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Energy Sources: A Realistic Outlook

Chauncey Starr, Milton F. Searl, Sy Alpert

Projections to the middle of the next century indicate that unabated historical global energy trends would lead to an annual global energy demand about four times present levels, primarily due to population and economic growth. But extensive global conservation and energy-efficient systems might reduce this value by half. The cumulative effect of the coming half century's use may strain the world's low-cost resources, particularly oil. The future fuel mix is further complicated by the environmental thrust to reduce the global use of carbon-based fuels. The interaction of the principal factors influencing future energy resource and technology options are projected.

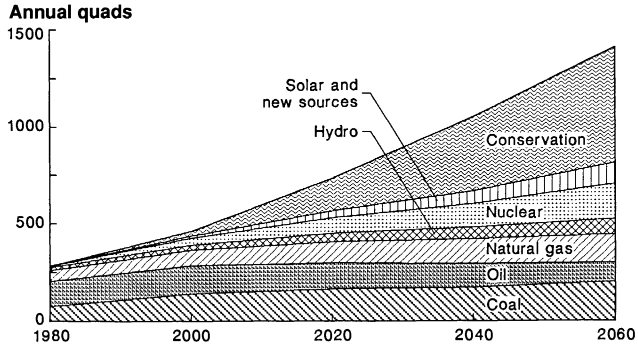
The energy supply mix of the coming century will depend on the magnitude of the demand growth for global energy, changing performance targets, and the technologies available to meet them. Historically, major changes in fuel use patterns have resulted from new conversion and end-use technologies and from shifts induced by demand growth and by changed societal priorities and objectives. The development of new technologies has been crucial to such fuel use changes by providing the means and options for new performance targets. This article reviews the spectrum of future supply options and their flexibility for meeting the large global energy needs foreseen in the next century.

The future adequacy of globally available fossil fuel resources will depend on the total societal costs of extracting and delivering such fuels and on their effectiveness in use to meet the broad performance objectives of energy systems. Projections of proven, probable, and speculative resources are often updated as new discoveries or extraction techniques are developed, but professional conservatism has often resulted in underestimating future resource expansion at acceptable costs. On a next century time scale, the traditional question is whether the cumulative effect of the increasing rate of depletion of these resources would result in a global constraint on energy systems, particularly on the future supply of liquid fuel for vehicles and airplanes. This question is technologically intriguing because of the now demonstrated large-scale convertibility of all fossil fuels to gas or liquid forms and the implications of the application of this technology as an option for a global source of liquid fuel derived from large coal resources.

The present global energy mix is likely to change substantially during the next century as a result of several factors. First, comparative scarcity attributable either to resource or to political constraints may increase the relative price of the most convenient fossil fuel, oil; second, the growing costs of reducing environmental degradation will alter the cost competition among fuels; and third, the potential threat of global climate change may stimulate a shift from carbon-based fuels to nonfossil alternatives. A resource perspective for the next century involves speculation on future energy demand, likely competitive supply al-

The authors are at the Electric Power Research Institute, Palo Alto, CA 94303.

Fig. 1. Global primary energy production showing a conservation case by energy type. The rise and eventual decline of oil and the continued role of coal as the primary fossil fuel source are shown along with growing levels of output from natural gas, uranium, solar, and other (for example, biomass) sources.



ternatives, and possible changes in energy systems and technologies. Such speculations are shaped by the long time periods required to develop new or improved energy technologies and to deploy them commercially. Although long-range projections are unavoidably judgmental and are dependent on present knowledge and experience, they permit the scoping of alternative trends and outcomes and thus help guide current strategies. A projected global energy supply mix (Fig. 1) based on such judgmental factors (*1, 2*) provides a conceptual basis for considering the factors discussed below, which are likely to shape future trends.

It is of particular interest that the availability of liquid fuels in the coming century and beyond is likely to be maintained as the rising cost of conventional oil brings into competition higher cost sources such as coal conversion, tar sands, and oil shale. This transition, initially based on the technologies described in this paper, should be under way by the middle of the century.

Future Energy Demand

Two major trends determine global future end use energy demand, population growth and economic growth. The primary energy input depends on the efficiency of conversion to end use, as determined by the choice of technology. Thus, if a permanent increase in the real price of primary fuel is expected, there exists an incentive to invest in more efficient or alternative technologies. The range of future energy demand and supply outcomes based on plausible projections of these factors has been studied by Starr and Searl (*2*). Two bounding efficiencies were applied to current trends: (i) maintenance of current conversion efficiencies and (ii) a full conservation concept, which assumed reduction of the present trend by one-third of all electricity use and by half of all direct energy (nonelectric) use. This full conservation was judged to be the maximum amount of conservation that could foreseeably be implemented without inhibiting economic growth (*2*).

