Effect: Options for Controlling Atmospheric CO_2 Accumulation, Berlin, December 9-14.

Jochem, E.K., 1990, *Potentials to Reduce Greenhouse Gas Emissions by Rational Energy Use and Structural Changes: A 20 and 50 Year Perspective*, presented at the Dahlem Workshop on Limiting the Greenhouse Effect: Options for Controlling Atmospheric CO_2 Accumulation, Berlin, December 9-14.

Keepin, B. and G. Kats, 1988, *Greenhouse Warming*, Comparative Analysis of Nuclear and Efficiency Abatement Strategies, Energy Policy, Vol. 16, No. 6, December.

Marland, G., et al., 1989, *Estimates of CO_2 Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data*, Oak Ridge National Laboratory Report ORNL/CDIAC-25 (NDP-030), May.

Ramanathan, V., 1988, *The Radiative and Climate Consequences of the Changing Atmospheric Composition of Trace Gases in the Changing Atmosphere*, T.S. Rowland and I.S.A. Isaksen, eds., John Wiley and Sons, Chichester, England.

Smelser, S.C. and G.S. Booras, 1990, *An Engineering and Economic Evaluation of CO_2 Removal from Fossil Fuel-Fired Power Plants*, presented at the Ninth Annual Conference on Gasification Power Plants, Electric Power Research Institute, Palo Alto, October 19.

Smith, G.D., ed., no date, *The Cambridge Encyclopedia of Earth Sciences*, Cambridge University Press, United Kingdom.

South, D.W., et al., 1990, *A Fossil Energy Perspective on Global Climate Change*, U.S. Department of Energy, Office of Fossil Energy Report DOE/FE-0164, January.

Steinberg, M., and M.C. Cheng, 1988, *Advanced Technologies for Reduced CO_2 Emissions*, Proceedings of the 1988 APCA Annual Meeting, Dallas, June.

U.S. Department of Energy, 1990, *Clean Coal Demonstration Program*, Annual Report to Congress, Assistant Secretary for Fossil Energy Report DOE/FE-195P, March.

U.S. Department of Energy, 1989a, *International Energy Annual*, 1988, Energy Information Administration Report DOE/EIA-0219(88), November.

U.S. Department of Energy, 1989b, *Clean Coal Technology, The New Coal Era*, Office of Fossil Energy Report DOE/FE-0149.

U.S. Department of Energy, 1988, *Energy Technologies and the Environment*, Office of Environment, Safety and Health Report DOE/EH-0077, prepared by Argonne National Laboratory, October.

U.S. Department of Energy, 1987, *America's Clean Coal Commitment*, Office of Fossil Energy Report DOE/FE-0083, February.

U.S. Department of Energy, 1986, *Report to Congress on the Relationships between Projects Selected for the Clean Coal Technology Program and the Recommendations of the Joint Report of the Special Envoys and Acid Rain*, Office of Fossil Energy Report DOE/FE-0072.

U.S. Environmental Protection Agency, 1989, *Policy Options for Stabilizing Global Climate*, Report to Congress, Washington, D.C., March.

U.S. Environmental Protection Agency, 1988, *The Potential Effects of Global Climate Change on the United States*, Report to Congress, Washington, D.C.

Warrick, R.A., and P.D. Jones, 1988, *The Greenhouse Effect: Impacts and Policies*, Forum for Applied Research and Public Policy, *3*:48-62.

Wolsky, A.M., and C. Brooks, 1988, *Recovery and Use of Waste CO_2 in Enhanced Oil Recovery, Proceedings of a Workshop in Denver, March 19-20, 1987*, Argonne National Laboratory Report ANL/CMSV-TM-186, June.

World Energy Conference, 1989, *1989 Survey of Energy Resources*, United Kingdom.

Yamaji, K., 1990, *What are the Prospects for Efficiency in the Electricity Sector in the Next 15, 50, and 100 Years?* presented at the Dahlem Workshop on Limiting the Greenhouse Effect: Options for Controlling Atmospheric CO_2 Accumulation, Berlin, December 9-14.

END

DATE FILMED

02 / 12 / 91