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Author
Brooks, H.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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Harvey Brooks and Jack M. Hollander

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UNITED STATES ENERGY ALTERNATIVES TO 2010 AND BEYOND: THE CONAES STUDY

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Harvey Brooks

Harvard University, Cambridge, Massachusetts 02138

Jack M. Hollander

University of California, Lawrence Berkeley Laboratory,
Berkeley, California 94720

INTRODUCTION

This paper reviews the results of a study performed by the US National Academies of Sciences and Engineering in response to a request from the US Energy Research and Development Administration in 1975 for a comprehensive analysis of the nation's energy future, with special consideration of the role of nuclear power. The chart below shows the organizational elements of the study which consisted of the parent Committee on Nuclear and Alternative Energy Systems (CONAES), (1), four assessment panels, and some two dozen subcommittees, involving, in total, over 250 persons. The Committee and study groups were selected from a broadly based representation in order to bring to bear a wide range of expertise and viewpoints on the major US energy issues.

Central to the study's charter was assessment of current and future options for the nation's energy supply system. To do this required establishment of the contextual relationships between major energy supply issues and plausible future levels of energy demand. To illustrate the study's conclusions regarding interactions among individual elements of the problem and cumulative impacts of different energy strategies, a number of hypothetical energy futures (scenarios) were constructed and examined.

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Organizational elements of the study on nuclear and alternative energy systems

Committee on Nuclear and Alternative Energy Systems (CONAES)

Co-Chairpersons: Harvey Brooks and Edward L. Ginzton
Executive Director: Jack M. Hollander
Kenneth E. Boulding
Robert H. Cannon, Jr.
Richard R. Doell
Edward J. Gornowski
John P. Holdren
Hendrik S. Houthakker
Henry I. Kohn
Stanley J. Lewand
Ludwig Lischer
John C. Neess
David J. Rose
David Sive
Bernard I. Spinrad

Demand/Conservation Panel

Chairperson: John H. Gibbons
Transportation: R. Eugene Goodson
Industry: Macauley Whiting
Buildings: Roger S. Carlsmith

Supply/Delivery Panel

Chairperson: W. Kenneth Davis
Deputy Chairperson: Floyd L. Culler, Jr.
Energy Resources: James Boyd
Coal Conversion: Eric H. Reichl
Petroleum: Allen E. Bryson, Theodore Eck
Nuclear Fuel Cycle: John W. Landis
Breeder Reactor: Milton Levenson
Gas Distribution: Derek P. Gregory
Electricity: Herman M. Dieckamp
Solar and Renewable Resources: Melvin K. Simmons
Geothermal: Morton C. Smith
Fusion: Peter L. Auer
Financial/Institutional: Donald G. Allen
Nonenergy Materials and Resources: Frank Ritchings

Risk/Impact Panel

Chairperson: James F. Crow
Emissions and Pathways: David Okrent
Health Effects: Carl M. Shy
Climate: Stephen Schneider
Ecosystems: John Harte
Sociopolitical: David Sills

Synthesis/Modeling Panel

Chairperson: Lester B. Lave
Modeling: Tjalling C. Koopmans
Consumption, Location, and Occupational Patterns: Laura Nader
Decision Making: David Cohen

When Alice, of *Alice in Wonderland,* asked the Cheshire Cat "Where do we go from here?," the latter responded, "That depends a good deal on where you want to get to." The CONAES study, like others before it, concluded that there are divergent pathways this nation can follow toward its energy future. Which path is pursued will ultimately be a matter of social choice. But, whichever road is followed, deliberate and timely actions by government will be required, and many will touch sensitive nerves in this pluralistic society. Building the political consensus necessary to an effective policy will therefore be difficult. An important ingredient of this effort is to replace myths with facts and to reduce uncertainties as much as possible. With these objectives, CONAES attempted to assemble a solid data base which would assist both the decision maker and the public to identify and evaluate the consequences of alternative and often conflicting energy goals, options, costs, benefits, tradeoffs, and mixed strategies.

The CONAES study produced a rich body of information, not all of which will be published by the Academies. Annual Review of Energy has already carried reviews in Volume 3 that make significant reference to this literature, (2–6) and continues this coverage in the present volume. This paper is the result of a decision by the ARE Editorial Committee that a review of the entire CONAES study would be useful. This account has not been subjected to the usual review process of the National Academy, nor has it been reviewed by the members of CONAES. While the authors have tried to avoid doing violence to the consensus of CONAES, the views presented here are wholly the interpretation of the study by the authors. Unless a view is specifically attributed to CONAES, it should be regarded as the opinion of the authors.

THE ENERGY PROBLEM

Roots of the Problem

The energy problem in the United States was brought about primarily by the nation's growing consumption of energy resources, especially oil and natural gas, in the face of declining domestic production. The growth in energy use was stimulated both by economic expansion and by decreasing real energy prices over the past three decades.

The causes of decreasing energy prices were several. First, technical improvements and economies of scale in obtaining and converting energy resources were reducing costs of energy and fuels production. Second, the remarkably low production costs of Middle East oil, combined with the control of distribution by the multinational oil companies, helped to hold prices to production and transportation costs; in fact, these provided part of the stimulus for domestic cheap-energy policies. Third, public policies such as tax stimuli to oil production and regulation of interstate gas kept the prices of these fuels below what they would have been in a more nearly ideal market (7). Fourth, the costs of environmental and public health protection were not fully incorporated into energy prices.

While the costs of fossil fuels declined, the efficiency with which they could be converted to electricity was also increasing; therefore, the cost of electricity decreased even faster than fuel prices. In 1971, the real price of electricity was about one third the 1946 price, and the real price of oil less than one half (8). Declining electricity cost was probably a factor in the failure of nuclear energy to capture an extensive market as early as expected.

The era of declining fossil fuel prices came to an end in the late 1960s, and then reversed abruptly in the "energy crisis" of 1973–74. The most important underlying factor in the timing of this dramatic change was that domestic oil and gas production peaked around 1970 and the United States, with more than a third of world petroleum consumption, rapidly became a major buyer in world markets at a time when demand for petroleum worldwide was growing at more than 5 percent a year (9). The abrupt shift from a buyer's to a seller's market in petroleum, coupled with the concentration of production in a small number of countries, made a large price increase almost inevitable.

Another contributing factor to the emergence of the energy problem was the heightened public concern about energy-related health and safety problems and environmental protection, and the growing political strength of the environmental and consumer movements. The principal near-term substitutes for oil and gas, namely coal and nuclear power, each presented especially serious problems for environmentalists, as did the search for and production of oil in ever more remote locations and fragile environments. The need for new energy supplies collided with this growing awareness of the risks posed by energy production and use, and the energy-environment trade-off has been elevated to the status of a major political issue in this country, and affects the political balance in other industrialized countries as well.

The oil price rise coincided also with rising public consciousness of the plight of the underdeveloped world and official concern with economic development of the large majority of the world's population that is desperately poor. The rising cost of energy posed a new and formidable barrier to development of the oil-importing poor nations, raising new issues of international equity and straining the international financial system.

The energy problem is not a crisis in the traditional sense, analagous to a military national emergency. It is, rather, a gradually deteriorating situation that could erupt into crisis at any time, nonetheless a situation on which it is difficult to focus sustained public attention because the symptoms of crisis appear only sporadically and unpredictably, as in the 1973 oil embargo, the 1977 US natural gas shortage, and the 1979 political upheaval in Iran.

The Energy Problem Today

The principal issues for US energy policy today concern the need to understand better the factors that will govern future US demands for various forms of energy, the possibilities for supplying those demands from domestic sources under various constraints as a result of various technical developments, and the interrelationships of US and worldwide energy demand and policies affecting supply.

The United States, with 6 per cent of the world's population, now consumes about one third of the world's energy production. In 1976, total domestic energy consumption was about 75 quads.[1] Almost three fourths of this, roughly 55 quads in 1976, was supplied by oil and natural gas. (Figure 1 shows the composition of the US energy system by energy supply source and consuming sector.) In 1976 the nation imported 15.6 quads of oil—almost half of its 33 quads of oil consumption—at a cost of over 35 billion dollars. Figure 2 illustrates that even the fourfold price rise subsequent to the 1973 OPEC oil embargo did not halt the trend to more imports, except during the temporary recession of 1973–1974.

Most immediately, the energy problem relates to this increasing dependence on oil imported from politically volatile regions, and the consequent threat this dependence poses to the nation's international freedom of action and to the long-term health of the US economy. However, the magnitude of the problem is reflected less in the current situation than in the consequences of extrapolating current trends. For example, if domestic energy *consumption* were to continue growing at the 1950–1972 annual rate of 3.4%, an annual energy requirement of 240 quads would be reached in the year 2010. By contrast, domestic energy production in 2010, projected by the CONAES Supply/Delivery Panel under assumptions of a continuation of recent policies and production trends, would be less than 80 quads (10). The gap of 160 quads is over 10 times current imports and about as much as current world petroleum production. This scenario represents a totally implausible future course for the nation. Even if world oil prices were to remain at current levels, and if so much foreign oil and gas were available to the United States—both highly unlikely—this would cost the nation over $300 billion a year and would carry untenable political costs as well. Radical changes in either supply or demand trends, or both, are thus inevitable.

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[1] 1 quad = 1 quadrillion Btu = 10^{15} Btu = 0.293 X 10^{12} kWh.

Whether these changes will be smoothly evolutionary or disruptively revolutionary will be influenced strongly by public policy.

The scenario just described, however, represents a highly improbable extreme case. The trends and policies of the recent past that caused decreasing energy prices and rapidly growing energy consumption are very unlikely to continue into the future. Possibilities for economies of scale in energy supply are diminishing; costs of new discoveries of oil and gas, mostly in

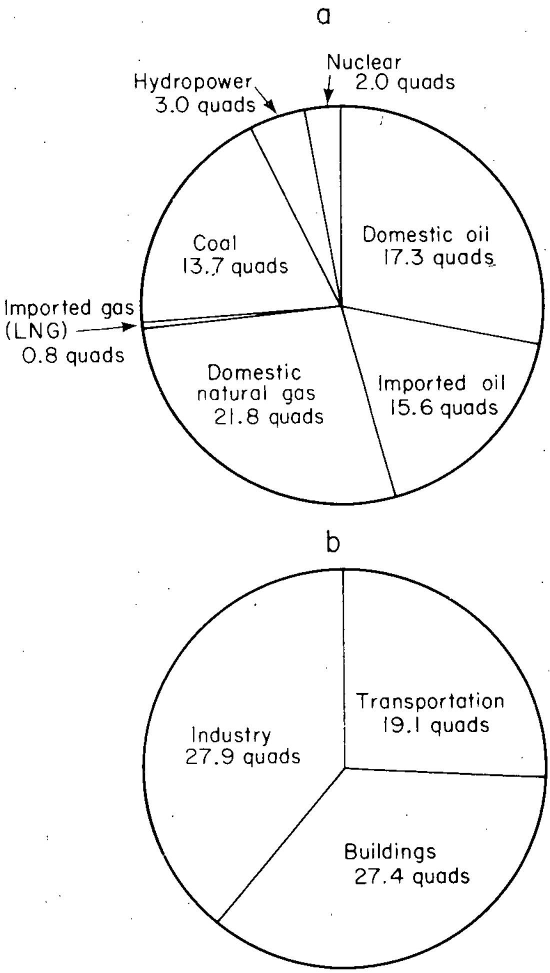

Figure 1 1976 US energy consumption. Composition of the US energy system by *a* energy supply source and *b* consuming sector. Source: *US Statistical Abstracts,* 1978, US Dep. Commerce

remote or inaccessible locations, are steadily increasing; stricter environmental standards continually raise the costs of both exploration and production. Barring major new oil discoveries in politically secure areas, the real price of energy will continue to rise. This will restrain demand growth even in the absence of special policy measures.

The econometric models of the CONAES Modeling Resource Group (11) suggest that the real prices of most energy forms will approximately double by the year 2010 under conditions of market equilibrium. This conclusion is compatible with those of earlier studies (12–14). According to the analysis by the CONAES Demand/Conservation Panel, an average doubling in price would be compatible with total annual US energy consumption of roughly 140 quads in 2010, if 3% average annual GNP growth is assumed, or roughly 100 quads if 2% annual GNP growth is assumed (15). This corresponds to a reduction in the ratio of energy consumption (E) to gross national product (GNP) to betwen 45 and 65% of its 1972 value. Such a reduction of the US economy's energy intensity would not be unprecedented. For example, this ratio declined by 35% between 1920 and 1955 (15). In addition, during 1977 the increment in energy consumption divided by the increment in GNP for that year was less than two thirds the historic E/GNP ratio (16). Such a reduction would also be compatible with experience in Europe and Japan, where energy prices to the consumer have been higher than in the United States, and where the E/GNP ratio has

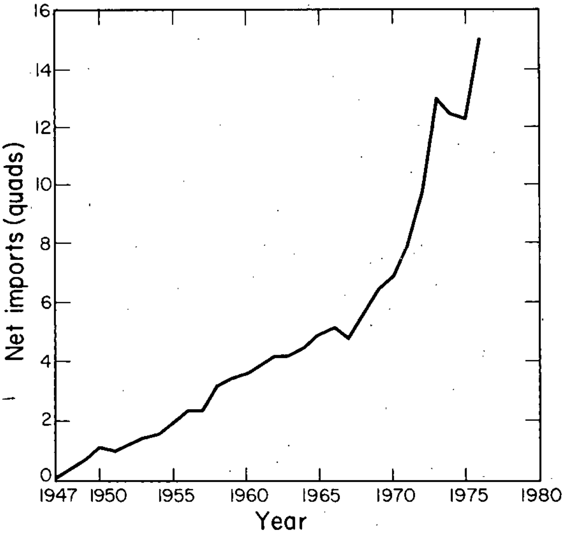

Figure 2 Trend in US oil imports over a 30 year period.

ranged from 55% to 75% that in the United States, although factors other than price are also involved in this difference (17).

A major question is the role of the market in the US energy future. Some argue that future market changes in energy price will be sufficient to equilibrate supply and demand without domestic or international economic and political disruptions. This view holds that the present US energy problem stems at least in part from various governmental interventions in the energy market, and that a gradual transition to an ideal competitive market would solve the energy problem provided that prices were also permitted to reflect environmental and other external costs as well as normal supply-demand relationships (18). A contrary view is that energy markets have so long been politicized, both domestically and internationally, that there are so many nonmarket sociopolitical determinants of energy supply and demand, and that energy supply has become so vital to national security that an ideal competitive market is a fiction that would not be tolerated politically even if in fact it could be attained.

As an example of the importance attached to nonprice variables in recent analyses, the CONAES Supply/Delivery Panel developed its projections of energy supply producibilities in the setting of various sociopolitical scenarios rather than in an economic market framework (10). This was done because of the Panel's conviction that sociopolitical variables such as environmental restrictions, permitting and licensing procedures, opportunities for intervenors, and leasing policies for government lands will be more important factors than price in determining future energy supplies.

Nevertheless, the simulated performance of an ideal competitive market may be a good standard against which to measure and to evaluate public policies, so that deviations from this standard should be undertaken only for well-understood reasons. With this view, the CONAES Demand/Conservation Panel adopted a market approach to their analysis of the potential for energy conservation, and the analysis indicated that the investment cost of increasing the efficiency of energy use to save a unit of energy is considerably less than the investment cost of producing a corresponding increase in energy supply (15). Public policy should ensure that market incentives and tax and regulatory policy reflect this fact in the long run.

Transition to a Long-Term Energy System

The US government's initial response to the 1973 oil embargo and the OPEC price rise was Project Independence, whose goal was to eliminate oil imports by 1980. However, studies of the economic, industrial, and political implications of the energy problem soon revealed the impossibility of independence in the short term, and emphasis shifted from immediate self-sufficiency to the longer term problem of finding domestic substitutes for oil and gas. People also began to realize that it takes 30–50 yr to bring a new energy supply technology from laboratory experimentation to deployment on a scale large enough to make a substantial contribution to the energy supply system (19).

A growing mismatch is now evident in US energy supply. Although the domestic shortfall in energy will increasingly be in fluid fuels (oil and gas), most of the new options being developed pertain instead to electric power, which accounts for only about 10% of US energy end uses. Synthetic liquids or gases from coal or biomass can replace only a small fraction of oil and gas use in the near term, while the domestic production of natural liquid fuels will be very difficult to maintain even at current levels. One of the major choices with which the nation is faced is whether to reorient technological development toward synthetic fluid fuels or to attempt to restructure the society's technological basis to reduce permanently our dependence on such chemical fuels.

In the very long term, the world will inescapably have to wean itself from oil and gas derived from nature. Oil and gas will not "run out" in the conventional sense, but will become gradually more difficult to find and more expensive to produce, so that alternatives will become relatively more economical and desirable. This would not be a matter for US public policy concern were it not for the long lead times involved in developing and deploying new energy systems on a large scale, the relatively short time horizons of private investment decisions, and the global political and environmental ramifications of immediately available alternatives to oil and gas.

How fast the transition to a long-term energy system will have to occur will depend both on the growth in total US and worldwide energy demand, and on technical success in developing substitute energy sources in forms suited to the required mix of end uses, i.e. gases, fluids, and electricity. The transition process must also be compatible with the eventual availability of an appropriate combination of indefinitely sustained energy sources.

There are severe limits to the degree to which such a transition can be mapped in advance. Therefore the nation's policy should be to develop a variety of options as a base for the evolution of a combination of energy supply and end-use technologies whose mix can change continuously in response to new knowledge about comparative economics, environmental and other risks, and acceptable social characteristics. An effort should be made to avoid entrapment in a "technological monoculture" that is as much dependent on a single set of technologies as is the present worldwide system dependent on petroleum. Diversity is desirable even at some sacrifice of economic efficiency, because a diversified energy system is more "resilient" in the face of unexpected developments such as strikes, accidents, embargoes, political events abroad, severe weather, and transportation interruptions than is a system overly reliant on a single technology.