The resulting demand growth (*2*) is shown in Table 1. By the year 2060, if present trends continue without modification, total energy demand is projected to increase 4.4 times and electricity demand is projected to increase 7.0 times the 1986 reference levels. If full conservation is accomplished, the total energy demand increase is reduced to 2.5 times and electricity demand is reduced to 4.7 times. Most of the anticipated increases are the result of the higher population and economic growth rates of the less developed countries. These large increases are the result of a global population increase of 1.95 times and an average per capita gross national product (GNP) increase of 2.8 times, for a combined product growth of 5.5 times. With the full conservation case, this implies that the efficiency of global economic productivity per unit of primary energy will be improved 2.2 times. The implication of these increases on the annual emission of carbon to the atmosphere (*2*) is shown in Table 2, based on an illustrative mix of energy sources. Three values were assumed for the nonfossil resource contribution (such as solar, biomass, nuclear): their present levels and expansion to a practical maximum, with a low and high nuclear contribution.

Future Supply: Are Fossil Fuels a Constraint?

There is little likelihood that a serious scarcity of fuels will develop during the next century on a global scale because of the intraconvertability of coals, oil, and gas. The major uncertainties arise from the constantly changing economic competition among the various sources and the eventual effects of environmental constraints and increased costs arising from the need to minimize undesirable effluents of fuel use. The prevalent situation that many reserves are only proven for several decades is an artifact of prudent investment in development of a future inventory. The scope of potentially available fuel resources, as periodically assembled by the Institute of Gas Technology (*3*), and the cumulative demand to 2060 for the full conservation case are shown (Fig. 2). The proven fossil reserves are nearly twice that needed to meet the projected cumulative global demand. The specific resource factors for near-term oil and gas have been recently discussed in some detail, suggesting that low-cost oil will become scarcer after the next few decades (*4*). Of course, the speculative higher cost resources are uncertain but may be large. In fact, the real resource cost of energy is lower today than at the beginning of this century, even though the world's population has tripled and its economic output increased by an order of magnitude. Economic incentives and technology have historically overcome perceived resource limitations.

However, it is likely that real primary energy costs from the conventional oil and gas sources will eventually increase. The average cost of exploration and development of new oil fields has risen steadily. At some increasing price level, unconventional oil sources gradually become competitive but require large capital investments. For example, at an oil price of about $30 to $40 per barrel (1990 dollars), large high-cost oil resources (for example, tar sands) become economically viable (*5*). Even the direct use

Table 1. Comparative energy and electricity increases to year 2060 (1986 = 100% for all cases).

	Present trend (%)	Full conservation* (%)
Population		
World	195	195
Less developed countries	211	211
Developed countries	143	143
Total energy		
World	438	242
Less developed countries	811	462
Developed countries	320	186
Energy per capita		
World	225	129
Less developed countries	385	219
Developed countries	225	130
Energy per GNP		
World	80	46
Less developed countries	68	39
Developed countries	74	43
GNP per capita		
World	280	280
Less developed countries	564	564
Developed countries	305	305
Total electricity		
World	704	469
Less developed countries	1497	998
Developed countries	515	343
Electricity per capita		
World	361	241
Less developed countries	709	473
Developed countries	361	241

*Full conservation is assumed to be the maximum improvement in energy use that can be obtained by year 2060 without reducing GNP.

of oil shales in utility boilers becomes marginally economic (6). Such oil-bearing bodies are the energy equivalent of giant oil fields (7), sufficiently large to provide the liquid fuel needs of the next century but require much higher capital investment for the same flow rates. This would change the character of the liquid fuel production industry.

