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Fuels for Future Electric Power

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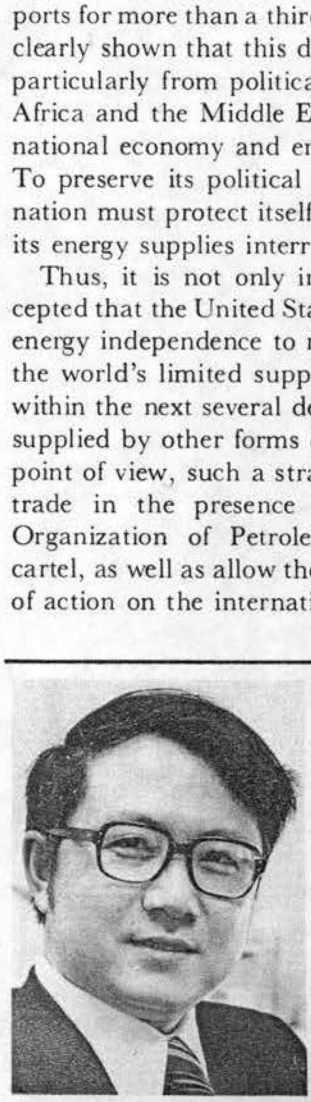
Fuels for Future Electric Power

By OLIVER S. YU

THE dominant energy sources in the United States today are based on hydrocarbons — crude oil, natural gas, and their derivatives. These fuels are obtained from limited resources that are being depleted at an increasing rate, and will likely be exhausted within forty years.

Furthermore, the U. S. is dependent on foreign imports for more than a third of these fuels. Experience has clearly shown that this dependence on energy imports, particularly from politically uncertain regions such as Africa and the Middle East, can and will damage our national economy and endanger our national security. To preserve its political and economic well-being, the nation must protect itself from the possibility of having its energy supplies interrupted.

Thus, it is not only imperative but also widely accepted that the United States must develop a strategy for energy independence to relieve its heavy reliance upon the world's limited supplies of oil and gas by moving within the next several decades toward a system that is supplied by other forms of energy. From a geopolitical point of view, such a strategy will help stabilize world trade in the presence of a vigorous and cohesive Organization of Petroleum Exporting Countries oil cartel, as well as allow the U. S. to maintain its freedom of action on the international scene.



Oliver S. Yu is a project manager on the technical assessment staff at the Electric Power Research Institute, which he joined in 1974 (energy systems modeling program). He is a council member of the energy systems group of the Operations Research Society of America and a consultant on systems analysis for Stanford Research Institute. **Dr. Yu** received a BSEE degree from Taiwan University and an MS degree in electrical engineering from Georgia Institute of Technology. From Stanford University he holds an MS degree in statistics and a PhD degree in operations research.

To achieve this transition toward energy independence the United States is fortunate in having a number of technical options, but it has relatively few choices. The options consist of adopting more stringent and effective energy-conserving practices; stimulating increased production of domestic oil and gas; transferring a greater portion of the energy demand to the more abundant coal and nuclear supplies; and learning to exploit such underused resources as geothermal power and waste heat, and such inexhaustible energy sources as solar radiation and fusion. None of these options by itself can make a large enough contribution during the next two decades to avoid increasing U. S. dependence on imports. The nation, therefore, has the limited choice of determining an appropriate combination of existing options.

Economists and engineers at the Electric Power Research Institute have devised and used a programming model to explore some of the options by which the United States may realistically move away from its present heavy dependence on oil and gas to a more diversified energy economy. One aim of their model was to allow for price-induced interfuel substitution and price-induced energy conservation. The findings of the study are summarized here. In particular, the author reports that the present value of benefits from both the fast-breeder reactor and coal-based synthetic fuels well exceeds their anticipated research and development costs. The direct cost to the United States economy from a nuclear moratorium is also calculated.

Unfortunately, none of the options is free from objections. For example, conservation of energy and reduction of waste in energy use are attractive concepts in principle until one examines in detail the social, technical, economic, and legal obstacles that abound. Then we find a polarization of views and much room for disagreement in the political arena. Expanding domestic production of energy by any of several means involves its own obstacles, licensing delays, and undesirable environmental consequences. Meanwhile, the hope that solar- or fusion-produced electricity will be free of many of the objections to coal-fired plants or nuclear reactors must await the outcome of developments that can provide more definitive information about the attractiveness and acceptability of those advanced concepts.