In summary, the energy problem, both for this nation and for the world, is to reduce, first, our relative dependence, and later, our absolute dependence, on oil and gas from nature as primary energy sources. This has to be done both by developing and deploying substitute sources and by learning how to use less of primary energy resources to produce the same ultimate level of consumer services or benefits, or—more broadly—the same quality of life.

ELEMENTS OF AN ENERGY STRATEGY

How Much is Enough?

The nation is engaged in a massive effort to augment its capacity for supplying energy in the future to meet growing demand. In planning for energy supply, it is no longer viable to assume, as tended to be done in the past, that our energy supply system should be able to accommodate almost any conceivable level of demand and to plan supply needs simply by trend extrapolation from historical consumption levels. Because energy supplies are bound to be constrained in the future, planning for energy supply needs to be done in the context of the level and types of energy demand that are likely to obtain. No question, therefore, is more central to the energy problem than this: *How much energy will this nation need to use in order to fulfill its social goals in the future?* The answer, of course, will depend on what the future consensus on ranking of social goals turns out to be. Thus CONAES did not attempt to predict future demand, but rather to delineate the factors likely to influence this demand, to explore the kinds of policies needed to achieve alternative future levels of energy supply and consumption, and to assess the benefits and costs of various pathways relative to various social goals.

Choices for the Future: The CONAES Scenarios

The development of an energy demand framework with a solid information base was a major objective of the CONAES study. The framework developed by the study is illustrated by a set of scenarios—hypothetical energy futures extending through 2010 based on data from the CONAES Demand/Conservation and Supply/Delivery Panels and on various assumptions about future energy prices, regulatory policies, and public attitudes. In developing these scenarios, the basic assumption on the demand side was that energy-efficient technology will be adopted over this period to the extent that it is economically rational. The supply mixes to fill the projected demands were arrived at by considering the producibility of various fuel and conversion technologies under the assumed conditions. The purpose of the CONAES scenarios was not to identify a particular future course as most probable or most desirable, but to describe the environs of future energy consumption and compare them with future energy supplies in order to illustrate the important issues and conclusions of the study and to clarify the major policy alternatives.

The energy demand projections of the Demand/Conservation Panel form the basis of the CONAES scenarios. The assumptions underlying these demand projections, involving various energy prices, GNP growth rates, and conservation policies, are summarized in Table 1. Population growth is assumed, in all scenarios, to follow the Series II projection of the US Census Bureau (279 million in 2010). Figures 3 and 4 show, respectively, the overall totals for primary energy consumption of the scenarios, and demands for particular fuel types (i.e. gaseous fuels, liquids, and electricity). A wide range of futures is described by the scenarios, from about one half to two times the present per capita energy consumption in 2010. The CONAES analysis indicates that *each of these energy futures is technically achievable and consistent with a doubling to tripling of real GNP by 2010,* provided that self-consistent policies are followed steadily over that period. But the policies required to achieve the different energy futures are quite different from one another, and the future societies they represent are likely also to be quite different.

Elements of an Energy Strategy

Which road this nation takes during the period of transition away from oil will be determined largely by political choices, guided by a developing consensus about the kind of society desired in the future as well as by considerations particular to energy. These choices will be influenced by many institutional, social, and value considerations that are difficult to quantify and impossible to predict. It is clear, however, that futures with

Table 1 Scenarios for energy demand in 2010[a]

Scenario	GNP growth rate (aver. ann. %)	Energy price ratio 2010/1975 (aver.)	Energy conservation policy
I_2	2	4	Very aggressive, deliberately arrived at reduced demand requiring some lifestyle changes
I_3	3		
II_2	2	4	Aggressive; aimed at maximum efficiency plus minor lifestyle changes
II_3	3		
III_2	2	2	Slowly incorporates more measures to increase efficiency
III_3	3		
IV_2	2	1	Present policies unchanged
IV_3	3		

[a] Source (15).

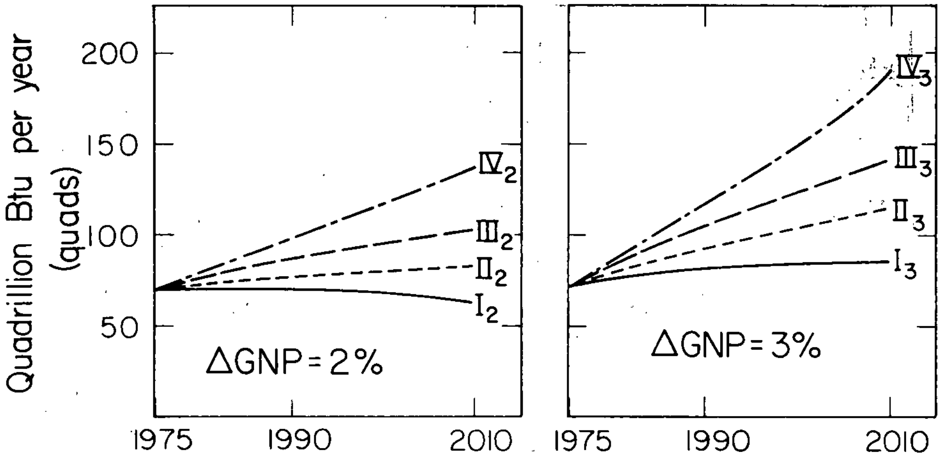

Figure 3 Overall totals for primary energy consumption in the CONAES scenarios.

the highest growth in energy consumption will require high political priority for the development of energy supplies and for holding energy prices down. This will probably require government subsidies and other economic and political incentives to stimulate investment in new energy extraction and conversion systems. Likewise, the lowest-energy-growth futures will entail government intervention in the market to reduce demand, in ways that include energy taxes to make up the difference between production costs and high energy prices to consumers, and also mandatory performance standards for energy-consuming equipment.

Regardless of how the nation sets its societal goals, any strategy for smoothing the transition must comprise four general elements:

1. Moderating the growth of energy consumption in a manner compatible with a healthy economy and future social expectations regarding quality of life.
2. Developing domestic energy resources during the intermediate term in a manner compatible with future social expectations regarding health, safety, and environmental quality.
3. Exploring and assessing several long-term options capable of sustaining a desirable quality of life for mankind through the 21st century, and ultimately beyond.
4. Ensuring the compatibility of US energy policy with foreign policy goals, including the maintenance of peace and stability, progress toward narrowing the gap between rich and poor, and protection of the global environment.

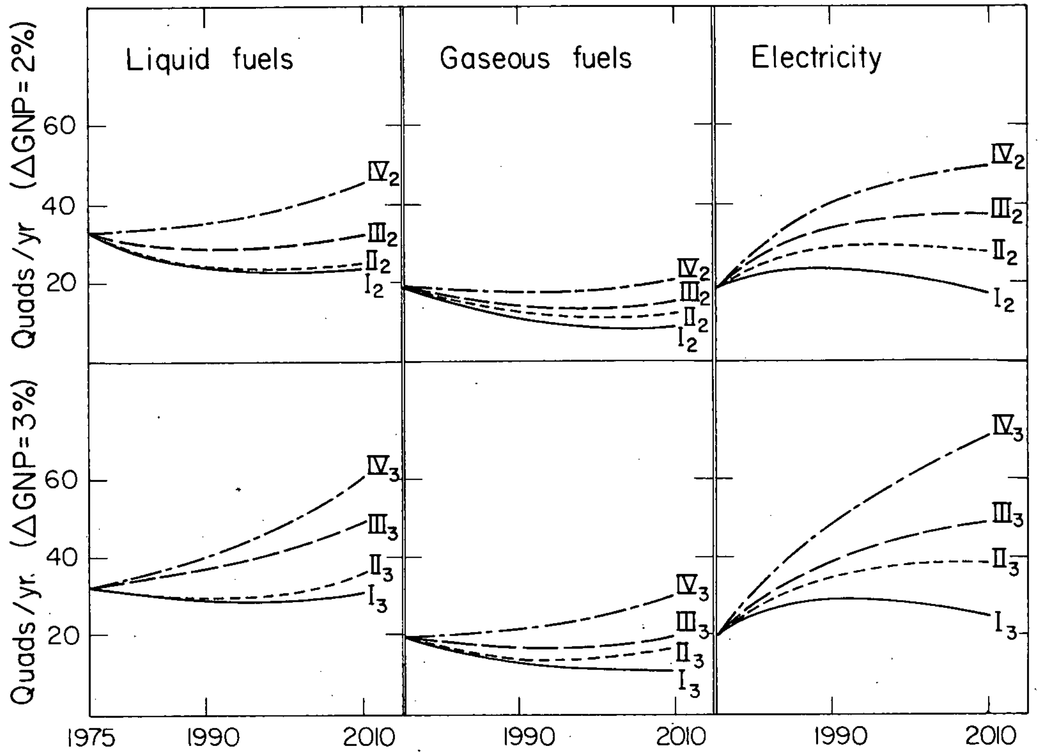

Figure 4 **Total primary energy consumption in the CONAES scenarios—demands for particular energy forms.**

Much of the effort of the CONAES study was devoted to building an improved information base about these elements to facilitate the development of long-term US energy policy. The remainder of this review describes the CONAES conclusions about them in light of that information base, both separately and in the context of the scenarios, which are representative of the nation's social choices regarding energy.

MODERATING DEMAND GROWTH

Technical Opportunities for Increased Efficiency

As we have seen by extrapolating current trends, slowing the growth of energy demand will be essential, regardless of the supply options that are developed during the transition period. *Therefore, the highest priority should be accorded to the demand element of the nation's energy strategy.* Some reduction in growth will inevitably result from rising energy prices, and this reduction could be intensified and accelerated by explicit government policies. These can take the form of taxes and tariffs on energy or standards for the performance of energy-using equipment, or both. In any event, studies by the CONAES Demand/Conservation Panel indicate that US energy demand growth can be reduced substantially, particularly after about 1990, by increases in the technical efficiency of energy end use and by price-induced shifts by consumers to goods and services that are less energy-intensive (15).

The focus of the Demand Panel's study was on these questions:

1. US energy demand through 2010, as shaped by a variety of factors including energy prices, income, population, and public policies.
2. Technological opportunities for increasing the efficiency of energy use and their socioeconomic implications.
3. Institutional and behavioral factors that can constrain or accelerate energy demand.
4. Policy initiatives consistent with the demand-shaping assumptions.

The Demand Panel explored the dynamics and determinants of energy use by performing detailed economic and technological analyses of the major consuming sectors: buildings, industry, and transportation. The projected energy intensities for each sector were based on (*a*) expected economic responses to price increases and income growth and (*b*) technical changes in energy efficiency that, at the prices assumed, would minimize the life-cycle costs of energy-using equipment such as automobiles, appliances, houses, or manufacturing equipment. No credit was taken for new technological breakthroughs; only advances based on currently available technology were considered. *A major conclusion from the analysis is that technical efficiency measures alone could reduce total US energy consumption by half compared to projections based on a constant E/GNP ratio.* This conclusion is relatively insensitive to the detailed assumptions of the analyses. It is also consistent with work by the CONAES Modeling Resource Group (11) which suggests that such reductions in E/GNP are also possible without appreciable impacts on the consumer market basket.

The above conclusion is illustrated by the scenarios (Figure 3). In Scenario II_3, for example, with 3% average GNP growth to 2010 and a fourfold increase in the average 2010 price of energy to users (phased in gradually), total energy consumption in 2010 would be 115 quads; this is only 58% of the total that would result from an assumed constant E/GNP ratio (200 quads). With the further assumption of considerable change in consumption patterns (Scenario I_3), total energy consumption in 2010 would be 85 quads, or 43% of the constant E/GNP value.

The scenario projections from the Demand Panel's sectoral analyses are given in Figures 5 through 8. The following are some examples of the Panel's results in the three sectors, under two representative scenarios (IV_2 and II_2).

TRANSPORTATION Under conditions of Scenario IV_2, with average energy prices unchanged from today's and little more than today's effort to conserve energy, energy use in the transportation sector could increase by 50%, rising from 17.3 quads in 1975 to 26 quads in 2010. In contrast, under conditions of Scenario II_2, with quadrupled energy prices and appropriately strong conservation measures, the transportation energy use could drop to 14 quads by 2010.

BUILDINGS AND APPLIANCES Under conditions of Scenario IV_2, total energy input into the buildings sector is projected to grow from 16.8 quads in 1975 to 20.3 quads in 2010, whereas Scenario II_2 shows a decrease to 9.5 quads in 2010.

INDUSTRY In Scenario IV_2, industrial energy use grows from 36.7 quads (including losses) in 1975 to 88 quads (including losses), whereas Scenario II_2 shows an increase only to 50 quads (including losses).

Several points need to be made regarding the CONAES energy demand analyses. First, the technical efficiency improvements assumed by the Demand/Conservation panel in estimating the possibilities for reduced energy growth are economically rational in terms of the assumed price trends; i.e. the cost savings of energy consumed over the lifetime of each piece of equipment, properly discounted to present value, more than offset the higher first cost of the equipment. However, while such economically rational behavior can reasonably be assumed for the industrial sector, it is less likely in the case of individual consumers, who do not have similar access to capital. Most purchasers of houses or automobiles tend to consider initial purchase price, as reflected in monthly payments, much more seriously than they consider operating cost. In many instances (e.g. automobiles), the lifetime cost of ownership is in fact rather insensitive to fuel efficiency even at very high fuel prices, because initial cost and lifetime fuel cost just offset each other over a wide range of efficiencies. In such cases, higher fuel prices may not be sufficient to promote increased efficiency, and mandated performance requirements, such as fleet-averaged miles-per-gallon standards or purchase taxes based on fuel efficiency, may be necessary to induce purchasers to make economically optimal choices. On the other hand, performance

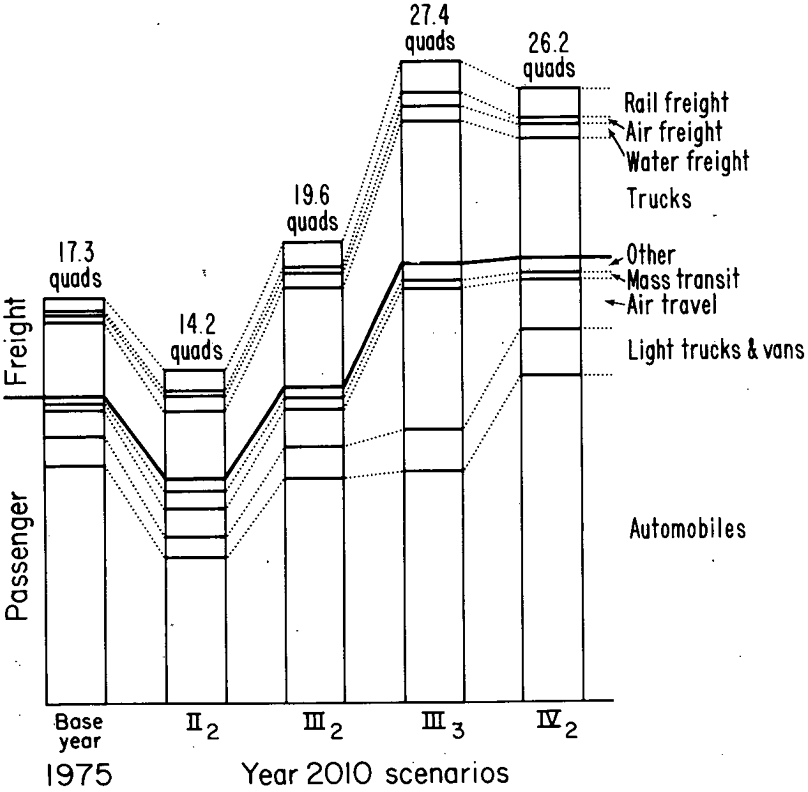

Figure 5 Projections of energy use for transportation by 2010. Quantities are quadrillion Btu (quads). Virtually all the energy used in this sector derives from liquid fuels. From (15), chapter 5.

standards alone may also be insufficient, because reduced operating costs may stimulate increased use, which would offset part or all of the energy savings unless the cost savings are offset by higher prices. These matters are discussed in detail in the Demand/Conservation Panel report.

Our other observation is that the various compilations of energy consumption generated by CONAES represent an oversimplification because they employ as the principal index of rate of energy growth only the equivalent total energy consumption of primary fuels (i.e. aggregate quads). Actually, primary resource demand varies with the *form* of secondary energy actually consumed (e.g. electricity, gas, or petroleum distillates) so that the same point-of-use energy demand can require widely different primary fuel demands. In addition, the social costs of different primary fuels are different, and therefore aggregate quads is not a good measure either of social cost or of demand-supply balance. Saving imported oil, for example, may have much greater social value than saving nuclear-generated electricity (although such a conclusion would be subject to widely different value judgements).

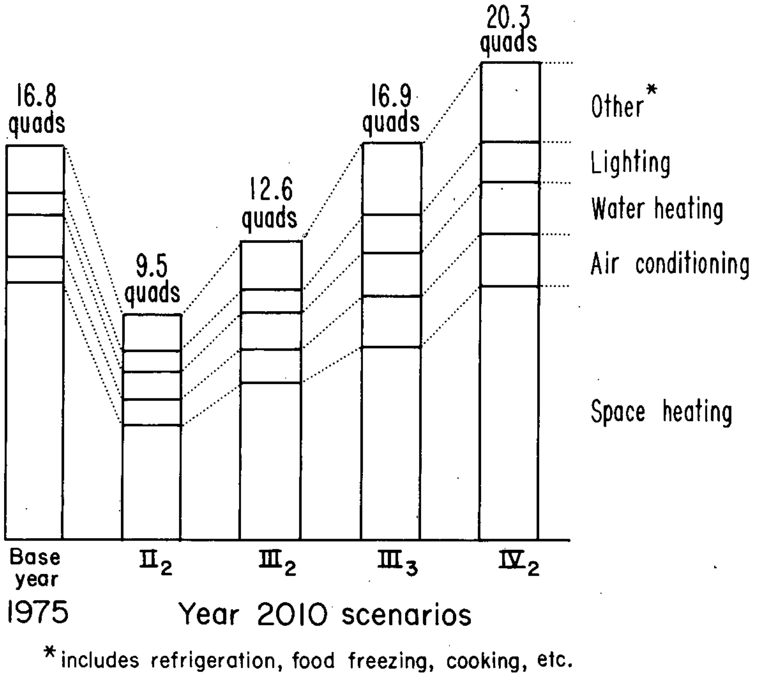

Figure 6 Projection of energy use in buildings in 2010. Quantities are quadrillion Btu (quads). Decentralized energy not included. From (15), chapter 3.

