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THE DILEMMA OF FOSSIL FUEL USE AND GLOBAL CLIMATE CHANGE

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THE DILEMMA

The energy systems of society are both parts of the means to achieve sustainability and the potential causes of instability. Fossil fuels (petroleum, natural gas, coal, oil shale, etc.) epitomize this dilemma. These are our principal energy sources, yet they are depletable on a time scale that is relevant to human history (~200—1000 years), and although their use may be changing the environment of the planet locally, regionally, and even globally (e.g., changing the greenhouse effect), we live in a developing society that demands more energy for more people. The challenge is to avoid the dilemma by technology and policy intervention so that fossil fuels are used to the net benefit of society and its environment.

Of course, concern about the changing greenhouse effect may ultimately limit the use of fossil fuels, and the issue is fiercely debated (Abelson 1990) because uncertainties permeate the entire matter. Although the increase in the concentrations of greenhouse gases in the atmosphere is indisputable, the evidence of consequential temperature or other climate change is not. Still, we tend to agree with T. A. Sancton (1989) that "it is far too risky to do nothing while awaiting absolute proof of the disaster" and with Senator Albert Gore of Tennessee (1989) that uncertainties about the greenhouse effect and the dire nature of the ecological crisis we face should not be used as excuses for inaction.

We should take those low-cost measures that slow greenhouse gas emissions, and we should be prepared technologically to accomplish much larger reductions if necessary. At present, our technological insurance is not in place, but the opportunities for improvement are great, even for fossil fuels.

WHY ARE FOSSIL FUELS SO POPULAR?

Presently, fossil fuels account for about 83% of the commercial energy sources used (not counting energy supplied directly by the sun and traditional biomass sources not traded in commerce). This situation hasn't changed much over the last 50 years (Table 1) and could persist for 50 more. Considering the environmental problems associated with the increasing use of fossil fuels, why are they so popular?

Fossil fuels are relatively marvelous energy sources. The variety of fossil fuels plus the technology mankind has developed to produce and convert them to useful purposes is a marvelous combination.

Furthermore, as a consequence of biomass production during past geologic epochs, when the planet was apparently much warmer, the reservoirs of fossil fuels were built rather ubiquitously. As a result, fossil fuels are available everywhere, and some (e.g., petroleum) are readily transportable. Technical advances have led not only to discoveries and production from the most inhospitable places but also to more complete resource recovery.

Although fossil fuels are depletable, the estimated resources are still very large (Fig. 1). In this figure, reserves are the discovered quantities in known reservoirs and locations that are technically and economically recoverable using current extraction technology. The undiscovered resources of oil and gas are judgmental estimates of those resources thought to be geologically possible and technically recoverable within a reasonable price range. For coal, ultimately recoverable geological resources is an estimate based on the assumption that 50% of the total coal resources-in-place can be recovered using current mining techniques as well as advanced techniques yet to be developed.

Coal, the most abundant fossil fuel, is located predominantly in the U.S.S.R, the United States, and China. Total world resources of coal are estimated to be over 10,000 Gt, and ultimately recoverable resources are estimated to be about 5,500 Gt, or about 150,000 quads (quadrillion Btu). At present use rates, these resources would last 1,500 years.

Oil resources are much less abundant. At historical recovery rates of about 34%, the remaining recoverable resources of conventional oil are estimated to be about 7,000 quads (Masters 1987); which would last only about 60 years at present use rates. But with enhanced oil recovery and the use of unconventional oils, the recoverable oil resources might be doubled.

The remaining recoverable resources of natural gas are distributed rather ubiquitously, but the U.S.S.R. has more than any other region (Dreyfus 1989). Estimates are similar to those of petroleum (about 8,000 quads), which is approximately 120 years supply at current use rates. The ultimate supply might be double that if unconventional sources such as Devonian shales; tight, deep formations; and coal seam gas are considered.

This resource situation would be much more limiting if it were not for the fact that one form of fossil fuel can be chemically transformed into another; for example, coal can be converted to gaseous or liquid fuels. Also, natural gas can be catalytically reformed to produce liquids for transportation albeit at some cost and thermodynamic penalty. The continuing challenge is to develop efficient and economic processes for performing these chemical conversions. Of course, fossil fuels, particularly petroleum and natural gas, are excellent feedstocks for making useful chemicals and plastics.

Fossil fuels are attractive not only because they are available and relatively inexpensive but also because we have learned to use them so effectively. The relatively simple technology of controlled combustion provides energy for both small- and large-scale applications. Almost exclusively, liquids refined from petroleum power the world's transportation systems (greater than 97% in the United States) because these fuels have such a high energy density, because they are so portable, and because of the development of the internal combustion engine and the modern jet engine.

Although many nonfossil energy sources exist, none, either separately or collectively, are ready to substitute for fossil fuels worldwide at the necessary large scale and with the performance, cost, and social acceptance required to be competitive. Nuclear power is perhaps the nearest to being ready, but a significantly expanded deployment is constrained by concerns over reactor safety, accidental reactor damage, and diversion of nuclear fuel to weapons; by problems with managing waste; and by escalating capital and operating costs. Even France, which produces 70% of its electricity by nuclear power, still uses fossil fuels to provide most of its energy (65%). Biomass and hydropower are resource-limited in many countries. Solar thermal electric, photovoltaics, and wind are still expensive, and the power they provide is intermittent. Geothermal sources are geographically constrained and often expensive to develop, as are ocean thermal, wave, and tidal power. Fusion is considered decades away from practical demonstration.