The most abundant fossil fuel is coal, representing about 90% of all known conventional fossil resources. Its convertibility to both liquid and gaseous hydrocarbons has been demonstrated. The production of complex hydrocarbons by coal conversion has been commercially deployed worldwide (8). All these plants utilize an initial step of controlled combustion of coal in the presence of an oxidant and water vapor, leading to the decomposition of the steam and reaction with the hot coal to produce syngas (carbon monoxide and hydrogen) with the component ratio depending on the system parameters. Subsequent downstream treatment can be varied to produce a spectrum of hydrocarbon mixtures including hydrogen. The production of methane or liquid fuel from such an initial step is conventional chemical engineering. The famous Sasol plant in South Africa has been producing liquid transportation fuel for decades from indigenous coal. The true costs have been stated to be marginally competitive currently but would be more competitive at higher oil prices. In the past 6 years, a plant in New Zealand has demonstrated the feasibility of converting methane into gasoline with a large-scale zeolite process. Low-cost and large natural gas reserves discovered in some remote locations have stimulated the investment in on-site conversion of natural gas to liquid fuel, so as to economically ship the product to a distant transportation market (9). It is thus obvious that if the price of oil becomes sufficiently high, coal conversion to liquid fuel can enter the oil industry investment structure. Estimates for producing liquid fuel from coal or gas indicate that \$50 to \$60 billion over the next 30 to 40 years would be required to satisfy 5% of projected U.S. demand for transportation fuel. This should be compared with the present worldwide expenditure of the oil and gas companies of more than \$50 billion annually for exploration and production, and the roughly \$500 billion of annual crude oil sales.

A direct use of coal conversion to gas for the generation of electricity has already been demonstrated with the 100-MW integrated gasification combined cycle (IGCC) power plant at the cool water station of Southern California Edison (10). This is the cleanest coal-fueled technique developed (11). A more advanced integrated gasification humid air turbine (IGHAT) cycle has been proposed, which eliminates the steam bottoming cycle by utilizing the residual heat in a modified combustion turbine. These advanced cycles are important steps for increasing the efficiency of coal use. A modern commercial coal station has a heat rate of about 10,000 Btu (British thermal units) input per kilowatt-hour of electricity produced (34% efficiency). The coal conversion IGCC has a heat rate of about 9000 (38% efficiency), and the IGHAT has a heat rate of about 8300 (41% efficiency). The advanced cycles now have a marginally higher capital cost, but continuing development will eventually make them competitive, particularly because of environmental factors.

A major future improvement in the efficiency of fossil fuel–based electricity gen-

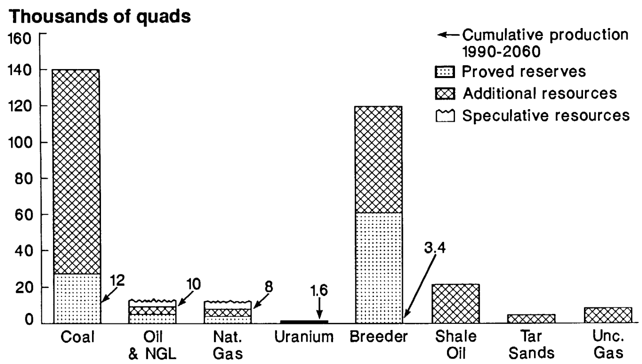


Fig. 2. Mineral energy resources and cumulative production (1990 to 2060). Major resources of coal, oil, natural gas, and uranium appear sufficient to satisfy projected energy needs for the next 70 years. Other resources that are not now utilized, that is, shale oil, tar sands, and unconventional gas, represent additional potential supply that depend on economic incentives for their development. Coal reserves are more than 90% of fossil reserves; 1 quad = 1.055 EJ. NGL is natural gas–based liquid fuels. Resources from IGT World Reserves Survey except for speculative (3).

Table 2. Energy cases for year 2060 CO_2 analysis with breakout for developed countries (DCs) and less developed countries (LDCs).

Energy source	Annual energy in quads per year		
	World	DCs	LDCs
Base case (nuclear at 1986 level, maximum hydro, no other renewables)			
Fossil	1365	753	612
Hydro*	28	14	14
Nuclear	15	15	0
Solar	0	0	0
Biomass	0	0	0
Total energy	1408	782	626
Gigatons of carbon	27.3	15.1	12.2
Ratio of carbon to 1986	5.0	3.8	8.1
Full conservation cases with maximum renewables (solar and biomass allocated between DCs and the LDCs in proportion to their electricity production)			
Low nuclear power version:			
Fossil	494	214	280
Hydro*	28	14	14
Maximum solar	54	32	22
Maximum biomass	99	59	40
Low nuclear	135	135	0
Total energy	810	454	356
Gigatons of carbon	9.9	4.3	5.6
Ratio of carbon to 1986	1.8	1.1	3.7
High nuclear power version: (only nuclear and fossil differ)			
Fossil	431	151	280
Hydro*	28	14	14
Maximum solar	54	32	22
Maximum biomass	99	59	40
High nuclear	198	198	0
Total energy	810	454	356
Gigatons of carbon†	8.6	3.0	5.6
Ratio of carbon to 1986	1.6	0.8	3.7