Low-Growth Scenario

Although most of the illustrative cases studied by CONAES were based on technical efficiency improvements alone without assuming significant changes in consumer preferences or living patterns, a few special cases were studied that depend on more drastic reductions in energy consumption resulting from changes in demand for final goods (20). These embody speculative extrapolations from changes in social values that seem to be appearing in today's younger generation, which will constitute the adult population of 2010. The assumptions of these special CONAES scenarios were that most consumers would be less interested in material consumption

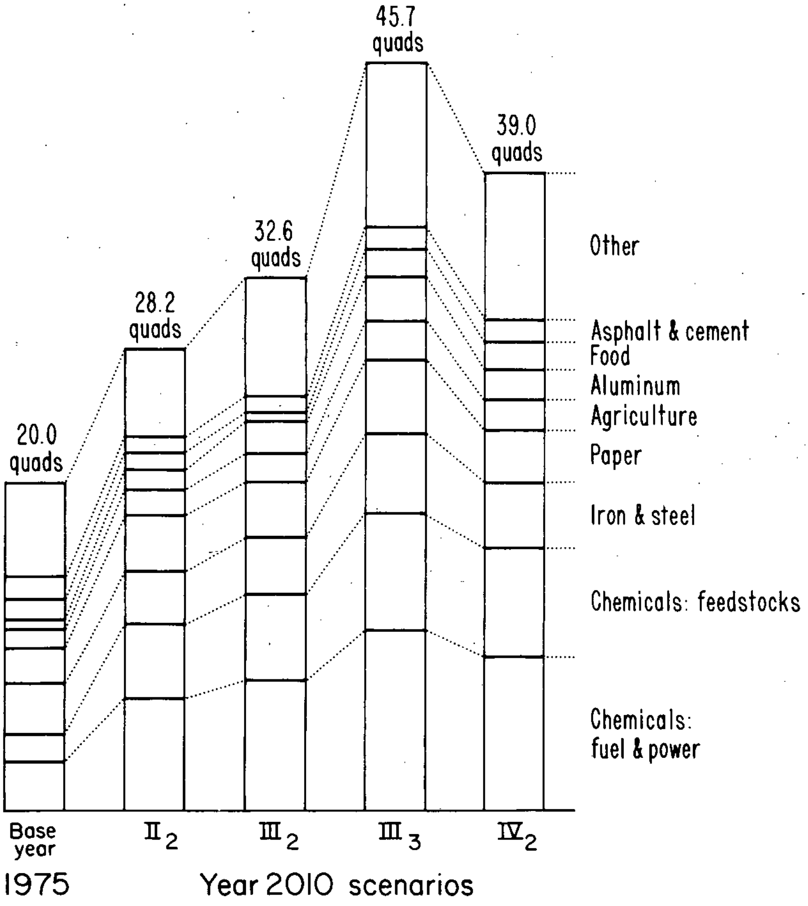

Figure 7 Projection of energy use by energy-consuming industries in 2010. Figures represent delivered energy, not primary inputs. Decentralized energy not included. From (15), chapter 4.

than at present, that goods would be more durable and repairable, and that work and living patterns would be such that less day-to-day travel would be required (e.g. people would live nearer to their work). Under these assumptions, it was possible to project a per capita energy demand about half of today's, while maintaining a quality of life in accordance with the postulated majority expectations. No assumptions were made regarding GNP growth in these scenarios, as this concept has little meaning in this context.

Sociopolitical Aspects of Conservation

One of the political concerns about policies to decrease energy growth has been the possibility of adverse effects on employment. Reducing energy growth will in fact shift employment away from energy production and to

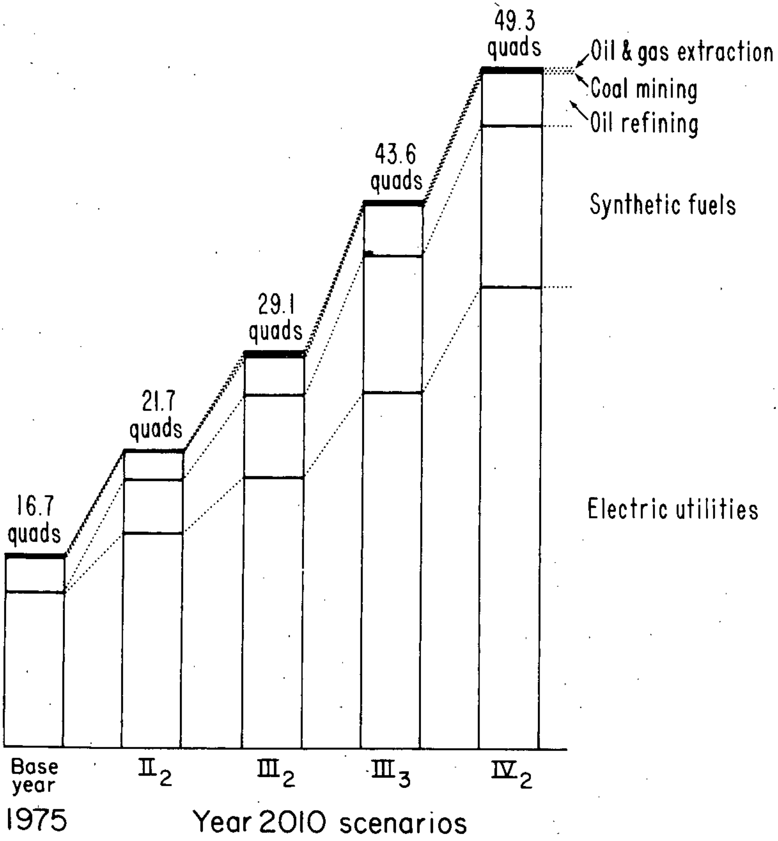

Figure 8 Projection of energy use by energy-producing industries in 2010 (losses). From (15), chapter 4.

some extent away from energy-intensive manufacturing. As shown by the Demand and Conservation Panel, however, the energy-producing sector is highly capital intensive, and several economic analyses suggest that labor and energy consumption are substitutable; i.e. that policies that decrease energy consumption per unit of output tend to increase labor per unit of output (21). Thus capital investments that increase energy efficiency are likely to generate more employment than those that increase energy supply by a similar amount. Moreover, using taxes on energy to increase energy prices and devoting the revenue thus derived to reducing employment taxes, (e.g. social security taxes) is likely to reinforce the substitution of labor for energy (21).

Large energy savings are possible without severe social disruption only if carried out by consistent policies over long periods of time. They depend on the replacement of capital and consumer durables with more energy-efficient equipment as present equipment wears out. Whereas the response of energy demand to changes in economic output is immediate, its response to prices or new standards on equipment occurs with a long time delay, ranging from the 10-year replacement time for automobiles to 50 or more years for most residential and commercial buildings. This is why sudden curtailments in energy supply or changes in price can have drastic economic repercussions, while the same changes phased in gradually and predictably over 30 years or more can have only minor economic impact.

GNP and the Quality of Life

In the absence of a more precise measure, GNP per capita was used as a surrogate for social and individual welfare in most of the CONAES analyses; i.e. it was assumed that societies having the same GNP per capita have the same quality of life. This traditional assumption has been called into question by much recent empirical social science research, which has indicated, for example, that the perceived well-being of individuals is related more to their relative incomes than to their absolute material standard (2, 22). Such evidence as exists indicates that there is little correlation over time or among nations between levels of satisfaction and average per capita GNP, although within a country those with higher income express greater satisfaction with their lot in life.

There is wide disagreement as to what policy consequences should be inferred from the above. Some argue, for example, that any further increases in GNP should be devoted to improving the welfare of the most disadvantaged in the nation and the world, or that basic social services such as health care, education, and environmental improvement should have primary claim on any increments of national output. In the absence of any better agreed measure of welfare, CONAES relied for its analyses on GNP per capita, coupled with qualitative estimates of the social costs in terms of health, the environment, and the quality of social and political interactions associated with the various options.

Summary: Energy Demand

In summary, CONAES reached the following conclusions on energy demand moderation:

1. Very substantial moderation in energy demand growth is realizable over a 20–30 yr period as a result mainly of technicial efficiency improvements in the use of energy without adverse effects on economic growth or employment.
2. Even at present energy prices, there are many opportunities for investments in energy-use efficiency that cost less per unit of energy saved than the investment cost of increasing energy supply by the same amount.
3. The potential for cost-effective energy conserving investment increases with increasing energy prices. Conservation could therefore be stimulated by energy taxes.
4. If the economically optimal response to energy price changes is to be realized in practice, especially by individual consumers and households, it will probably have to be encouraged by mandatory performance standards for durable goods, including housing.
5. A wide range of future growth rates in energy consumption is technically feasible and compatible with continued high economic growth and little change in consumption patterns in the nonenergy sectors. Which path should be followed is primarily a question for political and social choice. Political difficulties tend to increase at both the high and low end of the energy growth possibilities.
6. Sustained and predictable price and regulatory trends are necessary to the realization of any of the projected growth paths without social and economic disruption.
7. Continued research on the economic and distributional consequences of various tax, pricing, and regulatory practices and policies is necessary to improve the basis for energy conservation policy.

DEVELOPING DOMESTIC ENERGY RESOURCES FOR THE INTERMEDIATE TERM

The second major element of the energy strategy cited by CONAES is the prudent development and exploitation of a variety of exhaustible domestic energy resources in addition to oil and gas, to ensure adequate supplies for the near and intermediate term without excessive dependence on imports.

Sensitivity of Supply Policies to Demand Growth

The appropriate energy supply policies, and particularly the speed with which they must be implemented, depend strongly on which of the demand pathways discussed in the previous section is followed. To illustrate the tradeoffs involved, it is useful to look at the supply consequences of these alternative scenarios, ranging from those emphasizing conservation and low demand growth to those that entail heavy concentration on increasing supply. Tables 2–5 give the fuel mixes adopted for the CONAES scenarios, and also the sociopolitical conditions necessary for production of the stated levels, according to the Supply/Delivery Panel (10). Figure 9 illustrates the trends in fuel production represented by the various scenarios. Although the fuel mixes are more hypothetical than the projected demands given by the Demand/Conservation Panel, the scenarios have an overall internal consistency that makes them useful for comparing the different energy futures.

It is convenient to classify the scenarios into four groups:

Low growth: 50–100 quads in 2010; Scenarios I_2, I_3, and II_2.
Low-medium growth: 100–125 quads in 2010; Scenarios II_3 and III_2.

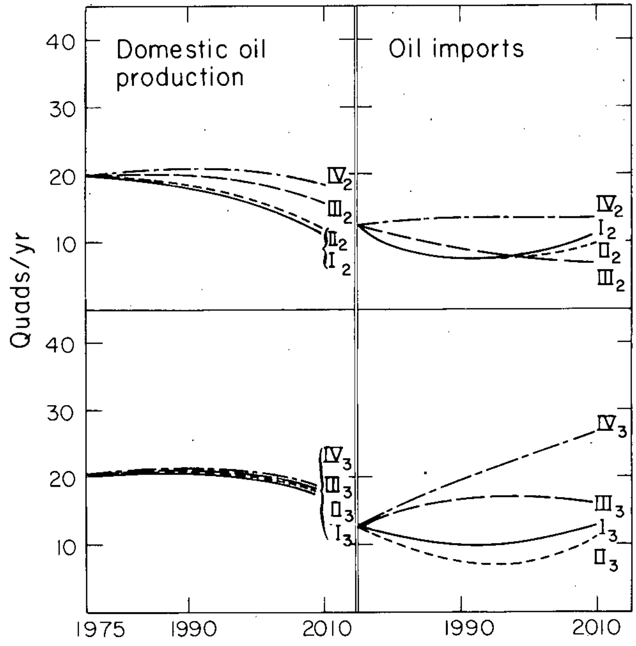

Figure 9 Trends in US fuel production and imports, adopted for the CONAES scenarios.

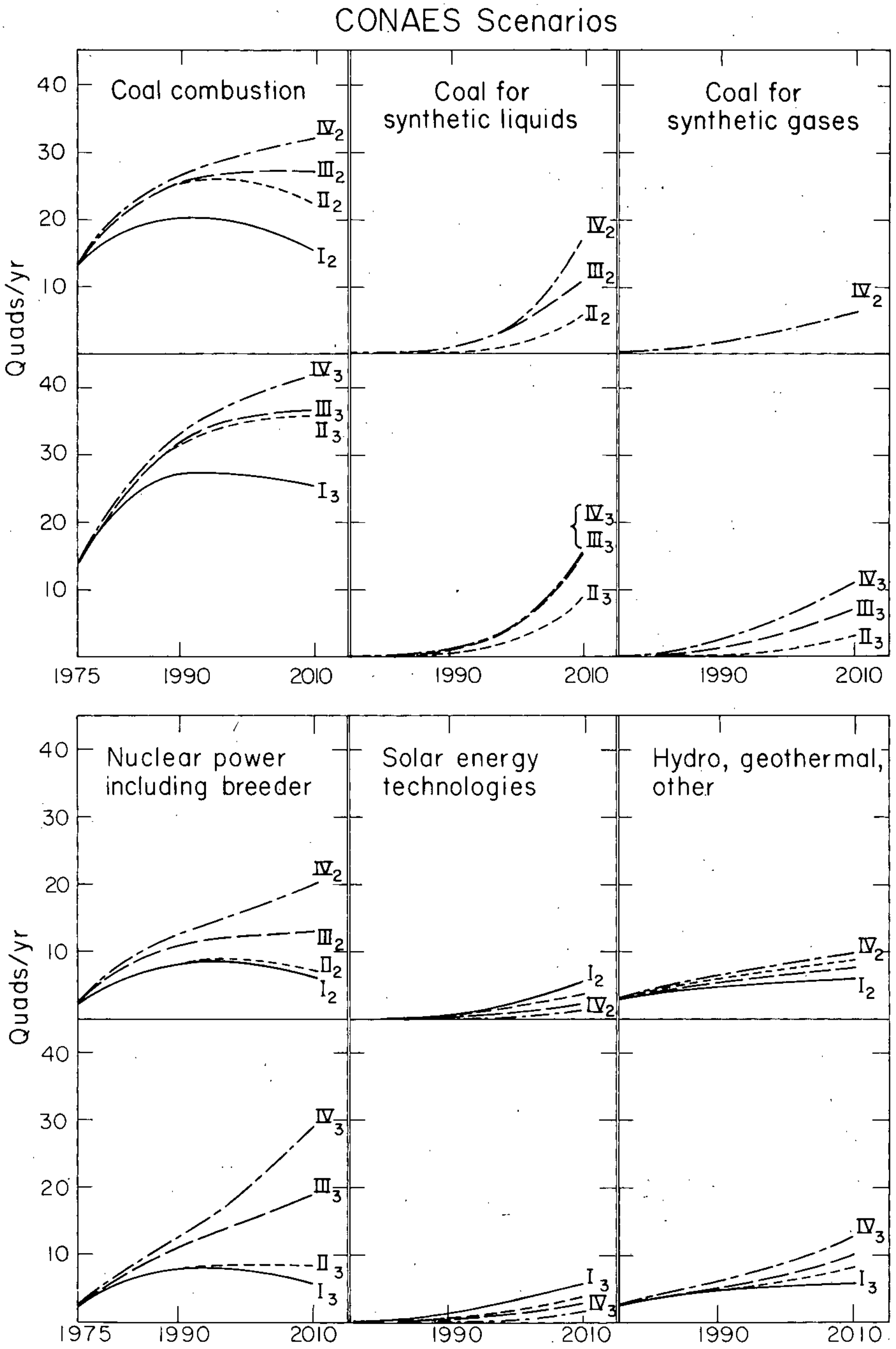

Figure 9 *(Continued)*

Table 2 CONAES Scenario I (fuel mix in quads/year)

Scenario	1975	1990	2010	Required supply conditions[a]
I_2: 2% GNP growth				
Oil				
domestic	20	18	11	PC—ES
imported	13	5	12	—
shale	0	0	0	PC
Gas				
domestic	19	13	8	PC—ES
imported	1	0	0	—
Coal				
combustion	13	20	15	PC
conversion to synthetic liquid	0	0	0	PC
conversion to synthetic gas	0	0	0	PC
Nuclear	2	8	6	PC
Solar	0	1	6	ES
Other (hydro, geothermal, etc)	3	5	6	PC
Total	71	70	64	
Liquid Fuels[b]	33	23	23	
Gaseous Fuels[b]	20	13	8	
Electricity[c]	20	25	17	
I_3: 3% GNP growth				
Oil				
domestic	20	21	18	NC
imported	13	8	13	—
shale	0	0	0	PC
Gas				
domestic	19	14	11	PC—ES
imported	1	1	0	—
Coal				
combustion	13	27	25	PC
conversion to synthetic liquid	0	0	0	PC
conversion to synthetic gas	0	0	0	PC
Nuclear	2	8	6	PC
Solar	0	1	6	ES
Other (hydro, geothermal, etc)	3	5	6	PC
Total	71	85	85	
Liquid Fuels[b]	33	29	31	
Gaseous Fuels[b]	20	15	11	
Electricity[c]	20	31	23	

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[a] Supply conditions: The Supply/Delivery Panel based its estimates of energy source availability on sets of assumptions regarding regulatory policies and public attitudes, which it judged would be more likely to determine availability than cost or price (10). These assumptions are: (*a*) PC, Present Conditions (Business-as-usual)—existing attitudes, policies, and practices are extended into the future with little change, and integrated, effective energy supply policies are not established and implemented. (*b*) ES, Enhanced Supply—a well-balanced, comprehensive set of energy supply policies is enacted and aggressively pursued; decision making and regulatory actions are timely and coordinated, and promising new technologies are appropriately supported. (*c*) NC, National Commitment—the same comprehensive set of energy policies is pursued as in the enhanced supply case, but more aggressively in specific areas. Adequate energy supplies are given the highest priority in allocating national resources, and calculated risks are taken in deploying promising new energy technologies before they are economically practicable.