The environmental problems with fossil fuels that command most of our attention today include acid deposition, urban air pollution, and climate change (global warming or the changing greenhouse effect). The acid deposition problem can be solved over time at reasonable costs. In the United States, all urban air quality probably cannot be brought into compliance with all present standards at reasonable cost, but the problem can be kept within acceptable limits (Russell 1988). However, climate change is a different type of problem for which no technological fix yet exists, and the global consequences could be very serious, if not disastrous.

CONTROLLING CO_2 EMISSIONS

Global warming may occur as a result of the release of the so-called greenhouse gases, notably carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs) (e.g., refrigerant gases such as the Freons), nitrous oxide (N_2O), and O_3 (Smith 1988). Because they are relatively long-lived in the atmosphere, dispersion of these gases is much broader than the acid gases, and, because of this wider dispersion, the concern is truly global as opposed to regional. These gases absorb heat energy (infrared radiation) that would otherwise be radiated from the earth to space, resulting in a warming of the troposphere (lower atmosphere). Of these anthropogenic gases, CO_2 is the major one, presently accounting for about one-half of the changing greenhouse phenomenon, and the burning of fossil fuels is estimated to contribute more than 75% of the increasing CO_2 concentration in the atmosphere. The other major source of CO_2 is from deforestation by slash and burn techniques. The consequences of global warming are poorly understood and are not yet predictable in detail, but they could include a 1.5 to 4°C increase in global annual mean-surface temperature for each doubling of CO_2 concentration; marked changes in the amount and distribution of precipitation; large seasonal changes in mean soil moisture; and reduction of some of the world's great ice masses and thermal expansion of the oceans, which would raise sea levels and flood coastal areas.

Our principal concern is how to control greenhouse gas emissions, particularly CO_2. Depending on the fraction of CO_2 retained in the atmosphere, burning all fossil fuel resources could quadruple the CO_2 concentrations in the atmosphere from the present value of about 350 to 1500 ppmv (parts per million by volume) (Table 2). If current models of warming are correct, such an increase in CO_2 concentration would lead to a global average temperature rise in the range of 3 to 8°C with even higher values at the higher northern latitudes.

If such an increase were to occur over a period of two centuries or so, it would likely be both too much and too fast (in the range of 0.15 to 0.4°C per decade). There exists, however, a CO_2 emission rate at which the atmospheric concentration does not increase, or at least it increases very slowly. A carbon cycle model has been used (Emanuel 1990) to examine several scenarios in which the emission rate is suddenly and dramatically reduced from what it is today and then maintained constant at that reduced rate (Fig. 2). The results indicate that CO_2 emission rates must be very low to prevent any increase in CO_2 concentration (of the order of 1 Gt(C)/year); however, rates of 2 to 3 Gt(C)/year lead to only moderate increases over the next 100 years.

Some have argued that the problem is not warming per se but rather the rate of change. A rate of change <0.1°C per decade has been suggested to be slow enough to be manageable. If we assume that half the increase is due to other greenhouse gases, this rate of change translates into an allowable CO_2 emission rate from fossil fuels of 1.6 to 3.5 Gt(C)/year where the range depends on the value of temperature change assumed for CO_2 doubling. This emission rate range may be extended upward if emissions of other greenhouse gases are also controlled.

The technological and social management challenge is to get maximum energy services from fossil fuels, hold the emission rate as low as practical, and control the rate within an acceptable range. The challenge is definitely formidable if not impossible. If it becomes necessary to reduce CO_2 emissions to a level much less than the present one, it will take decades to accomplish, and the rate will undoubtedly increase significantly before any reduction can be managed.

Also, the idea that there is some CO_2 emission ration raises allocation issues. Who gets to use what? Does the ration go to countries that have below average fossil fuel consumption? Do industrialized nations reduce their use rates so that the developing nations could use more fossil fuels to spur their economic growth? Most of the greenhouse gases are being generated in the developed world that comprises only a fraction of the world population. Of the two most prominent greenhouse gases, only 25% of CO_2 emissions and <10% percent of CFC emissions come from the developing world. On a per capita basis, the developing countries have extremely low absolute levels of energy usage and CO_2 emissions (See Figs. 3&4).

Indeed, the emission rates of CO_2 have moderated over the past decade and a half as a result of the Arab oil embargo and subsequent oil price shocks. Controlling emissions of CO_2 may be very expensive. A recent calculation (Manne and Richels 1990) indicates that with current technologies and with a ban on nuclear expansion the tax on a ton of carbon emissions would need to go as high as $600 to force United States emissions to be reduced to 80% of the current emissions of 1.4 Gt(C)/year, and the cost to the United States economy might be 5% of the Gross National Product. With advanced technologies, this cost might be reduced substantially, perhaps by a factor of 5 or more (Williams 1990).