*World hydro maximum is about four times 1986 level. Year 2060 hydro divided equally between the DCs and the LDCs. †Carbon calculated at 1986 ratio of 0.02 gigaton per quad of fossil energy consumed. Total carbon in 1986 was 5.5 gigatons, with the DCs producing 4.0 and the LDCs 1.5.

eration will come from the ongoing development of the fuel cell (*11*). An electrochemical process to go from the syngas to electricity can be used to avoid heat cycle thermodynamic limitations (Carnot efficiency). The molten carbonate fuel cell is the current focus of development. In principle, it directly replaces the combustion turbines in the integrated cycles described above. It would raise the efficiency of the two cycles to 46% and 55%, respectively, with the best heat rate being about 6000 Btu/kWh. If successful, the commercialization of the fuel cell would eventually decrease the electricity component of the global demand for coal to about two-thirds of that based on present power plant practice, reducing annual carbon emissions.

Nonfossil and Renewables: Significant or Marginal?

The potential role of the nonfossil and renewables in the future global energy mix depends on their developing economic competitiveness. This category includes biomass, solar, wind, geothermal, and the two commercial electricity sources, hydro and nuclear. Only hydro and nuclear are significant contributors today, with hydro about 20% of global electricity and nuclear about 17%. There are practical upper bounds for the potential contribution of the nonfossil and renewable sources (*2*) summarized here.

Both the energy input to manufacture the renewables and their initial capital cost are the issues. A basic consideration is net energy output, or the output minus the energy input from other resources required for their manufacture. This is particularly relevant to biomass, where the energy input for their growth (for example, fertilizer and irrigation) and processing are substantial (*12*). Both factors determine the competitive lifetime cost per unit of delivered end-use energy. As yet, renewables such as solar, wind, and biomass have been able to penetrate only limited niche markets, with much uncertainty about their net energy contribution.

The economic issues for hydro and nuclear are understood the best out of the renewables. Both require about the same capital investment per plant—about twice that for a coal-based unit. Compared to coal, hydro has no fuel cost and a low maintenance and operating cost; nuclear has a low fuel cost and a high maintenance and operating cost. Depending on the treatment of capital costs, hydroelectricity is usually cheaper than coal. In the industrial countries, nuclear electricity is now generally competitive with coal. The upper limit for global hydro growth is about four times the present level. Nuclear is limited only by available capital and manufacturing facilities. Both are constrained by environmental considerations. Hydro expansion involves flooding large areas and altering river flows and probably will not grow significantly for environmental reasons. Nuclear, when operating as designed, has small environmental impact but faces serious public concerns about the risk of off-design accidental release of radioactivity from either the reactor or spent fuel, and thus, nuclear has high administrative penalties. This has stimulated the current engineering concentration on reducing the probability of such accidents. Nuclear growth depends on the future public perception of the comparative benefits, costs, and risks of alternative energy sources. Based on the comparative evaluations of tangible risks to public health, safety, and environment, nuclear appears to be a better choice than coal. The intangible risk comparisons are more uncertain. Historically, such perceptions have changed with time. A century ago oil was perceived as too inflammable to replace coal, retarding its use in naval vessels for decades. During the recent decades, large naval ships turned to nuclear power because of its fuel longevity. Similarly, public opinion may shift with the changing priorities of the issues—costs, pollution, safety, global warming, among others. In the meanwhile, nuclear is slowly expanding worldwide, now providing 17% of world electricity.

Biomass is an unusual case. Much of the population in the underdeveloped regions has historically depended on noncommercial biomass energy sources, such as wood, shrubs, agricultural wastes, and animal dung, because these required no capital, only labor. In the industrial world, wastes from the paper, pulp, and lumber industries are used as on-site fuel. Less than 2% of the global energy supply is estimated to be from such noncommercial sources. The true cost of the noncommercial sources in the underdeveloped world is speculative because they are not market priced. However, in labor-hours required for their collection, noncommercial sources are costly. If the economic growth of the underdeveloped countries continues (*2*), the shift of this labor pool to more economically productive activity will result in a corresponding shift from noncommercial to commercial fuels, probably petroleum products initially.