More details on the application of these assumptions in the Supply Panel's analyses are given in the Panel's report (10).

[b] Includes losses in production and distribution, but not conversion for synthetic fuels derived from coal.

[c] Includes conversion losses.

Table 3 CONAES Scenario II (fuel mix in quads/year)

Scenario	1975	1990	2010	Required supply conditions[a]
II_2: 2% GNP growth				
Oil				
domestic	20	18	11	PC–ES
imported	13	5	10	—
shale	0	0	1	PC–ES
Gas				
domestic	19	13	10	PC–ES
imported	1	0	3	—
Coal				
combustion	13	25	22	PC
conversion to synthetic liquid	0	0	6	PC
conversion to synthetic gas	0	0	0	PC
Nuclear	2	8	7	PC
Solar	0	1	4	ES
Other (hydro, geothermal, etc)	3	6	9	ES
Total	71	76	83	
Liquid Fuels[b]	33	23	26	
Gaseous Fuels[b]	20	13	13	
Electricity[c]	20	31	29	
II_3: 3% GNP growth				
Oil				
domestic	20	21	18	NC
imported	13	7	11	—
shale	0	0	2	ES
Gas				
domestic	19	15	14	ES
imported	1	0	2	—
Coal				
combustion	13	31	35	PC
conversion to synthetic liquid	0	0	9	PC–ES
conversion to synthetic gas		0	3	PC
Nuclear	2	8	8	PC
Solar	0	1	4	ES
Other (hydro, geothermal, etc)	3	6	9	ES
Total	71	89	115	
Liquid Fuels[b]	33	28	37	
Gaseous Fuels[b]	20	15	18	
Electricity[c]	20	36	39	

[a–c] See footnotes to Table 2.

Table 4 CONAES Scenario III (fuel mix in quads/year)

Scenario	1975	1990	2010	Required supply conditions[a]
III$_2$: 2% GNP growth				
Oil				
domestic	20	20	16	ES
imported	13	9	7	—
shale	0	0	1	ES
Gas				
domestic	19	14	14	ES
imported	1	0	2	—
Coal				
combustion	13	24	26	PC
conversion to synthetic liquid	0	1	12	ES
conversion to synthetic gas	0	0	0	PC
Nuclear	2	11	13	ES
Solar	0	1	3	ES
Other (hydro, geothermal, etc)	3	5	8	ES
Total	71	85	102	
Liquid Fuels[b]	33	29	32	
Gaseous Fuels[b]	20	14	16	
Electricity[c]	20	33	37	
III$_3$: 3% GNP growth				
Oil				
domestic	20	21	18	NC
imported	13	16	14	—
shale	0	0	2	ES
Gas				
domestic	19	14	14	ES
imported	1	1	1	—
Coal				
combustion	13	29	34	ES–NC
conversion to synthetic liquid	0	2	19	NC
conversion to synthetic gas	0	1	7	ES
Nuclear	2	11	18	ES
Solar	0	1	3	ES
Other (hydro, geothermal, etc)	3	5	10	ES
Total	71	101	140	
Liquid Fuels[b]	33	38	47	
Gaseous Fuels[b]	20	16	20	
Electricity[c]	20	38	48	

[a–c] See footnotes to Table 2.

Table 5 CONAES Scenario IV (fuel mix in quads/year)

Scenario	1975	1990	2010	Required supply conditions[a]
IV_2: 2% GNP growth				
Oil				
domestic	20	21	18	NC
imported	13	14	14	—
shale	0	0	2	ES
Gas				
domestic	19	16	14	ES
imported	1	0	3	—
Coal				
combustion	13	25	31	ES
conversion to synthetic liquid	0	1	19	NC
conversion to synthetic gas	0	3	7	ES
Nuclear	2	12	20	ES–NC
Solar	0	0	2	PC–ES
Other (hydro, geothermal, etc)	3	7	10	ES
Total	71	99	140	
Liquid Fuels[b]	33	35	47	
Gaseous Fuels[b]	20	18	22	
Electricity[c]	20	39	52	
IV_3: 3% GNP growth				
Oil				
domestic	20	21	18	NC
imported	13	20	27	—
shale	0	0	3	NC
Gas				
domestic	19	18	16	NC
imported	1	0	6	—
Coal				
combustion	13	31	42	NC
conversion to synthetic liquid	0	1	19	NC
conversion to synthetic gas	0	3	12	NC
Nuclear	2	12	30	NC
Solar	0	0	2	PC–ES
Other (hydro, geothermal, etc)	3	7	13	ES
Total	71	113	188	
Liquid Fuels[b]	33	42	61	
Gaseous Fuels[b]	20	20	30	
Electricity[c]	20	45	71	

[a–c] See footnotes to Table 2.

High-medium growth: 125–150 quads in 2010; Scenarios III_3 and IV_2.
High growth: 150–200 quads in 2010; Scenario IV_3.

The lowest-growth futures imply an actual reduction in US per capita energy consumption by 2010. (In Scenario I_2 per capita energy consumption is just under two thirds of today's; in Scenario I_3 it is 80% of today's.) The essential point made by CONAES is that the technical means are available to carry out low-growth energy policies: these include mandatory performance standards requiring greatly increased efficiencies of energy-consuming equipment, and probably substantial government intervention to reduce demand, which includes energy taxes to raise prices to consumers considerably above the levels dictated by production costs.

The lowest-growth futures, exemplified by Scenarios I and II, would have clear environmental and health benefits. They would also provide extended time for resolving the remaining questions surrounding nuclear power, such as waste management and weapons proliferation, and the serious questions of the environmental and health impacts of rapid expansion in the use of coal. The extent to which these benefits would be offset by sociopolitical costs is difficult to estimate and the subject of heated debate. These futures would require energy-conserving actions by millions of individuals and thousands of businesses, as well as a sustained and consistent political consensus on a host of tax, pricing, and regulatory measures, all of which afford myriad opportunities for opposition by particular interest groups or geographical regions.

Although in general the low-growth futures pose the fewest problems of energy supply, liquid fuel supply may be critical even in these cases; note that Scenarios I_3 and II_3 call for "national commitment"[2] conditions for domestic oil production, even with the assumption of "enhanced supply"[2] conditions for synthetic liquid fuels and with oil import levels held approximately constant to 2010. It is far from certain that, under the sociopolitical conditions implied by these cases, a national commitment to oil production could be sustained.

High energy growth is also technically possible, but many difficulties would probably be encountered. The highest-growth energy future considered plausible by CONAES, (Scenario IV_3, with 188 quads annual consumption in 2010) would entail rapid deployment of virtually all available energy supply technologies. This scenario calls for a simultaneous national commitment to: coal production sixfold higher in 2010 than in 1975, rapid deployment of a major synthetic fuels industry, early deployment of the

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[2] See Table 2, footnote a for definition.

breeder reactor, and aggressive exploitation of oil shale. These national commitment supply goals would require substantial shifts of resources from lower priority uses into the energy sector. This would probably entail strong government incentives such as tax concessions or guarantees for energy investment, as well as the expediting of siting and regulatory decisions, as compared with the present emphasis on due process. Such policies would require a political consensus that seems quite at variance with current trends in public opinion. The level of energy prices that would encourage an expansion of demand as rapid as that of Scenario IV_3 would probably be lower than necessary to attract the capital required for the supply investments, so that government would have to subsidize energy technology, in effect, much as policies since the oil embargo have subsidized oil imports from the standpoint of the consumer.

The rate of expansion of coal production could be limited by availability of resources such as labor and water. Also, very rapid development and implementation of advanced pollution abatement and environmental protection technologies would be required to avoid major public health problems (probably adding to the need for additional government subsidy). Commitment to a large nuclear enterprise, including the breeder reactor, would have to be made before difficult issues regarding the nuclear fuel cycle could be fully resolved. The rapid growth of the synthetic fuels and oil shale industries might be damaging ecologically and could severely strain water resources. Large sociopolitical impacts would be caused by the large regional shifts in economic activity. In short, realization of the highest growth scenarios would require a rather abrupt change from the present political climate toward large-scale energy investment and resource exploitation.

The two medium-growth ranges (100–150 quads annual consumption in 2010) presuppose moderately aggressive policies on both the conservation and supply development side. Current conservation policy (present legislation) and 3% average annual GNP growth would carry us to the upper end of the range so far as demand is concerned (assuming the supply is available), but current supply policy would take us near the lower end of the range (assuming no large increase in imports). Thus medium growth would entail policy change on both the conservation and supply sides. With 3% GNP growth, the low end of the range would correspond roughly to Scenario II_3 which entails a fourfold average increase in real energy prices to the consumer between 1975 and 2010. The high end of the range would correspond to real prices in 2010 somewhat more than double 1975 values (15). The medium-growth futures do not imply a significant shift in the mix of consumer final purchases; consumers demand and get the same amenities, although in larger total quantity corresponding to growth of GNP, and with considerably greater efficiency in the use of energy. Of course, this may entail secondary consequences such as crowding, traffic, and environmental deterioration which may degrade "quality of life," in the view of many.

The low-growth scenarios, on the other hand, assume progressively greater changes in social values as one moves down in total energy, so that the consumer market basket is substantially altered as compared with the present and with the middle-range scenarios. A particularly interesting conclusion from the low-growth cases is that it is apparently possible to achieve nearly the same total energy demand either by a change in the mix of goods and services demanded (i.e. life-style change) or by a larger change in the technical efficiency of energy-consuming goods with much less change in the mix of consumer amenities.

The high-growth scenarios of CONAES would have been regarded as quite modest before the 1973 oil embargo. For example, the Ford Energy Policy Project "Historical Growth" scenario corresponds to 250 quads in 2010 and the "Technical Fix" scenario to 150 quads (12). At the time industry critics attacked the higher scenario because it was well below National Petroleum Council projections, and the Technical Fix scenario as severely cramping American lifestyles. When examined in the light of new values and expectations such rates of growth appear quite problematical.

Supply Implications of Declining Growth

Although we have here spoken of GNP growth and energy growth as though they will be uniform between 1975 and 2010, the CONAES analysis indicates that this will probably not be the case. For 2% annual GNP growth, the demand scenarios assume that the rate will drop from an average of 2.5% in 1975–1980 to 1.6% in 2000–2010, while for the 3% average growth rate, the drop is from 4.5% in 1975–1980 to only 1.5% in 2000–2010 (15). The reasons for the expectation of decreasing GNP growth rates are declining population and labor-force growth and declining rates of productivity gain. The latter could be due to increased leisure and also due to a shift in technical progress from labor-saving to energy- and materials-saving technologies. The above "saturation effect" will be even more pronounced for energy growth than for GNP growth. This is because of the extended time required to get energy-efficient technology in place and the fact that prices increase only gradually over the period. Therefore, especially in the low-energy-growth scenarios, the combined effects of the phasing in of conservation technology and the saturation of economic growth causes per capita energy demand to level off or even decline after about

1990. In the lowest-growth cases *total* energy use actually declines after the mid-1990s as conservation takes hold. These effects are visualized most clearly by reference to Figure 3 of this review and to Figures VI, 1–3, of Chapter VII of the Demand/Conservation Panel report. The saturation effects are, of course, much less pronounced for the higher growth cases (for example, Scenario IV, corresponding to constant real prices).

The implications for energy supply are rather striking, especially for electricity. This is illustrated by the values given in Tables 2–5 for total fuel inputs for electricity generation for 1975, 1990, and 2010 for progressively more stringent conservation scenarios. For the highest conservation cases, I_2, I_3, and II_2, electricity generation is actually *less* in 2010 than in 1990. (This is also illustrated in Figure 4). For the higher-growth scenarios III_3 and IV_3, electrical generation continues to grow. In the highest growth case considered (IV_3) an annual average capacity increase of 2.4 quads (about 40 GWe) per year is required between 1975 and 1990, but only 0.75 quads (about 13 GWe) per year have to be added between 1990 and 2010. For comparison, a recent forecast of US electricity capacity growth by the utility industry shows about 30 GWe per year increase between 1975 and 1990 (23). Indeed, the electrical capacity that the United States can have on line in 1990 is already determined by the long lead times of large coal-fired and nuclear generating plants. Further commitments for new generating capacity started today will have little impact on electricity production before the mid-1990s, even if the siting and permit process were to be streamlined.

Because considerable near-term potential exists for substituting electricity for oil and gas, the saturation of electricity growth discussed above is not the only possibility. Electricity has the advantage that it can be provided from almost any primary fuel, and thus adds a good deal of "resilience" to the energy mix. However, even in comparison with synthetic liquids and gases, its capital cost is high. There is thus a complex trade-off between fuel flexibility, which favors electricity, and cost, which favors fluid fuels in applications where they are directly substitutable, as in the case of heating and cooling of buildings and most industrial heat applications. Some utility analysts believe that electricity prices will rise less rapidly than the prices of oil, gas and synthetic fuels, owing to technological progress in the electricity generation sector, and to the fact that such a large fraction of electricity cost is capital charges which are assumed to escalate at the same rate as the general price level. The CONAES Demand/Conservation Panel assumed that electricity prices would rise nearly as fast as other fuel prices. These differences could result in an underestimate of electricity growth in the CONAES scenarios, if the utility assumptions are more nearly correct.

In the case of fluid fuels, a saturation of demand occurs only in the lowest growth scenarios, I_2 and I_3 (see Figure 4). However, even this saturation is offset by the decline in domestic oil and gas production (see Figure 9) and the ceiling assumed to be placed, by our own or producers' choice, on oil imports. Thus there is a strong incentive to bring in synthetic oil and gas production even in the low-growth cases.

Under the assumptions of the "present conditions"[3] supply, domestic production of oil and gas would be likely to decline to one third of current production by 2010 (10). Should this occur, there would be a very strong incentive for a high-electrification path in addition to aggressive deployment of a synthetic fuel industry. This problem is illustrated by Figure 4 and Tables 2–5. In Scenario II_3, for example, the combined fluid fuel requirement in 2010 is 55 quads, while only 21 quads would be available under present conditions supply (see Table 1–3, Chapter 1, Supply/Delivery Panel Report). For Scenario III_3, the fluid fuel requirement would be 67 quads. It seems unlikely that even the most ambitious electric scenario could fill so large a gap.

Dealing with the Liquid Fuel Shortage

A major conclusion from the CONAES demand and supply analyses is that the supply of fluid fuels will be critical in the 1985–2000 period. Oil production from Prudhoe Bay will temporarily relieve the supply situation, but it will begin to decline in the 1980s; without comparable discoveries elsewhere, the domestic supply of oil will decline after 1985 (10). It has already been pointed out that even the low-growth CONAES Scenario I_3, in which liquid fuel use is about constant to 2010, calls for a national commitment to domestic oil production. The scenarios in the 125–150 quad range, which assume about a 50% increase in liquid fuel consumption, call for, in addition, a national commitment to a synthetic fuel industry whose production in 2010 is about equal to present domestic oil production (19 quads). About 2 quads of oil from shale are also called for. There is considerable doubt that synthetic fuel production could come in as rapidly as this, or that the ecological impact of shale oil would be manageable at the assumed production level. In contrast, the scenarios in the 100–125 quad range, which assume only about a 20% increase in liquid fuel consumption by 2010, present less difficulty in regard to synthetic fuels (9–12 quads called for) but still do require a national commitment to domestic oil production.

Next to reducing demand (especially for fluid fuels) and to developing domestic oil and gas and synthetic fuels, the most important move in the intermediate term is to substitute coal and nuclear energy for fluid fuels in applications for which they are reasonably interchangeable—mainly elec-

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[3] See Table 2, footnote a for definition.

tricity generation and the production of industrial process and space heat. As stated, this potential for substitution is important because electricity is quite a flexible mode of fuel substitution. Two principal disadvantages of electricity, compared with alternatives, are, first, that it cannot readily substitute in the transportation sector, which will continue to depend on oil for the next few decades, and second, that the capital investment for electricity is high, so that its substitutability will be strongly dependent on the rate of escalation of capital costs relative to primary fuel costs.

With respect to both the supply and demand for fluid fuels, it is important to keep in mind that announced national targets for demand reduction or for supply enhancement are unlikely to be met precisely. Thus, prudent planning for the future should be based on demand projections somewhat higher than the nation hopes to achieve through conservation programs, and on supply projections somewhat lower than appear to be technically and economically possible within the foreseeable regulatory and political constraints. This is essential in order to leave a safe margin for unexpected developments or shortfalls from goals. Such a margin is necessary because the economic impact of shortfalls in supply tends to be immediate, while adjustment mechanisms operate only with a time lag of a decade or more (24).

Summary: Domestic Supplies

With respect to prudent development of domestic resources for the intermediate term, CONAES concluded:

1. The most critical problem of US energy supply will be that of fluid fuels after 1990. Conservation of fluid fuels is an urgent necessity. Even in the highest conservation scenarios, however, fluid fuel supply could be a serious problem if imports are constrained.
2. It appears likely that the tight supply for fluid fuels could be fully offset by a high-electrification policy only at the cost of very capital-intensive development; therefore, vigorous development of nuclear energy would be at best only a partial solution, although it could provide some insurance against rapid price increases for fossil fuels.
3. In the area of supply, exploration for domestic oil and gas and the development of a viable synthetic fuels industry should have the highest priority.

Technologies for Electricity Generation

COAL VERSUS NUCLEAR In 1977 the primary fuel resources devoted to electric power generation in the United States were 21.6 quads, distributed as follows (25):

Coal	10.0 quads	Nuclear	2.6 quads
Oil	3.7	Hydro	2.2
Gas	3.1	Other	0.04

At present oil is being substituted for gas, and the nuclear fraction is growing rapidly. On the basis of currently committed construction, a 15% average annual addition to nuclear capacity is projected to 1985, with 20% of total capacity [146 GW(e)] in 1985 being nuclear (23). It is likely that a significant shortfall from this trend would result in further dependence on oil for electricity generation, which would exacerbate the expected pressure on liquid fuel supply.