<u>More Efficient Use of Fossil Fuels</u>. Because nonfossil energy sources are currently poor competitors, it has been argued that improving the efficiency of fossil fuel use is the least expensive path to reducing CO_2 emissions (Keepin and Katz 1988). Indeed, the technological opportunities are very large for all segments of the economy. The major attractiveness of this option is that not only do technologies exist, but their increased applications are often economical even at current fuel prices. In addition, the potential seems to be large for developing nations as well as industrialized nations. This conclusion is brilliantly argued by Goldemberg et al. (1988). These authors conclude that the developing nations can achieve a level of affluence equivalent to that of Western Europe in the mid-1970s by a rate of energy use of only about 1.3 kW/person. This compares to the current level actually used by Western Europe, which is about 4.1 kW/person. In other words, it may be possible for developing nations to grow economically along a much more efficient path than those followed by industrialized nations. Despite the attractiveness of such a high efficiency path, it may prove difficult to achieve the degree that is economically justified without significant activity by governments to encourage it. Many barriers must be overcome, not the least of which are the tendency to make investments based on least first costs rather than least life-cycle costs or the tendency for governments to subsidize energy prices.

As more efficient and economical technologies for fossil fuel use are developed and adopted, however, the more difficult it will be for nonfossil sources of energy to compete. The higher efficiency will mean less CO_2 emissions per unit of energy service, but the reduction will be much less than could be achieved if nonfossil sources were substituted. As always, fossil fuel technology gets better and better, and it is a moving target for its competitors. Greater emphasis must be placed on research and development to improve the nonfossil sources.

<u>Substituting Natural Gas for Coal</u>. The second option for reducing CO_2 emissions from fossil fuels is to substitute natural gas for coal (see Figs. 5 & 6). The heat of combustion per molecule of CO_2 produced is 70% greater than for coal, and natural gas can generally be used more efficiently to produce the same energy services. One reason for higher efficiencies using natural gas is that it does not have the sulfur and nitrogen fuel-bound contaminants and ash content that plague coal and result in acid gas and particulate emissions that must be controlled.

Some of the same repowering technologies that are promising for reducing acid gas emissions from coal-fired electricity generation are also important in reducing CO_2 emissions by substituting natural gas for coal. These include advanced gas turbines and fuel cells; the former is much more advanced than the latter, and further improvements in gas turbine technologies are likely, particularly improvements in materials that will permit higher combustion temperatures and pressures. Additionally, Williams (1989) has proposed catalytic chemical reforming of natural gas with steam to produce hydrogen and carbon monoxide which are then burned in an intercooled steam-injected gas turbine (ISTIG). This chemically recuperated ISTIG may further increase power output, and efficiency may be as high as 52.5%.

Although much less developed than gas turbines, fuel cells offer promise for increasing the efficiency of electricity generation from fossil fuels. Fuel cells are devices (like batteries) that convert chemical energy into electrical energy. The fuel is oxidized at the anode to provide electrons that flow in the external power circuit to the cathode where oxygen is reduced. The anode and cathode are separated by an electrolyte that provides a transport mechanism for ions but not for electrons.

There are two limitations with this natural gas substitution strategy. First, the resources of natural gas are much smaller than those of coal (Fig. 1). However, substitution of natural gas for coal can be an important interim strategy to moderate CO_2 emissions while better nonfossil sources are developed and deployed. Second, leakage of natural gas from production and transport systems may partially offset the advantage of its use. Methane, the principal constituent of natural gas, is a much more effective greenhouse gas than CO_2. The infrared absorption of a methane molecule is almost 30 times that of a CO_2 molecule. However, the effective lifetime of methane in the atmosphere is much shorter. This problem requires much more investigation because the sources and sinks of methane are not well understood, but it should be possible to reduce leakages from the natural gas system to a negligible value.

The slow pace of growth in natural gas use in the developing world has been largely due to the relatively high cost of transporting the gas from the point of production to the point of use in the era of low oil prices. Indeed, historically, there has been little systematic exploration for gas in these regions, and most of the gas reserves were discovered while looking for oil. However, with the generally higher oil prices prevailing since the 1970s, natural gas use has become economic even in markets far from reserves. As a result, natural gas consumption has been rising, especially outside the United States.

Most gas is still consumed in the country where it is produced, but world trade in natural gas has been rising since the early 1970s. Currently, world trade via pipeline accounts for about 11% of total use and liquefied natural gas (LNG) trade accounts for about 3%. The distribution network in the United States is the most extensive in the world, and it is already linked to supplies from Canada by pipeline and from North Africa by LNG. A potentially useful pipeline link to Mexico also exists and projects are being considered to bring additional LNG from Trinidad, Venezuela, and Nigeria to the United States.

The gas distribution network in Western and Eastern Europe is also well developed and is linked by pipeline to large producing fields in The Netherlands, Norway, the U.S.S.R., and North Africa. Countries that are not already linked to the grid (Greece, Portugal, Turkey, etc.) are making plans to join soon. Recently, Iran has reactivated its earlier plan to supply Western and Eastern European countries by pipeline through the Soviet Union. Some LNG is coming into Western Europe from Algeria and Libya currently, and plans are being made to bring LNG from Nigeria.

While the major Eastern European countries have already integrated some natural gas from the Soviet Union into their energy mix, they still face immense environmental problems because of their heavy reliance on coal. These countries offer a very good opportunity for replacing coal with Soviet and Middle Eastern natural gas.