The concept of commercial biomass fuel production through managed agriculture and forestry has been studied in great detail (*12*). The production of ethanol from sugar cane in Brazil is a massive demonstration of this potential. Although it was initially undertaken for internal social and trade balance objectives, ethanol now appears embedded in that nation's structure and may continue for that reason. However, it does not appear to be economically competitive with petroleum products in a world market. From a net energy view, estimates range from marginal to providing about 20% more energy than it consumes (*13*). The tropical zone, including Brazil, is the optimum area for biomass production and provides the basis for the most optimistic estimates of managed forestry. As a feasible, although optimistic upper estimate, biomass might supply a fourth of the fuel for the electricity demand in 2060 with full conservation, provided that transmission to markets from such biomass plants is available. Hall *et al.* (*14*) suggest a slightly more optimistic estimate of the potential. If reduction of carbon emission becomes a global priority, managed biomass deserves a high weighting because it will either recirculate atmospheric carbon or sequester it. This capability suggests that managed biomass (that is, forestry) be encouraged to sequester carbon rather than use it as a fuel, particularly because of its uncertain net energy contribution.

The key technological issue for solar and wind is epitomized by the windmill-driven old-fashioned well-water pump and tank (once common on farms). It represents the ideal theoretical arrangement—an intermittent source coupled to storage end use. Its only handicap was the catastrophic windless drought that occurs for extended periods almost every year. Windmills were abandoned when power lines became available for reliable electrical pumping. Analogously, solar sources face the uncertainty of heavy cloud cover and reduced output. Nevertheless, the immensity of the solar energy available both by direct radiation and from wind is such that, even with low-efficiency conversion systems of a few percent, it is seductively apparent that most of the future global energy needs could be met. The big barrier is the technical and economic feasibility of overcoming their intermittent nature with energy storage and the required expanded collectors (*2*).

Solar and wind have made minimal entries to the present energy structure. Several windmill demonstrations have been installed on utility systems (*15*). Subsidized solar generators are supplying electricity during the peak hours, which roughly coincide with the diurnal cycle. As yet, their competitiveness is marginal. Both direct thermal absorption and photovoltaic systems should improve with development (*16*). Both have high capital costs per unit of electricity, which will be multiplied many times if their intermittent nature is compensated by the addition of energy storage facilities. Unless a low-cost electricity storage device is developed, the large-scale participation of solar and wind sources will be limited to a 12% maximum (*2*) of the total network capacity of fuel-based electrical systems. However, this is not inconsiderable. By the middle of the next century this limited fraction would be equivalent to about 60% of today's world electricity generation. Solar and wind in combination with batteries can today economically fill small power niches, such as remote signaling devices (*17*). This may establish a base for future improvements and growth.

Solar enthusiasts have suggested that solar electricity be used to dissociate water for the production of hydrogen as a transportation fuel (*18*). This would achieve the ideal system goal of energy storage, no carbon emissions or pollutants, and an eternal primary energy resource. Although scientifically sound, the practical barriers of economics and operable technologies are large. Many billions of cubic feet of pure hydrogen are routinely produced in the world's oil refineries, at costs that are a fraction of electrolytic hydrogen. Nevertheless, there are no indications that a transition from conventional end-use systems to hydrogen-based systems has been of practical interest. There are no developments now visible that are likely to remove these economic and technical barriers, although the obvious merits of hydrogen combustion producing only water as a by-product provides a tantalizing target.

Electricity—The Key to the Energy Future?

The known physical processes for the intraconvertibility of energy forms ensures that every future end-use could be met, provided any primary energy resource is available, although conversions might be costly. In such conversions, electricity has demonstrated a common intermediary role. Even though the cost of manufacturing electricity makes it the most expensive form per unit of energy content, electricity's versatility, controllability, cleanliness, end-use efficiency, and simplicity have made it a continuously growing choice for efficient economic systems. In the United States, about 40% of all primary energy equivalent now goes into electricity generation. By the middle of the next century, this may exceed 50%. Electricity's historic limitation has been the low energy density of electrical storage devices, principally the battery, as compared to the energy density of petroleum products and coal. Transportation-sector fluid fuel use represents about 27% of the total U.S. energy demand. A successful electric automobile for urban use might eventually replace about half of the internal combustion vehicles, bringing electricity to about two-thirds of the future total equivalent energy input in the United States.

Most relevant to electricity strategy is the ability of installed electrical transmission and distribution systems to transmit the generated output from any primary energy source, fossil or nonfossil. This allows the easy incorporation of new technology generation plants into the energy system. In the United States, transmission and distribution systems represent about half of the capital investment in electricity supply. In the absence of a strong transmission network, localized small power units form the basis for electricity supply; thus the strategy for large industrial regions differs from that of the underdeveloped countries.

Technology Transition—Why Does It Take So Long?

In considering advanced energy systems that might supply future energy needs, many decades will be required for a significant transition from today's conventional systems. Only in a crisis is it feasible to compress research, development, demonstration, and deployment into a decade or less. This has been accomplished in wartime by overriding all normal priorities and economic constraints. The history of energy fuel transitions (wood-coal-oil) shows that in a peacetime commercial environment almost a half century is required to significantly shift fuel patterns (*19*).