CONAES concluded that coal and nuclear energy are highly complementary as alternatives for central-station electricity generation, and a combination of the two is preferable to an either/or choice. The study therefore recommended that present construction schedules for conventional nuclear plants should be allowed to continue, to minimize growth in oil demand for utilities.

The principal points cited by CONAES in favor of nuclear electricity in its present form (LWRs operated with a once-through fuel cycle without fuel reprocessing) are (26):

1. In most regions, the average cost of nuclear electricity is less than coal-generated electricity, and the difference is likely to continue in the future. (For example, the Commonwealth Edison system, which derives 40% of its electricity from nuclear, estimates that its nuclear electricity costs are 20% lower than coal-generated electricity.)[4]
2. The cost of nuclear energy is less sensitive than coal to future increases of fuel prices and to changes in environmental standards. Because of this, the use of nuclear power could reduce future regional disparities in electric power costs.
3. Nuclear fuel supplies are more readily stockpiled than coal, hence nuclear electricity is less subject to interruption by strikes, bad weather, and transportation disruptions.
4. The environmental and health effects of routine operation of nuclear reactors are substantially less than for coal per unit of electrical power produced.

[4] G. Corey, testimony to Environment, Energy, and Natural Resources Subcommittee, Committee on Government Operations, US House of Representatives. September 19, 1977; also answers to questions submitted by Congressmen to T. N. Kindress and Leo Ryan, September 26, 1977; Prepared Testimony and Exhibits submitted by L. J. Perl, National Economic Research Associates, September 14, 1977; L. J. Perl, *Estimated Costs of Coal and Nuclear Generation,* unpublished memorandum, December 12, 1978.

5. If the CO_2 problem becomes a major global environmental issue in the early years of the 21st century, it will be aggravated by utility commitments to the use of coal, because power plants have lives of 30–40 years.

The principal points cited by CONAES in favor of coal are:

1. Coal power plants and the coal fuel cycle are not subject to low-probability, high-consequence accidents or sabotage, which are inherently uncertain and unpredictable. The hazards of coal can be made relatively predictable, given sufficient research on such matters as the health effects of coal-derived air pollutants. (This research will take perhaps 15–20 years to complete, however).
2. Coal burning in utilities has no major foreign policy implications, as does nuclear power via the problems of proliferation and safeguards. The outlook for political acceptance of coal may thus be somewhat more favorable than for nuclear energy.
3. Coal is better adapted to generation of intermediate load power, and in this sense is complementary to base-load nuclear plants. In addition, the lead time for planning coal-burning power plants is less than that for nuclear plants.
4. Coal-generated electricity has a much larger resource base than LWR nuclear reactors operated on a once-through fuel cycle (26), which will be important if fuel reprocessing and the development of more resource-efficient reactor systems and fuel cycles are further delayed.
5. In the absence of a demonstrated, licensable plan for waste management, the nuclear fuel cycle may be considered an incompletely proven technology, which is therefore subject to greater uncertainties as to whether its continued growth will be permitted. To the degree that this is so, nuclear energy runs a greater risk than coal of future capacity shortfalls due to unexpected technical developments.

The problems attendant on expanded use of coal depend strongly on the rate of that expansion. According to the CONAES Risk/Impact Panel, if the production and consumption of coal rises to levels more than about three times today's, risks to human health and ecosystems are likely to become serious (27). Although increased coal use is called for in all the CONAES scenarios, the following distinctions can be noted: in the lower-medium-growth cases (100–125 quads) a twofold to threefold expansion of coal use takes place by 2010, which would approach the threshold of significant problems. In the upper (125–150 quads) a fourfold to fivefold expansion takes place, which would exceed the level at which the Risk/Impact Panel judges these impacts to be significant. In the highest-growth futures (150–200 quads) the greater than fivefold increase over present coal utilization could present serious problems in environmental protection whose manageability is very controversial and difficult to assess with confidence in the present state of knowledge.

Both in the context of present coal use and future increases in coal use, as illustrated by the scenarios, it is vital to resolve the uncertainties presently surrounding the health impacts of coal emissions, especially the problem of sulfates. From an environmental standpoint, it is *ambient* air quality that is significant, and future emissions standards must take into account increases in the volume of coal use, its geographical distribution, and its additive effects with other pollutants. In the very-high-coal scenarios, even current new source performance standards could prove inadequate to protect health and the environment, especially in heavily populated regions.

In the case of nuclear power, uncertainty about how to safeguard the fuel cycle from illicit uses of nuclear materials is the most important issue cited by CONAES, and development of a national plan for waste management is a close second in priority. Neither can be definitely settled on the basis of present knowledge.

DIVERSITY IN THE ELECTRICITY SYSTEM The study recommends a goal of maximum diversity and experimentation in the development of the US energy supply system, both to increase its resilience and to gain experience with some of the regulatory and policy changes that may be necessary later when it becomes feasible to consider phasing renewable sources into utility networks. With this objective, other energy sources should be developed even though they cannot be expected to make major contributions until after 2000. In this period solar energy appears to be of interest mainly as a source of relatively low-temperature heat for space and hot water heating and for industrial process heat. (28). Generating electricity by burning municipal wastes, which is now practiced to a limited extent, could contribute as much as 5 quads as a primary source of fuel for electricity by the year 2000, and should be used wherever it is economical. The potential for wind-generated electricity is more limited, but again development of a viable industry should be encouraged, and regulatory policies that discourage interconnection of self-generated electric systems with utility grids should be removed where a good economic rationale can be developed for doing so (28).

Electricity generated from geothermal sources will have important local applications. It should be developed in areas where it appears economically attractive; licensing roadblocks in particular should be removed (29).

ADVANCED POWER CYCLES Two other technologies can make significant contributions to US electricity generation in the intermediate term. High overall coal-to-electricity thermal efficiencies in the conversion of coal to electricity are possible by use of *advanced power cycles.* These use direct combustion of coal in fluidized beds or medium Btu gas with on-site gasification of coal for combined generating cycles with high-temperature gas turbines in tandem with steam turbines (30). These cycles, which are especially suitable for peaking loads in relatively small plants, should be available within a decade.

COGENERATION Another opportunity for improving efficiency in the use of fossil fuels is *cogeneration* of electricity and process heat in industrial installations. In mandating conversion of industrial plants from gas or oil to coal, consideration should be given to permitting cogeneration with oil or gas as an alternative to coal conversion, in cases where favorable economics and net overall savings in oil or gas consumption can be demonstrated. A detailed discussion of the theoretical fuel savings obtainable from widespread adoption of cogeneration is given by the CONAES Demand/Conservation Panel (31). In practice there is a tradeoff between high thermodynamic efficiency and fuel availability, since cogeneration requires high-quality fuels. Complex regulatory, institutional, and practical barriers also limit the fraction of theoretical potential that is likely to be realized in practice from cogeneration. CONAES concluded that a savings of 3–4 quads in total industrial energy demand might be realized in 2010, although three to four times this is theoretically possible. This is an important area for further study.

NUCLEAR ENERGY IN TRANSITION

As an intermediate-term energy source, nuclear energy presents a special case. Unlike the situation with other nonrenewable resources, the effective size of the resource base for nuclear power is highly dependent on what form of nuclear fuel cycle is actually used. The present generation of light water nuclear reactors (LWRs) and their once-through fuel cycles utilize nuclear fuel very inefficiently, and are likely to exhaust the domestic supply of high-grade uranium in several decades. By contrast, if breeder reactors were to be developed and used, the domestic nuclear fuel supply could last for hundreds of thousands of years. An intermediate class of reactors and fuel cycles called advanced converters could under certain assumptions extend the domestic nuclear fuel supply for perhaps a century. Therefore, the future of nuclear energy in the United States will be determined by the timing and nature of follow-on developments and deployments to the present generation of LWRs. The principal issues are:

1. The extent of US and world uranium resources and the rate at which they can be produced at various costs. Both the future role of nuclear

energy in general and the relative roles of different nuclear options are critically dependent on evaluation of these resources.
2. The need for and pace of development and deployment of alternative advanced reactor types and fuel cycles, including breeder reactors, that offer more efficient use of fissionable fuel than present LWRs.
3. The rate of growth of electricity use. The higher the growth rate, the sooner the contribution of LWRs will become restricted because of shortages of low-cost uranium.
4. Public appraisal of nuclear power. Among the most important public concerns are the potential link of commercial nuclear power with international proliferation of nuclear weapons, and the uncertainty over the safety of the nuclear fuel cycle.
5. Need for early implementation of a workable nuclear waste management program. Adequate technical solutions can probably be found, but implementation of a specific strategy will require the solution of difficult political and institutional problems.

Uranium Resource

The availability of uranium will be a critical factor in determining both the maximum electrical capacity that can be provided by LWRs between now and 2010 and the timing for introduction of advanced reactors.

The Uranium Resource Group (URG) of the CONAES Supply/Delivery Panel concluded that only a modest domestic base of reserves and probable resources—a total of 1.8 million tons of uranium oxide—is sufficiently well established to serve as a prudent base for planning (32). However, considerable uncertainty surrounds the ultimate amount of low-cost uranium ore available. The Ford-Mitre nuclear study based its analyses on an estimated uranium availability of at least 3.6 million tons (33). A similar resource base is estimated by Harris (34).

Since a 1 GW(e) light-water reactor with once-through fueling requires about 5600 tons of fuel for a 30-year useful life, only about 320 such reactors could be built before 1.8 million tons of ore would be completely committed. Thus, the CONAES supply analysis indicates that the ultimate utility of the LWR in the United States may be limited to about 320 GW(e) of installed capacity for about 30 yr, unless a follow-on reactor is available that uses uranium more efficiently than the LWR. This capacity is less than twice that which would be provided by the reactors already on line, under construction, or now planned [variously estimated as 170–210 GW(e)].

These limits could be extended somewhat without fuel reprocessing by feasible improvements in LWR design (up to 15% improvement in U_3O_8 consumption) and by lowering the U-235 concentration in enrichment tails through the introduction of advanced isotope separation methods. However, the additional reactor capacity in 2000 that could be supported as a result of these measures would depend sensitively on how soon they could be introduced. The most optimistic estimate would probably not exceed 450 GW(e), which could not sustain scenario IV_3 and would be marginal for scenario IV_2.

Alternative Fuel Cycles

The present-generation LWRs operating with a once-through fuel cycle utilize only 0.6% of the energy potential in uranium as mined. By contrast, breeder reactors, which are capable of converting the abundant isotope U-238 to plutonium and of regenerating more plutonium than they use up in the process, can eventually make use of more than 70% of the energy potential of uranium ore. There are also so-called thermal breeders capable of converting Th-232 to another fissionable isotope of uranium, U-233, and in this way eventually making use of nearly 70% of the energy locked up in thorium, which is believed to be four times as abundant as uranium in the earth's crust. Thus, the ability to unlock the energy potential in the so-called "fertile" isotopes U-238 and Th-232 has a tremendous multiplying effect on available resources, much more than the factor of 100 implied by the numbers just quoted. This is so because the use of breeder reactors reduces the impact of resource prices on the price of electricity by a factor of 100, thus making available for economic use additional uranium and thorium ores much too low-grade to be used as a fuel source for conventional reactors. In fact, for practical purposes, the resource costs for either fast (Pu) or thermal (U-233) breeders make a negligible contribution to the cost of electricity. In effect, the economics of breeding are closer to those of renewable resources than to nonrenewable resources.

Because of their inefficient use of uranium resources the present generation of LWRs can be relied upon as an energy source only until the early 21st century. However, the resource base for LWRs could be extended by 35–40% by recycling spent fuel through a chemical separation process to recover fissile plutonium and uranium which would be refabricated into fuel elements and reloaded into the reactors. A problem with fuel recycle is that in this process plutonium becomes available in a form that can be converted into nuclear weapons much more readily than would be the case were the spent fuel elements merely removed from the reactor and stored. This is what gives rise to the serious concern over proliferation and diversion associated with the nuclear fuel cycle. Unfortunately, to realize the resource-conserving potential of all advanced reactors, including breeder reactors, also requires reprocessing and refabrication of fuel and thus presents the same risk of proliferation or theft of weapons-usable material.

With a once-through fuel cycle, the resource base could also be extended by about 40% through the use of the Canadian CANDU heavy water reactor loaded with slightly enriched uranium. In this configuration it utilizes about 1.0% of the uranium rather than only 0.6% as in LWRs. Although this might be worthwhile under some circumstances, it would still not be sufficient to preserve the option of supplying electricity by nuclear power much beyond 2000 unless the rate of growth of electric power were to diminish greatly after that date. A further extension of uranium resources by as much as 20% could be achieved if it proved feasible to strip uranium tails through laser isotope separation.

In brief, if the pessimistic estimates by the CONAES Uranium Resources Group of likely availability of high-grade uranium ores prove to be correct, advanced reactors and fuel cycles that utilize nuclear fuel more efficiently than the LWR will probably be needed for deployment in the United States by the first decade of the next century. Otherwise nuclear fission will have to be phased out slowly beginning at about that time. This will occur at a time when the demand for coal for synthetic fuels will be increasing rapidly in order to offset the decline in domestic oil and gas production, and when the problem of climatic change due to CO_2 production may first be becoming apparent. Thus, unless solar energy can be deployed very rapidly by that time, the phasing out of nuclear energy due to a shortage of high grade uranium may come at a peculiarly awkward time.

Electricity Demand

A prime factor affecting the need for and strategy for development of nuclear power is the rate of growth of electricity use. The relationship of nuclear power to electricity growth rates is illustrated by several of the CONAES scenarios. The pertinent quantities are reproduced in Table 6 (35). Scenario II_3, representing a low-medium-growth future with total energy use of 115 quads in 2010, employs a modest contribution of nuclear power, roughly equivalent to the number of reactors either already on line

Table 6 Energy used to produce electricity (in quads)

			2010		
			CONAES Scenario[a]		
	1975	1977	II_3	III_3	IV_3
Nuclear	2	2.6	8 (160)	18 (360)	30 (600)
Coal	9	10.1	23 (460)	20 (400)	29 (580)
Other	9	9.0	8 (160)	11 (220)	9 (180)
Total electricity	20	21.7	39 (780)	49 (980)	68 (1,360)
Total primary energy use	71	75	115	140	188

[a] Figures in parentheses are installed generating capacity in gigawatts. An approximate conversion factor of 20 GW/quad is used for 2010; this makes allowance for a reserve capacity of about 18%. The 1977 figures are from actual data.

or under construction. Coal-generated electricity reaches about double the 1977 level. If nuclear power were not available in 2010 and the gap filled entirely by coal, 31 quads of coal-generated electricity would be required —about three times the 1977 level. The lower level is certainly achievable; the higher one may be, but when other demands for coal are considered, it may be at the threshold of serious environmental and water-supply problems.

Scenario III_3 represents a high-medium-growth future with total energy use of 140 quads in 2010. In this scenario, nuclear power capacity is 360 GW(e), which is probably achievable only with the improvements in reactor design and isotope separation mentioned previously, using LWRs with once-through fuel cycle. Furthermore, such improvements would have to be deployable by the 1990s. Coal-generated electricity is at twice the 1977 level.

For the high-growth case represented by scenario IV_3 with total energy use of 188 quads in 2010, total electrical capacity is about three times today's. In this scenario, even with about 600 GW(e) of nuclear capacity, a threefold expansion of coal-fired capacity is required by 2010. If coal use (for electricity) were to be restricted to, say, twice the 1977 level in 2010, almost 800 GW(e) of nuclear capacity would be required. Realization of these levels would call for an extraordinary national commitment to nuclear and coal electricity supply, with attendant economic and political difficulties.

These examples illustrate some of the problems of high electricity growth rates, including the limited substitutability of nuclear energy and coal in the high-growth scenarios, and suggest that, if electricity demand growth is underestimated, a number of energy crises may begin to appear simultaneously during the first decade of the 21st century.

Advanced Converters and Breeders

Until recently this country concentrated its advanced nuclear R&D program on the liquid metal fast breeder reactor (LMFBR) and the associated plutonium U-238 fuel cycle. The main advantage of this approach as a resource extender is that it offers the greatest degree of independence from continuing inputs of natural uranium. For upwards of 200 years the LMFBR could utilize as fertile material the "tails" rejected in the enrichment process for weapons and reactors and now kept in storage.

Breeder reactors produce not only enough fuel for their own needs, but also for other reactors. Breeders could extend the life of the uranium resource indefinitely, for practical purposes, and they could be fueled initially with plutonium separated from spent LWR fuel as well as with natural uranium. Thus, the breeders offer true "energy independence" so far as electricity generation is concerned, not only to the United States but to other nations as well, as long as they have access to a small quantity of enrichment tails (to which they are now legally entitled if they have LWRs fueled with US-enriched fuel, but which are now virtually worthless unless they are used in a breeder reactor or can be stripped by laser-isotope separation or other advanced enrichment process.) Because the LMFBR generates almost 20% more fissile isotopes than it consumes, it can be used as the basis for a growing nuclear capacity without requiring the mining of new ore. For this reason, the LMFBR appears attractive over a wide variety of future scenarios of electrical capacity growth.

There is actually no sharp distinction between breeder reactors such as the LMFBR and converter reactors such as the LWR and CANDU. Once reprocessing and reloading of reprocessed fuel into reactors are permitted, a whole variety of possibilities exist. By definition, breeders generate more fissile fuel than they consume in this operation; converters generate less fissile fuel than they consume. Reactors that generate nearly as much fuel as they consume are generally referred to as advanced converters.