Japan has made considerable progress in natural gas usage with LNG imported from Indonesia, Malaysia, Australia, Alaska, and the Middle East, but consumption elsewhere in Asia is relatively modest, based mostly on available indigenous resources. However, the picture is changing. Korea has recently started LNG imports, and Taiwan will soon begin. A proposal for an Asian grid linking the producing fields in Indonesia, Malaysia, and Thailand with other Pacific Rim countries is also being pursued, and may be implemented during the 1990s (Cedigaz News Report 1990). India is exploring possibilities of importing LNG from the Middle East to supplement its own rising production. Iran is promoting a $12-billion project to bring its prolific natural gas resources to India and Pakistan by a 2000-mile pipeline from Bandar Abbas to Calcutta (Petroleum Economist 1990). The Soviet Union has recently initiated discussions with Japan to build a 3,100-mile pipeline, partly undersea between Siberia and Japan via South and North Korea (Wall Street Journal 1990).

International trade within South America is still limited, but recent bilateral agreements between Argentina, Bolivia, and Brazil portend expansion.

Helping the Soviet Union with advanced gas production, transmission, and utilization technologies would seem to be a stabilizing policy for the OECD countries to adopt in this day of "perestroika." Expanding the use of Middle East gas could make an important contribution, not only to Europe but also, perhaps, to Pakistan and India as well. Resources of Indonesia and Malaysia will likely underpin the growth of natural gas consumption in the Pacific Rim nations. Helping these countries use gas resources is environmentally sound as an interim strategy, and also economically desirable as a developmental strategy. These steps could have a very positive impact on the economics of the Soviet Union, the developing regions of the world, and on urban and regional ambient air environmental quality.

Recovering and Sequestering CO_2. The third strategy for reducing CO_2 emissions from fossil fuel is to capture the emissions and sequester them or find nondispersive uses for the recovered CO_2. This is an expensive proposition, at least for the techniques suggested so far. The difficulty of the problem is evident by the simple realization that 1 ton of fossil fuel produces almost 3 tons of CO_2.

One technique, of course, is to grow forests and recycle the carbon back into the biomass reservoir. Recently, Advanced Energy Services agreed to fund planting trees in Guatemala sufficient to offset the CO_2 put into the atmosphere during the lifetime of a proposed new coal-fired plant in Connecticut (Pearce 1988).

Although this is an interesting and perhaps important approach to afforestation, it probably cannot be practiced at the scale that would be required to make a significant offset to CO_2 released worldwide from fossil fuel use. For example, offsetting the emissions of a 500 MWe coal fired power plant operating at about 34% efficiency would require about 500 square miles of forest to be grown assuming the forest fixes 2 tons of carbon per acre per year over the lifetime of the coal plant. To sequester the total carbon emissions of the United States would require growing about one million square miles of forests at this productivity and using about 25% of the land area of the United States. Growing trees could, however, do much to offset the deforestation trend.

It should be acknowledged that the role of biomass in the global carbon cycle is still largely unknown. For example, Tans, Fung, and Takahashi (1990) recently analyzed the northern-hemisphere—southern-hemisphere CO_2 gradients and concluded that there must be a large northern hemisphere sink, presumably of terrestrial origin. If the analysis is correct, the effect could be due to CO_2 fertilization causing plants to grow more rapidly or to afforestation in the northern hemisphere. Much more needs to be learned about the natural carbon cycle.

Other strategies have been proposed for recovering CO_2 from the emissions of large fossil fuel facilities such as power plants. These involve recovering CO_2 from the exhaust gases and permanently sequestering the CO_2 either in the deep oceans or in depleted natural gas reservoirs or other geologic formations such as the hollowed-out salt domes used in the United States for storing strategic petroleum reserves. Steinberg (1985; Horn and Steinberg 1982) was one of the first to look at these possibilities carefully. He estimated that the added cost of recovering and sequestering CO_2 emissions would increase the cost of electricity generation by as much as a factor of 1.8 to 5. However, a recent calculation revises this range substantially downward (Table 3).

In summary, we suspect that CO_2 sequestering schemes (except perhaps for reforestation which, as noted, has its own limitations) will always prove to be more expensive than substituting nonfossil sources, but the calculations of Hendriks, Blok and Turkenburg (1990) clearly narrow the gap and point to needed research.

Hydrogen From Fossil Fuels. Fossil fuels can also be used as a source of hydrogen, an alternative to hydrocarbons as a fuel material. Carbon, hydrocarbons, and carbon monoxide are splendid reducing agents for producing hydrogen from water. Of course, a product of the reduction of water by carbonaceous materials is still CO_2, which must be recovered and sequestered. Nevertheless, we could imagine the use of hydrogen derived from fossil fuels as a clean source of energy for Los Angeles. In fact, it is not inconceivable that it could be an interim step to a situation 50-100 years hence when the principal energy carriers used by society are electricity, hydrogen and biomass-derived liquids for transportation.

To this end, Williams (1990) has used the calculations of Hendriks, Blok and Turkenburg (1990) to estimate the cost of producing hydrogen from coal using the Shell oxygen blown gasifier and sequestering the CO_2 in depleted gas or oil reservoirs. The estimates range from \$4.50 to \$5.74/million Btu on the basis of higher heating value. The lower cost assumes a 6% discount rate whereas the higher cost assumes a 12% discount rate. This is an extremely interesting range of costs given the potential importance of hydrogen as a clean fuel.