A projection of modern industrial experience to the future of advanced coal technologies suggests the typical time sequence of energy research, development, demonstration, and deployment shown in Fig. 3. Estimated cost magnitudes (1991 dollars) are also shown. The commonality of syngas production from both natural gas and coal as an input to either of the advanced IGCC plants or fuel cells is illustrated.

Coal-based IGCC is being commercially deployed following a successful program carried out in the 1980s. A commercial prototype will be started up in the Netherlands in 1993. Some 4000 MWe of IGCC systems are planned for installation in the United States, Europe, and Asia based on coal. As indicated in the figure, the synthesis gas from coal gasification systems may be linked to molten carbonate electricity generation sometime in the next 25 years.

The center portion of Fig. 3 shows costs and schedules for deployment of molten carbonate fuel cell technology. This technology is just emerging from research with development units (200-kW size) being field tested. It is likely that small early units will operate on natural gas or distillate fuels on an electricity distribution system. The completion of the engineering development and ultimate deployment of large (50 to 250 MWe) capacity fuel cell system based on synthesis gas from coal gasification systems will require $80 to $150 billion. These costs include the manufacturing facilities to produce the molten carbonate fuel cell units. A feature of such plants is their high efficiency (about 55%), low emissions of carbon dioxide, and no emissions of sulfur or nitrogen oxides. Probably 35 to 50 years are required to install 75,000 to 125,000 MWe of fuel cell equipment. In comparison, over the last 30 years, about 50,000 MWe of gas turbine equipment was installed by the U.S. electric industry. It is pertinent that nuclear power, despite its long history of deployment, which makes the U.S. nuclear industry the largest in the world, provides only 20% of U.S. power. Catalytic cracking, commercially introduced in 1942, took about 20 years to achieve general use in refineries.

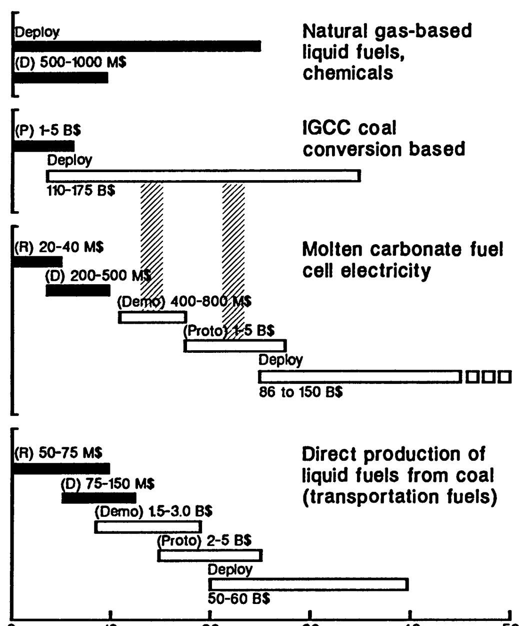


Fig. 3. Technology schedules and costs. Representative schedules and costs are estimated on the basis of the current status (black) of advanced technologies to produce commercial liquid fuels, chemicals, and electricity. Market penetration of 5% can represent a 30- to 50-year period. R, research, D, development; Demo, demonstration plants; Proto, first commercial plant; Deploy, 5% of U.S. market; IGCC, integrated gasification combined cycle.

The long time required for these transitions has serious implications for global energy strategies. It is likely that this time scale of three to five decades for significant energy contribution will also apply to the renewables, with the eventual limitations already described. By the middle of the next century perhaps a third of the global electricity-generating capacity might be advanced technology, and by the end of the century most of it should be. In the industrial countries, the entry of advanced technologies is limited by the slow obsolescence of existing plants (with a usual lifetime of 40 years) and by the rate at which additional capacity is needed. At a typical long-term annual growth rate of 2%, it takes 35 years to double total capacity. For the undeveloped countries obsolescence is less an issue than the scarcity of capital and the avoidance of performance risk. Thus, they are likely to purchase only well-proven conventional plants. Nevertheless, they are in particular need of small and dispersed power growth, providing a special opportunity for small solar, wind, and conventional fossil-fueled units.