The principal nuclear alternative to the fast breeder is to develop and deploy advanced converter reactors. The choice between breeders and advanced converters involves the weighing of a very complex series of considerations ranging from the growth of electric power demand after 2000, to the possibility of developing a more proliferation-resistant fuel cycle for advanced converters based on Th and U233 or Pu and U238. These issues are discussed in detail by CONAES (26). In brief, the study concluded that if the expansion of nuclear capacity after 2000 is slow enough (i.e. less than 1% per year after 2000), advanced converters could in fact be used in place of breeders and still provide a slowly growing nuclear capacity for around a century. The considerations favoring the development of advanced converters as an alternative to breeders would have most weight under three additional circumstances:

1. the capital costs of a commercial LMFBR turn out to be much higher than the capital costs of advanced converters, measured on a comparable basis;
2. the advanced converter can be used with a "denatured" thorium fuel cycle, (i.e. with U235 or U233 diluted with U238) which would provide a more diversion- and proliferation-resistant fuel cycle than would be possible with plutonium recycle in a breeder;
3. a large uranium ore resource is found of grade intermediate between currently mined ores (about 0.2% uranium content) and the very dilute but abundant ores such as the Chattanooga shales (about 0.005% uranium).

The CONAES study did not produce a consensus view as to whether these potential circumstances are likely enough to make worthwhile the development of an advanced converter as a "hedge" against difficulties and delays with the LMFBR, especially if this were to happen at the expense of the breeder program. The view favoring development of advanced converters argues that the present LMFBR program has been grossly overoptimistic in its cost and performance targets, that the potentially superior diversion resistance of the denatured thorium cycle would be fully worth the converter's lower resource efficiency compared with a breeder, and that licensability of advanced converters should be at least as favorable as that of LMFBRs. This view holds that advanced converters have especially important potential value as a complement to LMFBRs in the event that the decision were made, for proliferation reasons, to restrict LMFBRs and plutonium fuel recycling and refabrication to a small number of secure sites under international auspices. LMFBRs could then be used to breed U233 for use in national converter reactors burning only denatured U233. A given amount of LMFBR capacity could support much more advanced converter capacity than LWR capacity in this way.

The view that favors concentration of effort on the LMFBR breeder holds that advanced converters offer advantages only under very special assumptions and that the effort required to develop a licensable advanced converter design and associated thorium fuel cycle in the United States makes it improbable that an advanced converter design could be deployed sooner than an LMFBR. Probably the most serious problem with advanced converters, however, is that they would be most useful from a resource standpoint in circumstances where the economic incentives to utilities and suppliers to develop an entirely new line of reactors are least, that is, when the total market for new reactor capacity in the United States after 1990 is well under 10 GW(e) per year. If projected electrical capacity growth were to be sufficient to provide market incentives, available uranium resources would most likely have been committed before converters could be deployed to a significant extent, thus precluding substantial resource savings.

CONAES did reach general agreement that the LMFBR dominates the nuclear alternatives in the widest range of assumed circumstances, provided that its cost goals and other technical objectives can be realized. On the other hand, those who believe that low electric power growth after 1990 is readily achievable argue that the LMFBR increases the danger of proliferation and would only be needed in case of a rate of electricity growth that is unnecessary or readily avoidable through feasible conservation policies. In this view, the advanced converter provides sufficiently improved resource efficiency over present generation LWRs to fill the gap until truly benign long-term technologies such as solar energy become available. These arguments again underscore the importance of energy demand considerations in planning the future US energy supply system.

Nuclear Weapons Proliferation and Timing of Breeder Development

Two interrelated issues concerning the breeder reactor are the scale and pace of the near-term development program and the relationship of breeder deployment to the problem of nuclear weapons proliferation. Sharply different views are cited by CONAES (26). One holds that plutonium reprocessing and the "plutonium economy" would be a major step toward proliferation, and advocates that the United States forego for a considerable period the benefits of reprocessing and the breeder in order to demonstrate how seriously this nation regards the proliferation problem. This view acknowledges that proliferation can only be delayed, not prevented, but asserts that the deferral of reprocessing and of the breeder could provide critical time needed to develop the international institutions and procedures necessary to safeguard the nuclear fuel cycle. Thus, the LMFBR would be treated primarily as a long-term technology of last resort, to be deployed only if research in the coming decades indicates that other long-term options are much more costly or will not be available in time to offset the phasing out of LWR capacity.

The contrary view holds that the breeder has already been demonstrated to be the most promising option for the long-term future, with favorable economics and minimal ecological impact, and therefore a US commitment to large-scale development should be made now so that LMFBRs could be deployed before the 21st century. In the matter of proliferation, it is argued that the commercial nuclear fuel cycle is the least likely and most expensive of several possible paths to proliferation, and that inexpensive means for producing weapons-grade material by isotope separation are likely to be widely available by the time commercial reprocessing of plutonium becomes widely practiced. The counter-claim is that while there are other routes to proliferation, these require more deliberate political decisions, whereas a weapons capability could be "backed into" rather rapidly once commercial reprocessing and refabrication facilities had been deployed in a given country. Thus the critical consideration is not the availability of cheaper and less elaborate routes to weapons capability, which certainly exist, but the reduced "warning time" between a political decision to divert from the commercial fuel cycle and the production of the first weapons. In addition, the circulation of separated plutonium in commerce provides a temptation to terrorists and dissident groups.

The "full speed ahead" view holds that deferral of reprocessing and the breeder may actually enhance the risk of proliferation because it increases the potential claims of the United States on the world petroleum market and on the limited world uranium supply for its LWRs. This will in turn stimulate other countries, which are much more dependent than the United

States on outside energy sources, to pursue the breeder reactor—the one nearly available option that promises a degree of energy independence because of its extremely tiny resource requirements.

Public Appraisal of Nuclear Power

In the United States and worldwide, nuclear power is controversial, with environmental groups, opposed to nuclear power, vying with pronuclear industrial and professional groups to win public support. The scientific community is itself divided. Public appraisal of nuclear power is difficult to analyze: technical, political, and social issues flow together.

CONAES attempted to separate principal public concerns into those that are primarily technical, institutional, and social (26). Technical issues are:

1. the effectiveness of technical means to prevent or hinder diversion of weapons-usable material from the fuel cycle;
2. the safety of nuclear reactors, which includes protection against sabotage;
3. the long-term management of nuclear wastes; and
4. the release of long-lived radioactive effluents from the nuclear fuel cycle.

Other concerns stem from public distrust of institutions responsible for the management of nuclear energy programs in the past. Primarily institutional issues are:

1. whether human institutions can be relied on to provide long-term management of radioactive wastes, reactor safety, and secured weapons-usable material; and
2. whether international institutions can be created and maintained to guard effectively against the proliferation of nuclear weapons.

Other aspects of the public appraisal of nuclear power are principally social, reflecting differing perceptions of a desirable future society. Some examples:

1. Nuclear power has become the most visible symbol of large-scale centralized technology for which many citizens feel they have surrendered control to experts who cannot be held accountable.
2. A significant number in the public dislike nuclear power, particularly the breeder, because it promotes the continuation of a high-growth materialistic society that, in their view, will eventually prove disastrous to the physical and social environment of mankind.
3. Some see nuclear power as competing for capital resources with other energy systems that are more nearly autonomous and under local control and therefore, that both in itself and as a symbol, it excludes social organizational patterns that are based on such autonomy (20).

4. Others see nuclear power as essential if people are to have sufficient energy to live with dignity, achieve their aspirations and improve their own lives and those of their children (36).
5. Many people feel that institutions, including utilities, government, and regulatory bodies, exist to provide services to citizens; that they can and should be economical (whether large or small) and that technologies, including nuclear, can and should be controlled to serve man in a safe, environmentally acceptable way.

A significant observation made by CONAES is that even in controversies with mainly technical content, judgments are influenced by the social and institutional preferences of the judges. To some extent, therefore, such technical questions have to be resolved, as do social and institutional questions, by the political process.

Management of Radioactive Wastes

Wastes from nuclear power plants contain a variety of radioactive products with half lives from tens of years to hundreds of thousands of years. These wastes must be sequestered from the biosphere for as long as their radiation represents a hazard to people. Public concern with the management of radioactive waste centers on society's ability to obtain and maintain the necessary isolation. CONAES considered both the technical and societal aspects of this problem (26).

The current strategy for management of nuclear wastes involves geological isolation, i.e. underground burial of the wastes. The technical part of the problem has two parts: first, to package and isolate the wastes physically and chemically as well as possible, and, second, to secure a geological environment that would itself contain the radioactivity in the event of failure of containers after one or two hundred years, in the sense that migration of the waste nuclides in groundwater would be slow enough, or accompanied by so much dilution, that the radioactivity of the water when it reaches the biosphere would be a small fraction of natural background radioactivity.

The social and institutional aspects of the problem relate to questions such as: how safe is safe enough; how can solutions to a very long-term problem be demonstrated in the short term; and, how should equity issues be settled when the potential risks and the benefits of particular solutions are unevenly distributed in the population.

There is no lack of possible methods of disposal of radioactive waste, but there is lack of an adequate data base to allow a choice among these solutions and to prove that a given choice of sites and waste forms poses the lowest risk to the public relative to the cost of disposal. Much of the information that needs to be developed is site-specific, and relates to the geology and hydrology of the chosen site as well as to the characteristics of the particular waste form. For storage times of more than a century or two, geology and hydrology must be considered to be much more important than waste form or packaging, since almost any waste form may have interacted extensively with its immediate geological environment within that period.

Two other points should be kept in mind regarding nuclear wastes: first, it is not necessary to look upon waste disposal as a problem to which the perfect solution must be found before any action can be taken. The waste problem should be approached in an evolutionary fashion. It dictates caution in the rate of expansion of nuclear power, but should not be a bar to the continued use of nuclear power.

Second, the risk associated with inadequate waste disposal is not of the same character or magnitude as that associated with reactor accidents. With the knowledge already in hand, the hazards involved can almost certainly be kept less than those associated with routine exposures to radioactivity in nuclear operations, which are themselves very small. What dictates special caution and concern about nuclear waste disposal is the fact that the potential risks extend so far into the future, not the absolute magnitude of the risks in comparison with other contemporary risks. The major potential risks associated with waste management extend for a thousand years, and in addition the presence of actinide elements in the wastes is the source of a very small continuing risk running to millions of years. In this respect, however, nuclear waste disposal is not entirely unique; for example, elevated CO_2 concentration in the atmosphere, once established, will persist for many hundreds of years, and over this extended period could result in gradual melting of the Greenland and Antarctic ice sheets and the flooding of coastal settlements.

The following specific conclusions and recommendations represent the consensus view of CONAES:

1. There appears to be no reason to believe that a technical solution to the nuclear waste management problem cannot be found that reduces risk to a level small compared with that posed by other parts of the nuclear fuel cycle and other energy sources. On this point CONAES is in agreement with the recent American Physical Society study (37).

2. The maximum potential risks of geological disposal of nuclear waste are those of chronic, low-level radiation insults and are not comparable with the maximum possible risk from catastrophic nuclear accidents. This difference is not sufficiently appreciated by the public at the present time, and needs to be better explained.

3. A much greater effort should be mounted to involve the public in the discussion of waste management issues and in the site selection process; this may increase the difficulties of dealing with the problem in its early phases,

but should improve public acceptability of solutions in the long run. The present public apprehension about the nuclear waste management problem is the result mainly of the low priority given to this issue by government authorities and the nuclear industry in the past, and to a gross failure to deal with the problem of military wastes.

4. The federal government should proceed immediately to set criteria for geological waste disposal. These should be performance criteria (e.g. leach rates, heat rates) on waste forms that recognize the risks from different types of wastes, and site-specific criteria (e.g. ground-water standards, seismic stability, and resource and mining restrictions).

5. The federal government should accept full responsibility for all existing waste, and leave the question of joint state-federal responsibility to be resolved with regard to wastes generated in the future. However, charges by the government to utilities for the management of radioactive wastes should be sufficient to recover full costs.

6. Standards should be set and enforced for the treatment of abandoned uranium mines and of tailings from mines and mills. These standards should permit disposal of low-level alpha-active wastes in tailings piles. This will require collaborative effort between the federal government and the uranium mining states.

7. Several lines of development of waste management schemes should be pursued simultaneously, and these should rest on a solid foundation of basic geological and geochemical research.

8. Future treatment of the waste management problem should take much greater advantage of the scientific and engineering community outside government, and of foreign experience and ideas, than has been the case in the past. Ultimately waste management is an international problem and should be managed on an international basis, subject to international agreement and institutions.

9. The problem of waste disposal should be separated from the problem of spent fuel storage. Unreprocessed spent fuel should not be considered as waste, but as a potential source of fuel in the future.

10. Retrievability of waste forms after emplacement would be a desirable feature of a repository, if it could be designed without adding in a major way to the cost. However, retrievability ought not to be an overriding consideration in designing a repository for actual waste disposal.

Summary of the CONAES Position on Nuclear Energy

1. It would be imprudent either to abandon the nuclear option or to promote it at present as the keystone of a future US energy policy.
2. Until the risks of nuclear accidents, proliferation of weapons material, and management of high level wastes are better understood by experts

and the general public, it cannot be expected that the political consensus necessary for a large and rapid expansion of nuclear power will be achieved.

3. The growth of nuclear power in the United States is constrained for the rest of the century because the rate of discovery and production of uranium probably cannot support the fueling of much more than about 300 GW(e) of LWR capacity without fuel reprocessing.
4. If the contribution of nuclear power is to continue well into the 21st century, one or a combination of three possibilities will have to be realized by the turn of the century (*a*) major new uranium finds; (*b*) deployment of advanced converters and later of associated thorium fuel cycles; and (*c*) the development and public acceptance of breeder reactors and associated reprocessing and refabrication facilities with adequate controls on proliferation.
5. There is a consensus in CONAES that the breeder option in the form of LMFBR needs to be maintained so that it could be deployed early in the 21st century if necessary. There is major disagreement, however, on what kind of program this requires, and, in particular, how soon an industrial prototype reactor should be pursued.

INDEFINITELY SUSTAINABLE ENERGY SOURCES

Because it takes 30–50 yr to deploy a new energy source on a large scale, it is necessary to plan for the long-term future now and assess the options open. There are four possibilities:

1. Fission energy with breeding
2. Controlled thermonuclear fusion
3. Geothermal energy
4. Solar energy (in various forms)

Each of these sources has the potential to be indefinitely sustainable in the sense that it could supply around ten times our present energy requirements for thousands of years or much more. Each has its own environmental and social impacts, and they differ widely in their readiness for deployment, and probably in their economics. Our present knowledge of the long-term options is insufficient for meaningful economic comparisons, and permits only limited comparisons by other criteria, such as risk or compatibility with desirable social organization. CONAES takes the position that the government's program in long-term energy sources should aim to bring the nation to a position where it would be able to make realistic choices of the best mix among long-term options when such choices become necessary. This requires that a continuing R&D program be conducted on many long-term energy technologies. The development priorities accorded these options should depend more on the likelihood of significant technical progress than on economic comparisons of existing versions of the technologies, because new technical developments and changes in resource economics are likely to change comparative cost assessments radically. Furthermore, a combination of long term options may be superior to reliance on a single system because they tend to be complementary both in their social characteristics and in their risks and technical development problems.

The Breeder Reactor

The breeder reactor, in the form of the LMFBR, has benefited from a sustained and relatively massive federally financed R&D effort, and is also the choice of several other countries, including the United Kingdom, France, West Germany, and the USSR, all of which have LMFBR development programs. Worldwide, about 3.8 GW(e) of LMFBR capacity is on the drawing boards—under construction or on order. If a number of technical and political problems are solved as a result of the worldwide effort, construction of a commercial breeder could begin within 10 years and significant capacity could be in place by the year 2000. However, there are still many uncertainties about the LMFBR breeder which should be taken seriously. Other forms of breeder, such as the gas cooled fast breeder reactor (GCFBR) and the molten salt thermal breeder reactor (MSBR), are in much earlier stages of development, but have some potentially attractive features (38). If the LMFBR is pursued vigorously and successfully, the other types may never be able to compete, but if breeders are developed more deliberately the others could be realistic alternatives and might ultimately be superior to LMFBRs on a number of technical grounds.

Controlled Thermonuclear Fusion

As a potential source of electricity, nuclear fusion has a resource base at least equal to that for fission breeders. However, despite many hundreds of millions of dollars spent on research in the basic science and technology, fusion has yet to be demonstrated as technically feasible, though there is rising optimism that a scientific demonstration will be made within the next five years. Until that time little can be said about engineering or economic feasibility; the configuration of an ultimate device is too uncertain.

It is not certain that the first approach to demonstrate feasibility will be the one most appropriate to carry forward into engineering development. For this reason, CONAES concluded that it is yet much too early in the development of fusion to make a commitment to any single approach. The Federal program should continue alternative approaches to the study of confinement science before attempting to move to pilot plant scale experiments (39, 40).

Although fusion has some of the same problems as fission, the radioactive waste management problem is probably less severe, (there is some argument about this because of the large amounts of radioactive tritium that must be handled at high temperatures), and the problems associated with commercial traffic in weapons-usable materials are largely absent. However, present fusion devices are prolific sources of neutrons and, if surrounded by a natural uranium blanket, could be used to manufacture plutonium for weapons. There is general agreement, however, that this is one of the harder ways of getting weapons-usable material, and that this proliferation risk is not comparable to that associated with fission power. The radioactivity produced in fusion devices could be from ten to several hundred times smaller than that from fission (depending upon choice of materials), and the troublesome problem of alpha-active actinides is avoided.

Geothermal Energy

Sources of geothermal energy include crustal rocks, sediments, volcanic deposits, water, and steam and other gases at usefully high temperatures that are accessible from the earth's surface. Although these sources of earth's heat are not indefinitely sustainable in the same sense as solar energy, their total energy is sufficiently large that their potential as an energy source will depend mainly on their economic producibility.

For the long-term future, the possibility exists to extract heat from the natural thermal gradient in the earth's crust and from unusually hot rock formations lying close to the earth's crust. However, there is no demonstrated technology for using these resources, so cost and producibility can only be grossly estimated. The usability of dry rock depends upon developing an appropriately large fracture system so that heat can be extracted from a large enough volume to be economic. The possibility of so doing and the possible environmental impacts are speculative at the present time (39, 41).