By adding heat from nonfossil sources such as from a high-temperature gas-cooled nuclear reactor or perhaps a solar furnace, the yield of hydrogen per unit of CO_2 produced can be increased. For reforming of methane, hydrogen production can be increased by 1/3 and by 70% from coal. Whether such heat sources to boost hydrogen production from fossil fuels will be practical depends on the cost of competing sources of hydrogen such as direct electrolysis of water using nuclear, solar, or wind electricity.

Hydrogen could be produced near coal fields, the CO_2 pumped to sequestering sites, and the hydrogen piped to centers of fuel use. However, hydrogen is not very portable. Gaseous hydrogen at 2400 psi has a volume about 18 times the volume of an equivalent amount of energy stored as gasoline and weighs three times as much if the weight of the storage vessel is included. Hydrogen can be stored as metal hydrides and released by heating. Hydrides weigh about as much as high-pressure gas cylinders but occupy only about 25% more space than a gasoline tank containing the same energy value (Amann 1990). By increasing the efficiency of conversion dramatically, these storage limits may one day be acceptable even for automotive transportation systems. As we have mentioned, hydrogen can be used very efficiently; for example, by fuel cells where conversion of chemical energy to electricity may be accomplished at 60% efficiency, indicating the possibility of a practical hydrogen fuel cell electric vehicle.

From this discussion it is clear that the near-term moderation of the emissions of CO_2 from fossil fuel use depends on two strategies. The first is to use fossil fuels more efficiently across the board from conversion to end uses. This applies both to the conversion to electricity and the efficient use of electricity. Of course, the development and adoption of much more efficient technologies for using petroleum products particularly for transportation is an essential ingredient. The second, related to the first, is to substitute high efficiency gas technologies for coal wherever practical. Stimulation of the use of natural gas at the expense of coal will, of course, increase natural gas prices and hasten depletion of resources. But it can also buy time to develop better nonfossil sources and improve air quality at the same time. Sequestering of CO_2 emissions from the exhausts of fossil fuel combustion or conversion seems presently expensive and impractical except, of course, as it is accomplished by afforestation. Nevertheless, the possibilities including that of hydrogen production should be intensively researched.

CONCLUSIONS – MANAGING FOSSIL FUELS

Fossil fuels can only make a transient contribution to the energy supply for a sustainable planet because they are finite and depletable resources. Nevertheless, that transient contribution is most significant because fossil fuels are mankind's primary commercial energy source, and their use worldwide is growing, especially by the developing nations. Fossil fuels are so important because they are still relatively abundant, cheap, ubiquitous, and some forms (notably petroleum) are readily transportable. Hydrocarbon liquids with high energy density are portable and make superb fuels for powering transportation systems, and one form of fossil fuel can often be readily converted to another (e.g., gases and solids to liquids and solids to gases). Furthermore, they can be used at almost any scale employing simple or complex technology, and they are the source of an enormous variety of chemicals and plastics.

Nevertheless, as the use of fossil fuels has grown, the problems of protecting the environment and human health and safety have also grown, providing a continuing challenge to technological and managerial innovation. Today that challenge is to control atmospheric emissions from combustion, particularly those emissions that cause acidic deposition, urban pollution, and increasing concentrations of greenhouse gases. Technology for reducing acidic deposition is available and needs only to be adopted, and the remedies for urban pollution are being developed and tested. How effective or expensive these will be remains to be determined. The control of emissions of the greenhouse gas, CO_2, seems possible only by reducing the total amounts of fossil fuels used worldwide, and by substituting efficient natural gas technologies for coal. Long before physical depletion forces the transition away from fossil fuels, it is at least plausible and even likely that the greenhouse effect will impose a show-stopping constraint. If such a transition were soon to be necessary, the costs would be very high because substitute energy sources are either limited or expensive or undesirable for other reasons. Furthermore, the costs would be unevenly felt and would be more oppressive for developing nations because they would be least able to pay and, on average, their use rates of fossil fuels are growing much faster than those of many industrialized countries.

It is prudent, therefore, to try to manage the use of fossil fuels as if a greenhouse constraint is an important possibility. This suggests taking several low-cost actions in the near-term such as:

- policies including R&D that encourage the development of more efficient and economical end-use and conversion technologies (e.g., more efficient gas turbines, fuel cells, oxygen-blown gasifiers, and processes for producing hydrogen from fossil sources);

- more intensive R&D to accelerate the development of better nonfossil sources including direct solar, biomass and other renewables, fission, and fusion;

- policies that encourage the substitution of hydrogen-rich for hydrogen-lean fuels and expansion of the natural gas system, particularly in developing nations;

- cooperation by western industrialized countries in providing technical assistance to developing and Eastern Bloc countries for producing energy technologies that are both economically and environmentally more attractive, including expanding the development and use of the natural gas resources of the Soviet Union;

- R&D to increase our understanding of the global cycle of CO_2 releases to the atmosphere and its removal by the oceans and by terrestrial ecosystems so that climate stabilization targets and policies can be better established; and

- experiments with CO_2 recovery and sequestration techniques so that the economic and environmental impacts are better understood.