Conservation is sometimes considered as equivalent to an energy resource because it extends the life of conventional resources, although it has practical limits. The conservation concept includes both (i) providing end-use functions more efficiently and (ii) modifying consumer habits to reduce energy demand. Reducing automobile speed limits and using public transportation are examples of the latter. Both approaches are cost dependent. The oil price increases of the 1970s did result in reduction of U.S. total energy demand (2). A detailed analysis showed that the bulk of this reduction came from industry, over about a 5-year period, by investment in equipment to minimize energy losses. The economic value of such industrial programs is clear and tangible. The nonindustrial consumer is less motivated by long-range economics and appears to await normal obsolescence of capital equipment. Thus, the time for significant transition to more efficient energy use is 10 to 30 years in industrial societies, depending on economic incentives.

Modifying consumer habits to reduce energy demand depends on the cost of energy relative to consumer income, as weighted by the priorities of the consumer for services, convenience, comfort, and time. Thus, for the motor vehicle user, the time saved by high-speed travel may be more valuable than the incremental cost of fuel consumed. Obviously, the user's cost of energy is key to both efficiency investment and changing consumer habits. Ideally, intangible social costs of environmental degradation should be included in such evaluations and be part of the price structure perceived by the consumer. These intangibles are balanced by the intangible benefits of low-cost energy supporting society's goods and services. In the absence of strong economic incentives, the time needed for implementation of comprehensive worldwide conservation is likely to be as long as that for advanced technologies, or about a half century.

Future Environmental Influences

It is recognized by all political bodies that poverty is the most devastating social pollutant and that economic growth provides the essential resources for reducing pollution, both social and environmental. Economic growth consistent with reducing pollution can obviously be accomplished by the efficient use of the energy supply, and thus conservation through efficiency has become a global strategy. Its role is basically limited only by the additional capital that may be needed to install the most efficient systems.

It is important to perceive the spectrum of alternative mixes that may result from future technical developments. Much will depend on the changing comparative status of technical options. Thus, a commercially successful fuel cell could offer the most efficient, cleanest, and most versatile means of converting gasified fossil fuels to electricity, reducing carbon and pollutant emissions to about two-thirds of present practice (*11*). If the reduction in carbon emissions becomes a major global objective, the move to nonfossil sources would, of course, be accelerated. As only about a fourth of the world's hydro is now developed, the ecological constraints might be eased to permit more growth. The development of "user friendly" and economic nuclear power plants would shift the mix in industrial countries to a large nuclear fraction, comparable to the 70% in France today. Uranium ore requirements would then raise the technical priority of advanced reactors with a high conversion ratio, or of the breeder, or of accelerator-produced neutrons, or of fusion-fission hybrids, so as to use uranium resources more effectively (20). For solar and wind, a major role will depend on the advent of an economic electricity storage system to overcome the handicap of intermittency.

In the consumer end-use systems, a move to electrification of space conditioning and transportation with advanced technologies could reduce oil demand and environmental degradation. The advanced electric heat pumps now available are already the most efficient space heating and cooling devices. The electric automobile is approaching a marginal competitive status in niche applications, such as heavily polluted urban areas. The electric train, particularly the magnetically levitated version, may soon benefit from high temperature superconductivity developments. The deployment of such equipment depends, of course, on the establishment of supporting systems and the adjustment of regional transportation plans to accommodate them. Presumably, the increased electricity demand would be met by nonfossil plants (for example, hydro, nuclear, solar).

Conclusion

Primary fuel resources are foreseeably available and are unlikely to be an economic constraint for the next century, although their absolute and comparative costs will shift with time. The long-term future global energy supply mix will be determined by a few mostly independent factors. Predominant are the growth of population and per capita economic income; followed by the commercial availability of systems for supplying regionally diverse needs; and finally, the comparative social benefits, social costs, and risks of these options. Both tangible and intangible (for example, environment and health) values will be implicitly included in such determinations.

For the first half of the next century, the time required for a global transition to more energy-efficient advanced technologies and use patterns will inevitably slow the effect of practical responses to the issue of global warming. Such advanced systems should be mostly embedded during the second half of the century. The more investment the world makes over the coming decades in developing efficient and environmentally benign technologies based on a full scientific understanding of their interaction with the environment, the lower will be the long-term cost of energy and the less the probability that economic growth will be constrained by high energy costs or that composite environmental goals will be compromised. However, such investments in energy technologies come either at the expense of reduced current consumption or at the expense of investment in other activities. A balanced and stable program has the best prospects of achieving lowest long-term social costs. The wisest course does not lie in pursuing extreme policies of energy supply, conservation, environmental protection, or economic growth. All that we can be certain of is that the future is best faced with an array of options and flexible strategies.