The geothermal option suffers from the fact that the only really large potential resource, the natural thermal gradient, is the most speculative as to its practical exploitability. As an indefinitely sustainable source it also suffers the inherent disadvantage that the normal heat flux from the inside of the earth is only about one thousandth as great as the solar energy flux falling on the same area.

Solar Energy

In the long term it will be possible for solar energy to provide each of the energy forms used by people: heat (and thus cooling), electricity, and fuels. Assessing the long-term potential of solar energy in each of these areas will require an extended period of research and development. A major issue for national solar energy policy, according to CONAES, is the balance of R&D

effort among the solar technologies that provide these different energy forms (28). The federal solar energy program now heavily emphasizes technologies for electricity production, yet the most important use of solar energy in the long-term future may in fact be the synthesis of fluid fuels.

The Solar Energy Resource Group of CONAES assessed the status of each of the solar technologies (39), and these are briefly summarized here:

SOLAR-GENERATED ELECTRICITY The amount of electricity that can, in principle, be generated by solar energy could more than provide for present US electricity requirements. The main obstacle for solar electricity is cost: unless major technical breakthroughs occur, solar electricity will be expensive compared with alternatives.

A second major issue for solar electricity is its effect on the overall reliability of the power grid. Because of the intermittent nature of the resource, most solar electric technologies will be limited in application unless inexpensive and efficient storage technologies are developed, or alternatively, oil and gas are used as backups. The problem of integrating solar electricity into existing energy networks is also discussed in the review by Kahn in this volume (42).

Four kinds of solar electric technologies are under active development: solar thermal, photovoltaic, wind, and ocean thermal energy conversion (OTEC). The favored system for solar thermal electricity generation is the solar tower concept, with mirrors focusing sunlight on a boiler at the top of a tower. Although this concept is technically feasible, not enough information is available to make reliable cost estimates for a commercial solar tower system. The cost appears to lie in the range of 5–10 times the current busbar cost of electricity, when storage costs are included.

At present, photovoltaic conversion is a commercial technology only for space applications and remote installations where performance rather than cost is paramount and where other sources are unavailable. Photovoltaic arrays have demonstrated adequate efficiency and reliability, but the problem is cost—more than 50 times present electric power generating costs. There is debate about whether large cost reductions are achievable by bringing improved versions of present technology to mass production, or whether a breakthrough in materials or device configurations arising from exploratory research is required to make photovoltaic conversion ultimately competitive. Unlike solar thermal conversion, this is an area in which fundamental investigations could have a dramatic payoff, and recent technical progress has been very rapid (43). Given the high stakes in solar energy and the long-term nature of its potential benefits, the present investment in general background research concerned with photovoltaics is still inadequate although recently much improved (28).

WIND Wind generators constitute a form of solar energy that is already economic for a few sites and markets. However, integrating this highly variable power source into utility grids will generally increase total generating costs because of the backup capacity required. An exception would be utility districts with a high proportion of hydroelectric generating capacity or with extensive pumped hydroelectric storage, either of which could accommodate the variations in wind power output.

Sites for wind generation are limited by wind conditions and aesthetic considerations. The amount of land required per unit of electrical capacity is much larger than for most other forms of solar energy (although land used for wind generation is by no means excluded from other uses). Interference with communications can also be a problem because television and microwave signals are reflected by the moving surfaces of wind turbines.

The immediate problem for wind technology development is to foster a diversified design and manufacturing effort directed generally at the level of about one megawatt electrical capacity. The market potential is likely to be highly differentiated and, in terms of total US energy demand, modest.

OCEAN THERMAL CONVERSION Another system of solar electricity generation is ocean thermal energy conversion (OTEC), which uses temperature differences between surface and deep ocean water in the tropics to generate electricity at very low thermodynamic efficiency. Its attractive aspect is that it does not require storage technology and is thus directly usable for base loads. OTEC will probably be technically feasible, but there is not yet a basis for choice among design options, for example between open cycle and closed cycle plants. Lack of knowledge and inadequate research on problems of fouling of the very large heat-transfer surfaces by marine organisms are the main weaknesses of present plans. The present federal program heavily emphasizes prototypes and demonstration, and should instead concentrate on assessment of basic system and subsystem alternatives rather than proving out one particular design at sea.

FLUID FUELS In the long term, whatever mix of sustainable energy sources is used will have to provide a large supply of fluid fuels for many of the applications now served by oil and natural gas. The production of fluid fuels from solar energy represents a very large and promising field of research. The stakes are high because such a process would avoid the problem of storage connected with other solar energy systems and, at the same time, would open up the possibility of providing a replacement fuel source for the nation's existing fuel-distribution networks which presently handle natural fuels. Such a development, if successful, could provide an easier transition to the ultimate long-term energy system than one that emphasizes electricity production alone. However, at present, the federal solar energy R&D program (in fact, the energy program as a whole), places major emphasis on electricity production and gives far too little attention to production of fluid fuels (28).

For the long term the most attractive potential solar energy alternative for the production of fluid fuels is probably direct photochemical conversion. This involves the decomposition of water to produce hydrogen, which can be used either directly as a fuel or to synthesize hydrocarbon fuels from various sources of carbon, including CO_2 from the atmosphere. In one promising approach, a complete chemical system would be designed which would not require any component taken from plants. Alternatively, if it becomes possible to provide an economical high-temperature heat source with solar energy, then a new means for production of hydrogen may be opened up, namely thermochemical decomposition of water, with or without a catalyst. (It should be noted that if electricity is available from solar or other sources, it can in principle also be used to produce hydrogen by electrolysis, a very efficient process. However, if the electricity source is of high capital cost, as is the case of solar electricity, the cost of resulting fluid fuels will be very high compared with natural fluids and even synthetic fluids made from coal.)

Theoretical calculations indicate the possibility of photochemical conversion efficiency in the range of 20–30%, based on incident solar energy, compared with average photosynthetic efficiency of 0.1% for natural ecosystems and up to 1.0% in "energy farms." A level of fluid fuels approximately equal to present consumption of oil and gas (55 quads) could be provided by efficient photochemical conversion from the solar energy falling on about 50,000 square kilometers, less than 1% of US land area. However, it must be emphasized that fuel production research using solar energy is at a much earlier stage than other solar energy research. There does not yet exist even a promising laboratory system worth scaling up to an engineering experiment. Thus, barring unexpected developments in fundamental research in the near future, the production of fuels from solar energy is probably much further in the future than even such sophisticated technologies as photovoltaics.

INSTITUTIONAL ISSUES The extent to which the various long-term energy sources lend themselves to "centralized" or "decentralized" deployment will be an important consideration. A widespread political interest seems to be developing in decentralized systems as opposed to large integrated networks as the electrical and fluid fuel distribution system (44, 45). Fission breeders and most probably fusion reactors are economically attractive only in large sizes, and are thus suited only for use in large integrated networks, with energy generation concentrated at a few nodes. They must be sited far from centers of population; indeed, in the case of breeders there is much discussion of colocation of many power plants and recycling facilities in safeguarded "nuclear parks" in remote areas. Solar technology appears to lend itself to deployment in a wide variety of capacities, because very large solar systems appear to offer no great economies of scale. Geothermal energy may be intermediate in this respect, lending itself to fairly small, local installations, but we know too little about how normal gradient geothermal heat may be exploited to be sure of this.

There is the problem of how to introduce a decentralized technology into a centralized network without degrading the economics and the reliability of the network. This problem could be mitigated by the development of cheap and effective energy storage systems, to absorb excess energy production capacity when the energy is not being used. One way to achieve the same effect would be to use solar energy to generate fluid fuels, which could either be stored locally or distributed in networks similar to present oil and gas distribution systems.

An important institutional issue is the degree to which regulation, taxes, and subsidies could or should be designed to encourage market penetration of solar technologies even though they may be uneconomic under existing circumstances. An argument usually advanced in favor of this is that the social costs of solar energy are so much less than for other energy forms, that its higher economic costs should either be offset by taxes on other energy forms that are potentially more damaging to the environment, or it should be the object of special government subsidies or tax benefits.

The CONAES Solar Energy Resources Group concluded that solar energy technologies could contribute substantially to the US energy system by 2010 if there were purposeful government intervention in the energy market, but that energy prices in the range considered by the CONAES study would not alone stimulate a large market penetration by solar energy before 2010 (28). For this reason, the CONAES scenarios show relatively small solar contributions (3–6 quads). One scenario was explored to see how fast solar energy could be introduced if tax policies and economic incentives were deliberately tailored to encourage its adoption in preference to other energy forms, virtually regardless of cost. By this means it was found that solar or solar-related technologies could provide as much as 25–30 quads of total energy needs by 2010. The additional economic cost would be considerable, probably measured in trillions of dollars over 35 years. If a public consensus were to regard solar energy as a form of environmental and social "national security," there is probably no technical barrier to the achievement of such a scenario. On the other hand, the environmental benignity of solar energy on such a large scale cannot be taken for granted.

In the very long term large-scale deployment of solar energy could have important effects on the earth's heat balance. Thirty quads of solar energy would probably use well over 10,000 square miles of land area. The construction of most solar energy systems would require considerably more energy-intensive materials such as steel and cement, than a nuclear plant of equivalent capacity. The effluents involved in extracting and processing these materials, and the associated occupational hazards, would greatly exceed the corresponding effects for a nuclear plant in routine operation (46). On the other hand, because designs of solar energy systems are still very primitive, the prospects for future reduction of materials requirements are substantial. If solar technologies are introduced only when and where they are economically competitive the materials requirements and associated risks would probably not be a very significant consideration. However, a crash program for rapid deployment of solar technologies would have to be assessed more carefully to make sure that materials requirements and associated risks and energy consumption were acceptable.

RISKS AND IMPACTS OF ENERGY SYSTEMS

Introduction

All energy systems entail risks to and impacts upon the environment and the health and welfare of people. It is difficult to make quantitative comparisons among such risks and impacts, however, because our information about them is beset with great uncertainties and because there is no widely agreed upon calculus for aggregating or comparing different kinds of risks and impacts. There are also differences of view based on relative valuation of statistical and catastrophic fatalities, and also different value judgements regarding risks to the environment, particularly to natural ecosystems. Although there is a danger that quantitative estimates of risks will be taken too literally, it is difficult to reach meaningful conclusions without them. Nonetheless, it is likely that judgmental factors will always predominate in making decisions and choices about energy systems and strategies.

Three bases for comparison of energy-related risks have been used:

1. Comparison of energy-related risks of a given kind with risks arising from background effects of the same kind; for example, comparison of cancer risk from nuclear power plants with average cancer risk in the population.
2. Cross-comparisons of alternative energy technologies, systems, or strategies with regard to similar kinds of risks; for example, comparison of relative risks to ecosystems from coal combustion and hydropower.

3. Comparison of energy-related risks with nonenergy risks with which people are familiar; for example, comparison of fatalities from nuclear reactor accidents with fatalities from commercial airline accidents.

There are difficulties with each approach. In the case of comparing risks with background effects of the same kind, the way that quantitative results are presented—in absolute or percentage terms—can have an impact on the public perception of the risk involved. Even if the additional risk from a particular source is very small, if the exposed population is very large, then the absolute number of deaths attributed to the source can be large, even though they constitute only a miniscule fraction of the deaths that would have occurred anyway.

In the case of cross-comparing risks from different technologies, the difficulty stems from the value judgements required in weighing the different kinds of risks and time scales involved. How should fatalities be compared with various kinds of injury and sickness? How should immediate catastrophic deaths be compared with similar numbers of (statistical) deaths or genetic effects occurring much later in future populations? People may place quite different valuations on these different kinds of adverse effects, and these valuations may change over time as well as differ within different age cohorts and subgroups of the population.

There are pitfalls also in comparing energy-related risks with nonenergy risks with which people are familiar, such as automobile fatalities, industrial accidents, or natural disasters. The problem here is that people may accept risks of technologies they are familiar with when the benefits of those technologies are clear, yet reject much smaller risks associated with new technologies whose benefits are less clear or at least less widely acknowledged because they are mostly in the future.

In the CONAES study, comparison of energy risks with nonenergy risks was avoided because it was believed to be of questionable policy relevance. The first two approaches were followed, with an emphasis on the comparison of specific risks across different energy technologies and strategies.

Principal Kinds of Energy-Related Risks

The following is a summary of the conclusions reached by CONAES regarding the principal kinds of risks posed by energy systems. This subject is treated in considerable depth in the report of the Risk/Impact Panel (27).

ROUTINE ACCIDENTS Accidents are the most highly quantified of energy-related risks. In this regard, coal is the most dangerous of all major energy sources: about ten times as many accidental deaths occur in the coal fuel cycle, from mine to power plant, as in the production of an equivalent amount of power with oil, gas, or nuclear energy. Most of the accident risk with coal is associated with deep mining and rail transportation. A conscientious program, largely to improve mine safety and railroad crossings, could reduce accidental death and injury rates by at least threefold.

AIR POLLUTION A great variety of pollutants that may affect human health are released from the combustion of fossil fuels, especially coal. These include sulfur and nitrogen oxides, carbon monoxide, hydrocarbons, particulates, and heavy metals. Local air pollution containing this atmospheric brew, in a variety of proportions, is known to be associated with increased disease and death rates. However, epidemiological studies done to date have not been adequate to quantify these risks of air pollution within sufficiently narrow limits. There is a high probability that even with the best control technology available, air pollution from coal-fired utilities will cause considerably more premature deaths per GW-year of electricity generation than the routine operation of the nuclear fuel cycle, or even the statistical expectation value for nuclear accidents (47).

Environmental quality standards have been promulgated for some, but not all, of these pollutants. Workers in the health field generally agree that adhering to existing air quality standards is necessary, but there is concern that existing standards for particular pollutants may not be sufficiently protective of public health. For example, the emission standard for sulfur dioxide (SO_2) may not protect the population adequately from the health effects of transformation products of SO_2 such as sulfates (SO_4^{2-}), which are presently unregulated. There are also no regulations for other substances that are suspected to be harmful, e.g. respirable particulates of submicron size, heavy metals, and hydrocarbons.

Another difficulty is that thresholds, i.e. pollutant levels below which there are no health effects, have not been demonstrated. Thus there is reason to question whether the impacts of air pollution on health will be held to an acceptably low level even if present emission standards are adhered to —especially if the future level of coal use is much higher than today's.

In consideration of the highly uncertain state of understanding of air pollution risks, prudence would dictate a near-term policy of strict adherence to the present air quality standards. In the longer term, pollution control strategies should be reassessed with a view to building in greater incentives for suppliers not just to meet minimal present standards but to improve on them with time. The goal should be a strategy producing the greatest environmental improvement, as measured by reduction in estimated social costs, for a given overall economic cost; we are very far from this optimum with present strategies. A greatly enlarged program of epidemiological, laboratory, and field studies should also be undertaken, aimed at understanding the formation, transport, chemical interactions, and health effects of combustion-generated effluents and their transformation products. This research is required for the continuous evaluation and improvement of air quality standards.

CANCERS It is known that cancer deaths can be caused by ionizing radiation, and also possibly by emissions from coal combustion and industrial operations that use energy. By adopting the linear dose-response hypothesis, the Risk/Impact Panel estimates that each year's operation of a conventional 1-gigawatt nuclear reactor with fuel reprocessing would produce, over an exposure period of 500 years, somewhat less than one cancer. Half the cancers so produced would be lung cancers. For comparison, the annual number of naturally occurring cancers in a population of the size served by the equivalent amount of electricity is about 1500.

Carcinogens are also present in fossil fuel emissions, particularly those from coal combustion, but there is essentially no quantitative information on their actual health effects. In the past, under less stringent occupational standards than are in force today, workers exposed to coal emissions suffered increases in cancer rates. Coal-based fuel processes involve many carcinogens, but with careful plant design it should be possible to keep the occupational risk very low. In the products themselves, most carcinogens will remain with the heavy residues, and synthetic gas and distillates should present no cancer risk to the general public; however, as new technologies are introduced, these issues will have to be kept under constant surveillance and research to make certain that the potential for unforeseen risks of delayed cancers, either among workers or the general public, do not build up before they are detected and controlled. For residual liquid fuels, including those derived from shale, close attention must be paid to emissions within plants and to releases to the atmosphere. Such fuels would be used mainly in large industrial boilers and power plants, where the necessary occupational safeguards could be applied.

On the basis of current knowledge, it is impossible to rule out the possibility that coal-fired power plant emissions cause more cancers per unit of power output than nuclear plants. Moreover, coal contains varying concentrations of uranium, and coal combustion thus releases radioactivity into the atmosphere (48). The solid wastes from coal combustion can also be a source of alpha emitters. These radiation effects are generally thought to be less important than those of uranium mining, but the subject has been insufficiently studied.

GENETIC EFFECTS Genetic changes are known to be produced by radiation and by a number of chemicals found in coal and to some extent in other fossil fuels. Impacts on the human population and their distribution over time, especially for fossil fuel emissions, are very poorly known. These uncertainties are not likely to decrease in the near future. The Risk/Impact Panel estimates that each year's routine operation of a one-gigawatt nuclear power plant produces today about 0.015 severe genetic effects. These would be considerably reduced with the introduction of advanced reactors that require less uranium, since the main effect arises from uranium mine tailings. The genetic risk could also be reduced by a factor of 100 or more by proper covering of the mine tailings. The genetic effects of fossil fuel combustion, if any, are completely unknown. Emissions contain mutagenic compounds, but in unknown quantities and dispersions. Although the effects from fossil fuels are unlikely to exceed those of nuclear power, this problem needs further research.