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Table 1. World primary energy use and associated CO_2 emissions by year for the past 50 years

	Oil		Gas		Coal		Fossil		Hydroelectric		Nuclear		Total	CO_2	E/P
	q	%	q	%	q	%	q	%	q	%	q	%	q	Gt(C)/y	MMBtu
1937															
US	7	33	2	11	12	55	21	99	0	1			21	0.4	161
World	12	20	3	5	45	75	60	99	0	1			60	1.2	29
1947															
US	12	36	4	13	16	50	32	99	0	1			32	0.7	221
World	18	24	6	9	48	66	72	99	0	1			72	1.4	32
1957															
US	18	44	10	25	11	27	39	96	2	4			40	0.8	236
World	35	33	12	11	53	50	100	94	6	6			106	2.2	37
1967															
US	25	44	18	31	12	21	55	96	2	4			58	1.0	290
World	70	40	30	17	65	37	165	94	11	6			176	3.3	51
1973															
US	35	47	23	30	13	17	70	95	3	4	1	1	74	1.3	351
World	111	47	42	18	66	28	220	94	13	6	2	1	235	4.5	60
1977															
US	37	49	20	26	14	18	71	93	3	3	3	4	76	1.3	346
World	118	46	46	18	73	28	237	92	15	6	5	2	258	4.8	61
1985															
US	31	42	18	24	17	24	66	90	3	5	4	6	74	1.3	309
World	112	38	59	20	90	31	260	88	20	7	14	5	295	5.3	61
1986															
US	32	43	17	23	17	23	66	89	3	5	4	6	74	1.3	308
World	115	38	59	20	92	31	266	88	21	7	15	5	302	5.4	61
1987															
US	33	43	17	23	18	24	68	89	3	4	5	6	76	1.3	312
World	117	38	62	20	95	31	273	88	21	7	16	5	310	5.5	62
1988															
US	34	43	18	23	19	24	71	89	3	4	6	7	80	1.4	
World	121	38	65	20	96	30	282	88	22	7	17	5	320	5.5	

q - quads (quadrillion Btu); Gt(C) - gigaton (billion metric tons) carbon as CO_2; y - year;
E/P - Energy per capita (person); MMBtu - million Btu

Although alternative energy sources, most notably nuclear and hydropower, have become available during the last fifty years, total energy production from fossil energy sources has grown dramatically. Percentagewise, fossil fuels will probably continue to shoulder much of the energy burden for many years to come because alternative energy sources are either not economically competitive or cannot be implemented on a large scale.

[Source: Fulkerson, 1989]

Table 2. If all recoverable resources of fossil fuels were burned, significant increases in atmospheric CO_2 would result, with the absolute magnitude of the increases being dependent on the fraction of CO_2 released that is retained in the atmosphere. Of the fossil fuels, only coal is sufficiently abundant to increase atmospheric CO_2 by more than a factor of two.

Fuel	Recoverable Quantity	Energy Value (1000s of Quads)	Carbon[a] Content 10^{15} g	CO_2 Concentration Increase (ppm)[b] Fraction Retained in Atmosphere 0.4	0.55	0.7
Oil	1255 x 10^9 bbl	7	130	24	34	43
Gas	8200 tcf	8	120	23	31	39
Coal	5500 x 10^{15} g	153	3850	723	994	1265
Totals	(Rounded off)	168	4100	770	1060	1350

Source [Fulkerson, et al., 1989]

[a] In addition to these amounts of carbon, comparable or larger amounts may be available in other fossil resources such as heavy oils, oil shales, tar sands, lower grades of coal, etc. Thus, the quantity of carbon ultimately released to the atmosphere as CO_2 could conceivably be half again as much, or twice as much, as the total shown in the table.

[b] These hypothetical *increases* may be compared with the preindustrial CO_2 concentration (about 270 ppmv), the present concentration (350 ppmv), or the current annual increase (about 1.5 ppmv/year). In the atmosphere, 1 ppm of CO_2 by volume, uniformly distributed, equals about 2.13 Gt of carbon, or 7.81 Gt of CO_2. Thus, 350 ppmv CO_2 corresponds to 745 Gt C. (1 Gt = 10^9 metric tons = 10^{15} g)

Table 3. The estimated costs of CO_2 recovery and sequestration from central power plants are large , but may not be prohibitive. The economically viable method at present appears to be afforestation, but it is severely limited.

Process	Relative Increase In Electricity Cost	Reduction in Efficiency for CO_2 removal	% CO_2 removed
Steam (Coal Fired)/ Selexol (Air)	1.68[a]	-----	88
Steam (Coal Fired)/ MEA Scrubbing	1.85[a]-2.33[b]	28	90
Steam (Gas Fired)/ Selexol	1.32[a]	-----	88
Steam (Gas Fired)/ MEA Scrubbing	1.44[a]	14	90
IGCC/Selexol (Oxygen blown gasifier plus air combustor)	1.30[a]	13	88
Afforestation	1.02	N/A	100

a--Includes disposal in depleted natural gas wells
b--Includes deep ocean disposal

Sources: Steinberg, 1985, 1986, 1987; Blok, Hendrix, and Turkenburg 1989;
Hendrix, Blok and Turkenburg, 1990.