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Airborne Studies of the Smoke from the Kuwait Oil Fires

Peter V. Hobbs* and Lawrence F. Radke

Airborne studies of smoke from the Kuwait oil fires were carried out in the spring of 1991 when ~4.6 million barrels of oil were burning per day. Emissions of sulfur dioxide were ~57% of that from electric utilities in the United States; emissions of carbon dioxide were ~2% of global emissions; emissions of soot were ~3400 metric tons per day. The smoke absorbed ~75 to 80% of the sun's radiation in regions of the Persian Gulf. However, the smoke probably had insignificant global effects because (i) particle emissions were less than expected, (ii) the smoke was not as black as expected, (iii) the smoke was not carried high in the atmosphere, and (iv) the smoke had a short atmospheric residence time.

As the Iraqi army fled Kuwait in February 1991, they damaged or destroyed 749 oil wells, storage tanks, and refineries, 610 of which were ignited (*1*). The resulting fires produced a large plume of smoke that had significant effects on the Persian Gulf area and the potential for global effects. To evaluate the effects of the smoke, we obtained airborne measurements from two aircraft during the period 16 May through 12 June 1991 (*2*). The goals of the study were to determine the chemical and physical nature of the smoke and to investigate its potential effects on air quality, weather, and climate. We give here an overview of this study and describe some of the results (*3*).

P. V. Hobbs is professor of atmospheric sciences and director of the Cloud and Aerosol Research Group, University of Washington, Seattle, WA 98195.
L. F. Radke is manager of the Research Aviation Facility, National Center for Atmospheric Research, Post Office Box 3000, Boulder, CO 80307.

*To whom correspondence should be addressed.

Overview of the Fires and Smoke Plumes

The main oil fields in Kuwait (Fig. 1) can be divided broadly into those north and those south of Kuwait City. The individual fires in these fields generally produced distinct, isolated plumes over short distances, after which they merged. Low-level, stable atmospheric layers (*4*) were common in the region. When the smoke reached these layers, it generally fanned out horizontally. During our measurements, smoke was never detected above an altitude of ~6 km and was generally well below this level. The composite plume of smoke from the north fields generally merged with that from the south fields to produce a supercomposite plume, which was ~40 km wide 25 km south of Kuwait City (Fig. 2). Between ~0.3 and 1.2 km in altitude, the winds were nearly always from the north or northwest and were often quite strong (the "Shamal" wind), whereas at higher altitudes the winds were more westerly. The tops of the smoke layers were generally flat, although, on occasions, they contained wave-like features, including breaking waves and shallow convective features (Fig. 3). The base of the smoke plume was normally between ~0.5 and 2 km high and was also generally quite flat.

Close to the fires the smoke rained oil drops (Fig. 2). This oil, together with soot fallout, coated large areas of the desert with a black, tar-like covering. Oil spewing out from uncapped wells formed large pools of oil on the desert, some of which were alight (*5*).

Individual fires produced different plumes, ranging from black to white in appearance (Fig. 4). A few fires, presumably of natural gas (CH_4), produced no visible plume. Before our airborne measurements it was speculated that the white plumes were due to the presence of water. However, this explanation can be discounted because the dew points in these plumes were not measurably different from that in the ambient air, and relative humidities were low. These plumes contained a considerable mass of salt (*6*), which scattered light efficiently to produce the white appearance. More than 80% of the mass of the particles in one of the white plumes was salt (mostly NaCl). The salt no doubt originated from oil-field brines expelled from the wells together with the oil (*7*). Very little soot (~4% by mass) was present in the white smoke; the black smoke contained 20 to 25% soot and variable amounts of salt. Fires associated with pools of oil on the desert produced the blackest smoke, which contained up to 48% soot by mass. The mass of the smoke particles in the supercomposite plume was ~30% salt, 15 to 20% soot, 8% sulfate, and ~30% organics.

The optical properties of the supercomposite plume were dominated by submicrometer-sized particles, with number and volume size distributions sharply peaked near 0.1- and 0.3-μm diameter, respectively (*8*). These were the primary combustion particles and the building blocks for chain aggregates of soot (*9*). When the submicrometer aerosol was heated to 300°C to remove volatiles (including sulfate), about 30% of the mass was removed (*8*). Near the lateral edge and in the upper regions of the plume, where the solar radiation was greatest, there was photochemical production of nucleation-mode particles (~0.01 μm). Total particle concentrations within a few kilometers of the fires frequently exceeded 10^5 cm^{-3}; at 300 km from the fires the concentrations were ~5,000 to 15,000 cm^{-3}, and beyond 1000 km they approached background levels (~300 to 500 cm^{-3}). The supermicrometer fraction of