LARGE-SCALE ACCIDENTS AND SABOTAGE Risks of low-probability, high-consequence accidents are associated chiefly with nuclear reactors, hydroelectric dams, and transportation and storage of liquified natural gas (LNG). The subject of nuclear reactor accidents has been extensively studied, especially by the Reactor Safety Study (WASH-1400), commissioned by the Nuclear Regulatory Commission (49). That study concluded that over the long term, the expected health damage from nuclear accidents (treated as the mean of the product of probability and health consequences for all significant events) is smaller than from radiations emitted in routine operation of reactors. This conclusion will probably not be altered significantly as the result of information provided by the 3-Mile Island reactor accident, because in the Reactor Safety Study the main contribution to public damage arose from radiation exposures with considerably more severe health consequences than the 3-Mile Island accident, in which radiation exposure was very low. Nonetheless, the conclusions of the Reactor Safety Study may be of only limited relevance to the public appraisal of nuclear power. The intense negative public reaction following the 3-Mile Island nuclear accident illustrates that people have much less tolerance for infrequent and highly publicized accidents, especially those involving radiation, than for risks of routine operation, even if the total number of deaths spread out over long periods of time may be comparable.

CONAES is in general agreement (50) with the appraisals of the Reactor Safety Study conducted by the American Physical Society study group (51) and more recently by the Reactor Safety Review Group (52). WASH-1400 contains some estimates that are excessively conservative and others that are almost certainly too optimistic. Which way this would shift the median probabilities for accidents of various severities is uncertain. The consequences of a given accident are probably underestimated, but probably not by more than a factor of 3. However, the uncertainties in the estimates are almost surely several times larger than estimated in WASH-1400. This has the consequence of raising the statistical expectation of fatalities from nuclear accidents by a factor of 10 or more compared with the value of 0.025 latent fatalities per reactor year given in WASH-1400.

It is possible to combine the relative probabilities for events of varying severity of consequence estimated in WASH-1400 with reactor operating experience to obtain an upper limit estimate for the possible number of latent cancer deaths per reactor year. If we assume 200 reactor years without a meltdown, then this upper limit is about 1 latent cancer death per reactor year. The true statistical expectation almost certainly lies between this value and the estimate of 0.025 latent deaths per reactor year given in WASH-1400.

Catastrophic accidents can also occur with other energy sources, especially large hydroelectric facilities. Between 1918 and 1958 there were an average of 40 deaths per year in the United States from dam failures, though fewer in the more recent period. Some individual failures killed hundreds. Worst-case scenarios for both dams and LNG facilities lead to numbers of casualties comparable to those associated with the more severe nuclear accident probabilities. The calculated probabilities are higher, although the analyses on which they are based have been much less thorough and systematic than for nuclear plants. Whereas in the case of nuclear accidents the predominance of fatalities consists of delayed statistical deaths due to low level radiation exposure of a large population, in the case of dams and LNG accidents the casualties are immediate, with no lingering effects.

Nuclear plants, dams, and LNG facilities are probably similarly vulnerable to sabotage, but nuclear plants are presently better guarded and may be inherently easier to guard. The several consequences of sabotage of nuclear plants appear to be in about the same range as those of the severest postulated accidents discussed in the Reactor Safety Study. The probability of such severe consequences could be much higher, however, because saboteurs could choose the time and place for maximum effect. The safety analysis techniques developed for assessing nuclear reactor accidents ought to be applied to sabotage, diversion, and other safeguards issues, both for nuclear power and other energy technologies.

MANAGEMENT OF WASTES All energy systems have wastes, and their management involves risks to health. Although coal ash and coal mining wastes pose significant problems, nuclear waste management is considerably more difficult. The CONAES view of the nuclear waste problem has been covered previously in this review (See page 46).

ECOSYSTEM IMPACTS The CONAES Risk/Impact Panel considered energy impacts on ecosystems to include loss of arable land, water resources, open spaces, wilderness areas, natural beauty, habitat, and wild populations or species (50). Among the public there is wide divergence of value judgments regarding the importance of these criteria: Some people value them very highly, while others regard them as less pressing than a number of other human economic and social needs.

By these criteria alone, the Panel judged that the energy source most destructive to ecosystems, per unit of energy output, is hydroelectric power (probably including small dams on tributaries). This comes about because of the destruction of natural habitats in the vicinity of dams, changes in the health, productivity, and ecological balance of downstream areas, and acceleration of siltation and eutrophication in the lakes created by the dams. Nearly as destructive is biomass production (i.e. growing crops on "energy farms" to be burned or converted into fuel). Among the adverse ecological effects of energy farms are land use in competition with agriculture, depletion of soil nutrients and consequent additional requirements for chemical fertilizer, and the fact that hardy, fast-growing species required for economic energy production could become a widespread nuisance. Among fossil fuels, the Panel judged that shale oil and coal-derived synthetic fuels are probably the most damaging. Oil has varying impact, depending on locale; offshore developments in northern regions are especially risky.

In the Panel's judgement, nuclear energy has a relatively small ecological impact. However, if LWRs were to continue to be deployed to the point at which they must be fueled from low-grade ore, the ecological impact of uranium mining could become comparable to that of coal mining. This problem would be absent with breeder reactors.

The ecological impacts of solar energy are poorly known, but for most applications are probably mild (50). Significant effects, comparable to those of fossil fuels, might be encountered with materials extraction and processing requirements for widespread decentralized solar installations. In contrast, very important ecological impacts might occur from a truly large-scale use of ocean thermal conversion owing to exchange of heat and plant nutrients between deep and shallow water strata.

WATER PROBLEMS CONAES concluded that the supply of fresh water may severely constrain the expansion of energy production generally, but particularly electricity generation (nuclear or coal), coal mining, and synthetic fuel production, in most regions of the country (50, 53, 54). A twofold to threefold expansion of coal production (from the present 15 to between 40 and 45 quads), especially if accompanied by conversion to 8–12 quads of synthetics, will cause problems that can be alleviated only by greatly improving the efficiency of water use in these processes, by developing now-unused water sources such as brackish groundwater, or by further extending interbasin water transfers. This case is illustrated by the low-medium-growth CONAES Scenario II_3. Higher-growth futures will, of course pose the problem more severely. Competition will grow with other uses such as agriculture, municipal use, or recreation and maintenance of ecosystems, although these uses also are amenable to efficiency improvement, especially in agriculture. This constraint may be considerably alleviated by advances in the efficiency of water use and by tapping new sources of water, but there is considerable disagreement about the extent to which the problem can be mitigated. Clearly the subject requires much more attention than it has received. Most studies that have been made do not extend to the magnitude of synthetics industry and electricity generation that might be required after 2000.

CLIMATE Were all the world's fossil fuel resources to be burned, the carbon dioxide (CO_2) content of the atmosphere would increase by a factor of between five and eight, and the climatic impact of this would almost certainly be catastrophic (55). The uncertainties connected with the CO_2 problem pertain to the timing rather than to the reality of the problem. If worldwide combustion of fossil fuels, particularly coal, continues to increase, the problem could begin to be perceptible as early as the first few decades of the 21st century, or it might not become significant until the latter part of the 21st century. Even if fossil resources were consumed at no greater than the present rate, the CO_2 problem would eventually become important, though it might be postponed for a century. A serious concern is that, owing to various positive feedback mechanisms, climatic changes due to CO_2 would be irreversible by the time they were detected above natural climatic fluctuations.

It needs to be emphasized that the CO_2 problem is global, not local or regional. It depends on the total world consumption of fossil fuels and not on what happens in a single nation, even one as large as the United States. The *net* climatic effect of increasing atmospheric CO_2 might conceivably even be beneficial, for example by improving the growing season in marginal northern latitudes, but the principal effect would almost certainly also be to redistribute agricultural productivity, and even with net benefits the effects in some regions are almost certain to be disastrous, and to be a source of political conflict.

Nuclear energy is likely to have a much smaller impact on climate than fossil fuels, since the heat radiation balance effects of CO_2 are much more important globally than are thermal releases. Solar collectors could have a global effect in the far future if they were deployed in such a way as to alter the average reflectivity of the earth's surface in the regions where they are located. Worldwide reliance on ocean thermal energy conversion could induce climatic effects by changing the average surface temperature of the tropical oceans. The possible impacts of solar energy have only just begun to receive careful study (56). They could be of no concern unless the use of solar energy becomes very large, and, in any case, there would be plenty of time to deal with the problem as it began to become important, provided it was not altogether overlooked. Hydroelectric and geothermal sources are likely to have less serious climatic effects, although large-scale water impoundments and irrigation can affect the hydrologic cycle and thermal balance regionally.

Should considerations of diversion and proliferation lead to the deployment of breeder reactors and reprocessing facilities in "energy parks" of more than 30-gigawatt total capacity, these might alter local or regional atmospheric circulation patterns and even generate severe artificial convective storms in certain regions and under certain meteorological conditions.

SOCIOPOLITICAL IMPACTS The sociopolitical aspects of energy planning need to be much more thoroughly explored than they have been. For example, conventional analysis of the risks associated with energy systems and strategies gives relatively little emphasis to the distribution of risks and benefits, although from a sociopolitical standpoint, distributional inequalities may be more significant than net impacts. For example, there is considerable disagreement about the distributional impacts of energy conservation measures. Distribution should not be used as an excuse to forego conservation, but it must be analyzed so that it can be dealt with by compensatory measures.

Another sociopolitical aspect of risk is that public attitudes to risks may have symbolic and institutional dimensions that relate more to confidence in the institutions that manage the technologies than to their actual characteristics. This is exemplified by the wide difference in attitudes toward nuclear and solar energy. To some, nuclear power symbolizes big government, big business, and impersonal centralized bureaucracy unresponsive to local needs and sentiments, while solar energy represents a "natural" form of energy that can be controlled by average citizens. To others major conservation measures require an intrusion of government on consumer decisions which are regarded as intolerable. Decentralized solar technologies, if deployed on a scale sufficient to provide a significant fraction of US energy needs, will require a large-scale mass production, distribution, and service industry which may not look in practice so different from existing electric and fuel distribution networks. How such symbolic attitudes are likely to develop over time or be affected by the dialogue between the public and various groups of experts is difficult to assess.

A conclusion reached in many parts of the CONAES study was that noneconomic factors will play an important, often dominant, role in influencing future energy demand or supply availability. Life style, value, and welfare implications may strongly influence energy consumption patterns, and political acceptability will affect both energy supply availability and energy conservation. Because of their importance to policy, these aspects need much more systematic study.

Some General Conclusions on Risk

1. CONSERVATION For the most part, conservation is the least risky energy strategy from the standpoint of direct environmental and health impacts. The main reason that conservation cannot be the only strategy is that at some level of application conservation would give rise to indirect socioeconomic and political effects, mostly through economic adversity, that would predominate over the direct benefits. We cannot be sure where that point is, but all the CONAES technical analyses suggest that it is a long way from where we are now, quite possibly at an E/GDP ratio of ⅓ to ½ present values. The CONAES consensus is that the maximum conservation achieveable without adverse socioeconomic effects will likely be beneficial from the standpoint of health and environmental quality, and therefore should have highest priority from the standpoint of risk. Particular attention should be paid to managing indoor air pollution, which is a direct risk of tightening air leakage standards in buildings.

2. FOSSIL FUELS Among fossil fuels, natural gas presents the smallest health and environmental risks both in production and consumption, although there is the possibility of serious accidents in connection with the importation and storage of liquified natural gas. Oil is next, and coal is much higher in risk. This ranking is likely to persist even with improvements in technology, such as coal-based synfuels. Research is most urgently needed on the health effects of coal combustion by utilities and industry and on the possible occupational and public health hazards of producing and using synthetic fuels.

We must be prepared for the possibility that adverse health effects, global CO_2 increase and associated climatic change, problems of freshwater supply, and ecological considerations will eventually severely restrict continuing expansion of coal use. These problems are likely, though not certain, to become critical at three times current coal output or less.

3. NUCLEAR ENERGY In routine operation, nuclear power presently has smaller health and environmental risks than coal. This will probably remain true even with fuel reprocessing, deployment of advanced reactors, and large-scale disposal of nuclear wastes. However, it is not possible to make a definitive comparison between nuclear and coal because of the great

uncertainties associated with reactor accidents, sabotage, and the problems of diversion and proliferation. Resolution of the radioactive waste management problem is also urgent from a public acceptance viewpoint, though probably less urgent on a objective basis than the above-mentioned coal-related research. To the extent that the nations's electricity system needs to expand it is prudent to depend on both nuclear and coal rather than exclusively on one or the other, because their risks are quite different and are therefore not likely to have simultaneous or similar effects.

4. SOLAR ENERGY Several solar energy technologies appear very promising from the standpoint of health and environmental risk. Hydroelectric power, on the other hand, especially if it involves new dam construction, is very destructive of ecosystems per unit of output. Energy farms are also likely to be ecologically destructive if deployed on a scale large enough to provide more than a few percent of total energy needs.

5. PUBLIC APPRAISAL OF ENERGY SYSTEMS There is an urgent need for research that will contribute to better understanding of the factors that determine the perception of and response to health and environmental risks of energy systems by different subgroups within the public. No strategy for risk reduction in the energy system can be truly rational if it does not take into account these public perceptions and judgments even when they are seen as irrational by experts. It is unlikely that appraisal of risk will ever be able to bypass difficult relative value judgments between different kinds of risks as well as between risks and economic or other benefits of energy technologies. This is not to say that present methods of risk assessment cannot be improved, however. Nevertheless the judgmental factor will continue to predominate in the final decision among energy alternatives, and is unlikely ever to be superseded by formal analysis of risks and benefits.

SUMMARY

The CONAES study examined contextual relationships among the many factors likely to be involved in determining US energy policy, and in particular, emphasized the importance of energy demand considerations in planning future US energy supplies. Because of great flexibility in the technical efficiency of energy use, a wide range of future energy demand growth rates is possible and compatible with the same rate of growth of GNP. Thus, there is a great deal of scope for reducing energy growth without appreciably sacrificing GNP growth or changing nonenergy consumption patterns. Although there is some uncertainty in this conclusion because of possible feedback effects of energy consumption on labor productivity, labor force participation, and propensity for leisure, it is likely that E/GNP one half of today's, and conceivably one third of today's, could be reached before significant impact on GNP growth is felt.

CONAES recommended that reduction of energy demand growth be accorded the highest priority in US energy policy. Low-energy growth futures could be stimulated by a combination of expected higher prices and regulatory policies, applied gradually and consistently over the next several decades. For most of the future scenarios considered plausible by CONAES, policy changes both to improve energy efficiency and to enhance energy supply alternatives to imported oil will be necessary. The continuation of present policies relating to both supply and demand, including prices, will cause a widening of the gap between domestic supply and demand, which could only be made up by increased imports.

The most critical near-term problem in US energy supply is fluid fuels, since petroleum supply worldwide will be severely strained beginning in the 1990s owing to the peaking of world production. Severe problems could occur earlier because of political disruptions or cartel actions. Next to demand-growth reduction, therefore, highest priority should be given to the development of a US synthetic fuels industry, both for liquids and gas.

As fluid fuels are phased out of use for electricity generation, coal and nuclear power are the only alternatives for the near term, prior to 2000. A balanced mix of coal and nuclear-generated electricity is preferable to predominance of either, because many of their characteristics are complementary. After 1990, coal will be increasingly required for synthetic fuels production. The requirements for nuclear capacity depend on the growth rate of electricity demand; in this regard, the CONAES estimates of electricity growth between 1975 and 2010, for up to 3% average GNP growth, are considerably below industry projections, and in the highest conservation cases actually level off or decline after 1990. Such projections are sensitive to assumptions about end-use efficiency, technological progress in electricity generation, and escalation of electricity capital costs relative to primary fuel costs.

In terms of public risks from routine operation of electric power plants, coal-fired generation presents the highest overall level of risk, with oil-fired and nuclear generation considerably safer, and natural gas the safest. With respect to accidents, fossil generation presents very low risk of catastrophic accidents. The statistical risk associated with nuclear accidents is probably less than its risk from routine emissions, especially from uranium mine tailings, but the high degree of uncertainty that still attaches to nuclear safety calculations makes it difficult to provide a confident assessment of the probability and consequences of catastrophic nuclear accidents. High-level nuclear waste management does not present catastrophic risk potential, but its long term low-level threat demands more sophisticated and comprehensive research and planning than it has so far received. It is likely that the satisfactory assessment of waste management for the long term will be the pacing item in the growth rate of nuclear power capacity.

The problem of nuclear weapons proliferation is real, and is probably the most serious potentially catastrophic problem associated with nuclear power. However, there is no technical fix—even the stopping of nuclear power—that can avoid the nuclear proliferation problem. At best the danger can be delayed while better control institutions are put in place. There is a wide difference of opinion as to which represents the greater threat to peace, the dangers of proliferation associated with the replacement of fossil resources by nuclear energy, or the growing competition for access to and control over fossil fuel supplies.

Because of their higher economic costs, solar energy technologies will probably not make a major contribution to US energy supply in this century unless there is massive government intervention in the market to penalize the use of nonrenewable fuels and subsidize the use of renewable energy sources. Such intervention could find justification in terms of the generally lower social costs of solar energy in comparison with alternatives. Technical progress in solar technologies, especially photovoltaics, has accelerated dramatically during the last few years; nevertheless, there is still insufficient effort on long range research and exploratory development of novel concepts. Much increased basic research effort should be directed at finding ways to use solar energy to produce fluid fuels, which may have the greatest promise in the long-term future.

Major further exploitation of hydroelectric power, or of biomass through "energy farms," presents ecological problems that make it inadvisable to count on these as significant future energy sources for the United States. There is insufficient information to judge whether the large-scale exploitation of hot-rock geothermal energy or the geopressured brines will ultimately be feasible or economic. Local exploitation of geothermal sources is already feasible and should be encouraged where they offer an economical substitute for petroleum.

It is too early in the investigation of controlled thermonuclear fusion to make reliable forecasts of its economic or environmental characteristics. Nevertheless, fusion warrants sufficient technical effort so that a realistic assessment can be made, by the early part of the next century, of its long-range promise in competition with breeder reactors and solar energy technologies.

Finally, there is great need to understand better the social and institutional characteristics of energy systems and the factors that determine public, official, and industry perception and appraisal of them. However, difficult value judgments will probably always predominate in decisions among energy alternatives.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720