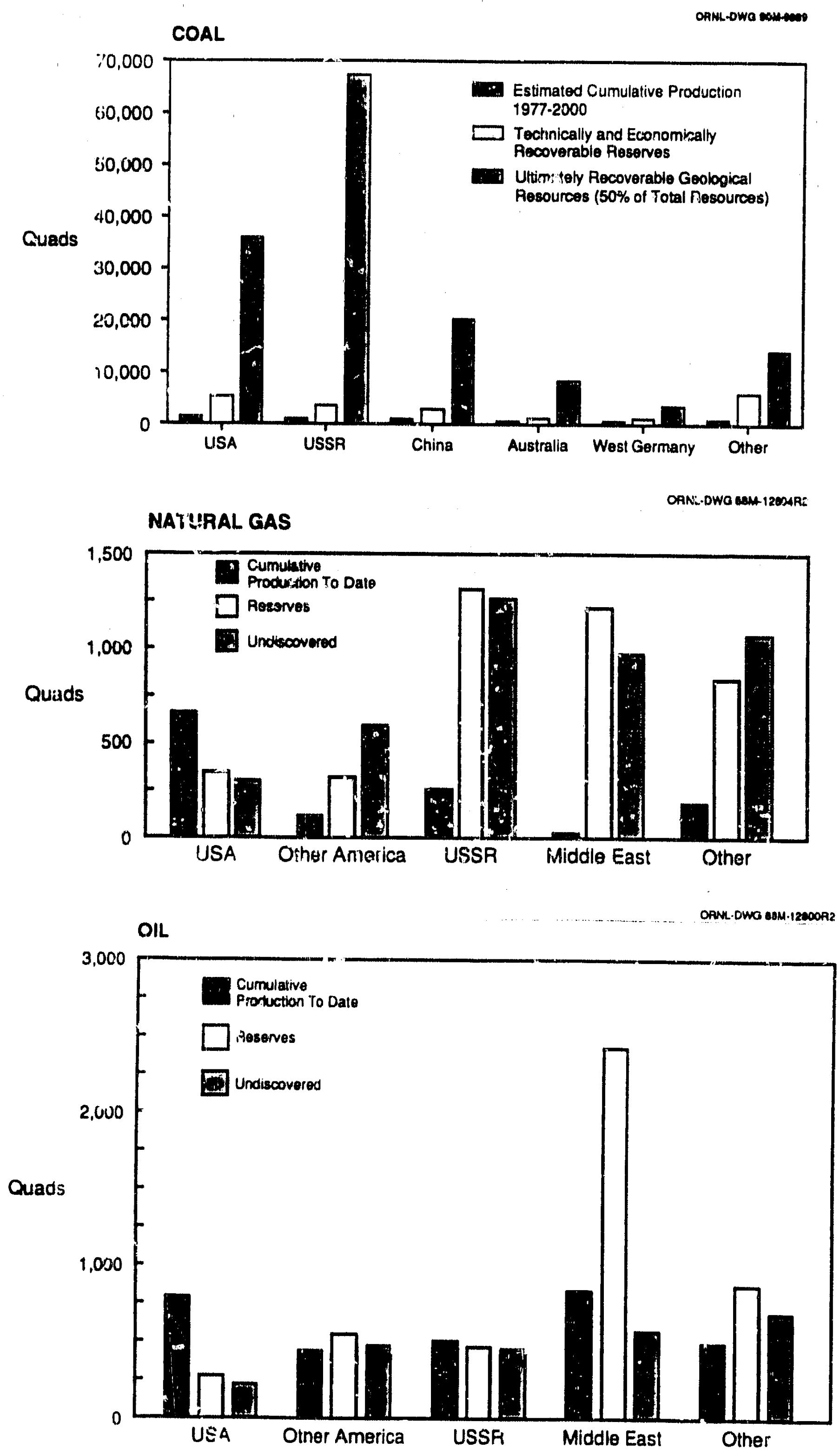

Figure 1. Fossil fuels are presently our most used and obtainable energy resources. They are dispersed throughout the world, and coal is by far the most abundant of the fossil fuels. Although coal is depletable, it would last about 1500 years at present use rates; oil, 60 years; and gas, 120 years.

Sources: Masters, et al., 1987; Wilson, 1980.

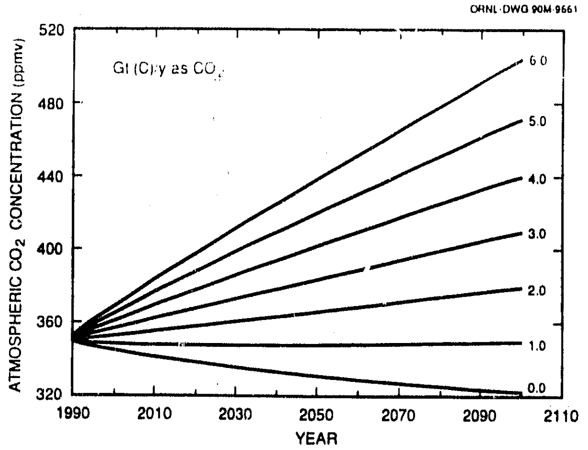

Figure 2. Atmospheric concentrations of CO_2 calculated by assuming that the current rate of emissions is suddenly changed to the values indicated and maintained constant thereafter.

Source: Emanuel, 1990.

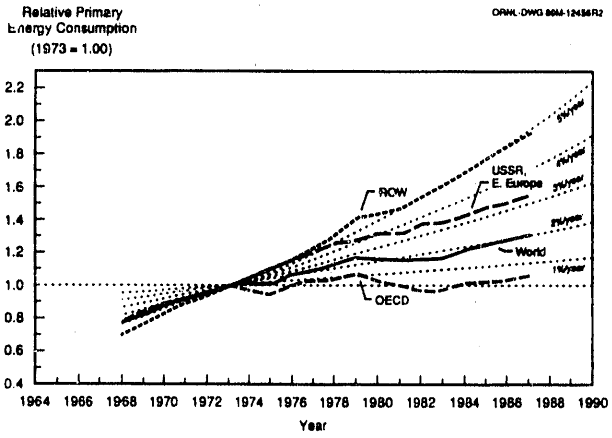

Figure 3. Primary energy demand of the developing nations and the centrally planned economies.

Source: Fulkerson, 1989.

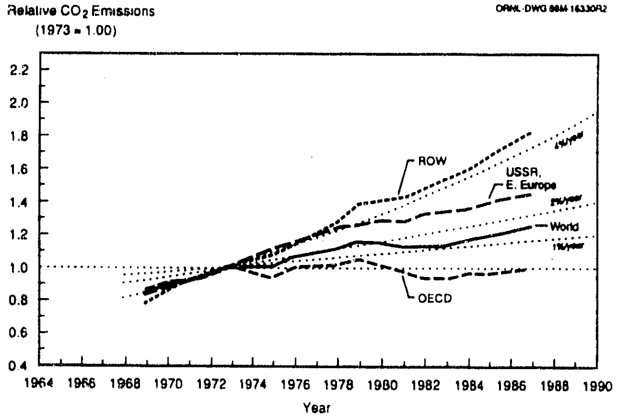

Figure 4. Extrapolation of CO_2 emission growth rates for the decade 1977 to 1987.

Source: Fulkerson, 1989.

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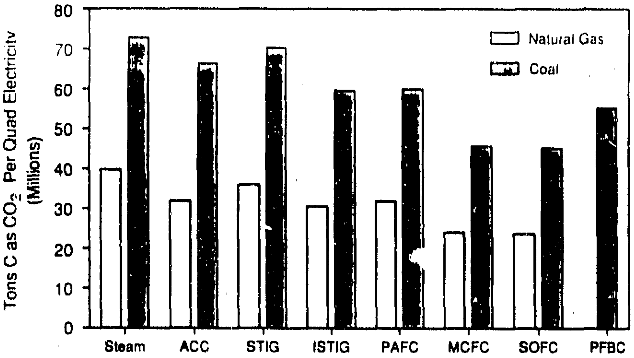

Figure 5. Carbon emissions from electricity generation using fossil fuels depend in large measure on the fuels used and the efficiencies of the generation techniques used. This figure compares emissions of carbon, expressed in terms of millions of tons of carbon as CO_2 per quad of electricity produced, for several electricity generating options using natural gas and coal as fuels. The options include conventional steam-electric plants (Steam), advanced combined cycle (ACC), steam-injected gas turbines (STIG), intercooled steam-injected gas turbines (ISTIG), phosphoric acid fuel cells (PAFC); molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and pressurized fluidized-bed combustors (PFBC).

[Millions of metric tons C as CO_2 emitted per quad of electricity = 52.5 (natural gas) or 92.0 (coal) x (12/44)/efficiency; for example, for a steam plant fired with an efficiency of 34.6%, the amount of carbon dioxide that is released per quad is 92 x 0.2727/0.346 = 72.5 million tons]

Sources: *Clean Coal Technology*, 1989; Pillai, 1989; Schora and Camara, 1990; Williams and Larson, 1989; Blomen, 1989.

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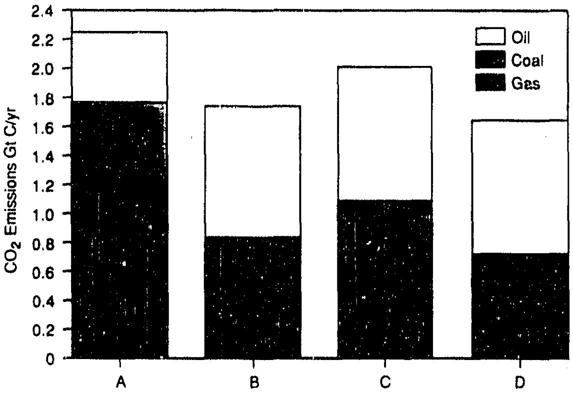

Figure 6. Four scenarios for CO2 emissions from the use of fossil fuel by the USSR, other Eastern European countries, and Western European countries. Scenario A assumes future emissions are the same as for 1988. Scenario B assumes all coal use in Scenario A is replaced by natural gas but with efficiencies 20% greater than coal. Scenario C is the same as Scenario B except that all oil use is replaced by methanol made from natural gas at a conversion efficiency of 60%. Scenario D is the same as Scenario C except that nuclear or solar heat improves the efficiency of conversion to 90% and the CO2 emissions are reduced accordingly. In Scenario A, 34 quads of natural gas are used per year; in Scenario B, 645 quads; in Scenario C, 141 quads; and in Scenario D, 115 quads. The estimated recoverable gas resources and reserves for Europe would last about 90 years for Scenario A, but only 45 years for Scenario B and 21 and 26 years for Scenarios C and D, respectively.

END

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