To overcome present difficulties, the United States will need a diversified research and development program, but its investment in plants and equipment will have to be concentrated on two major options that are realistically available within the next twenty to forty years: (1) expanding the supplies of energy provided by nuclear fission and coal, and (2) curtailing the growth of the demand for oil and gas, partly through conservation and partly through substitution of coal- and nuclear-fueled electricity and synthetic fuels in their place. Purposeful planning will be necessary to achieve a measure of energy independence. And we may have to take some environmental risks in developing our domestic petroleum, gas, and oil shale resources over the next decades.

Beginning in the 1990's the United States must develop a synthetic fuels industry — initially coal-based fuels such as methane and methanol, then hydrogen derived from nuclear fission, and eventually perhaps hydrogen from fusion or solar, or both. In evaluating these options, timing is crucial. The fast-breeder reactor (FBR) is needed as insurance againist high-cost uranium and coal during a period of transition away from an energy economy based upon oil and gas and toward one with a potentially infinite resource base. Either solar or fusion, or the FBR, itself, could eliminate United States dependence upon scarce natural resources for energy production in future years.

Recently at the Electric Power Research Institute, my colleagues Peter Auer, a Cornell University physicist, and Alan Manne, a Harvard political economist, and myself conducted a study to examine the implications of these realistic pathways to energy independence. The prospective benefits of new technologies, particularly the fast-breeder reactor and synthetic fuels, were then assessed within this framework. Highlights of the results of the study are summarized here.

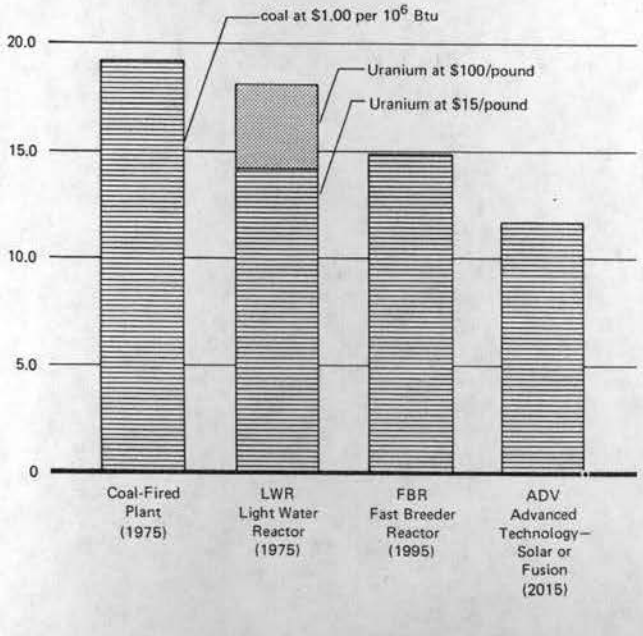


Figure 1 Electric energy costs

Principal Assumptions

The study uses an economic resource allocation model. The model is formulated as though all decision makers had a common objective: to meet the projected energy demand at minimum discounted costs for capital investment, fuel, operation, and maintenance over a 75-year planning period. All costs and benefits are expressed in terms of "real" 1975 dollars. Thus, any price rises due to general inflation would not affect the analysis.

In this analysis, we were concerned primarily with two secondary forms of energy — electric and nonelectric (e.g., liquids and gases). Coal can supply both the electric and nonelectric sectors either by direct combustion or by conversion to synthetic fuels. Nuclear fuels may be used to generate electricity and also to produce hydrogen by electrolysis to supply the needs of the nonelectric sector. Consequently, there are paths in our model by which either coal or nuclear fuels can meet all energy demands, with the proportions of their contributions being determined by the relative costs of interfuel substitution.

It should be emphasized that the model used in this analysis is *not* a forecasting model, but rather a planning model by which the consequences of alternative future energy-economic scenarios can be examined. For example, despite the fact that recent domestic political developments have not brought the United States close to the goals of energy independence, it is a fundamental assumption of the model that the nation will strive toward these goals by limiting its future energy imports to a certain level.

It also should be pointed out that the study is particularly interested in assessing the economic viability of two major near-term energy technologies: coal-based synthetic fuels and the fast-breeder reactor. For this reason, the developments of many other technological options, such as oil shale and the high-temperature gas-cooled reactor, are deliberately assumed to occur at their potential upper limits rather than at more achievable lower levels.

Discount Rates

The costs of developing new technologies are incurred in the near term, but their benefits require a long time to accrue. Therefore, in order to compare costs and benefits, it becomes necessary to discount both to their present values. This is sound economic practice and provides useful planning information when the time span of concern is brief. The practice of discounting, however, weighs heavily against benefits when they are expected to accrue over extended periods. Thus, for ex-

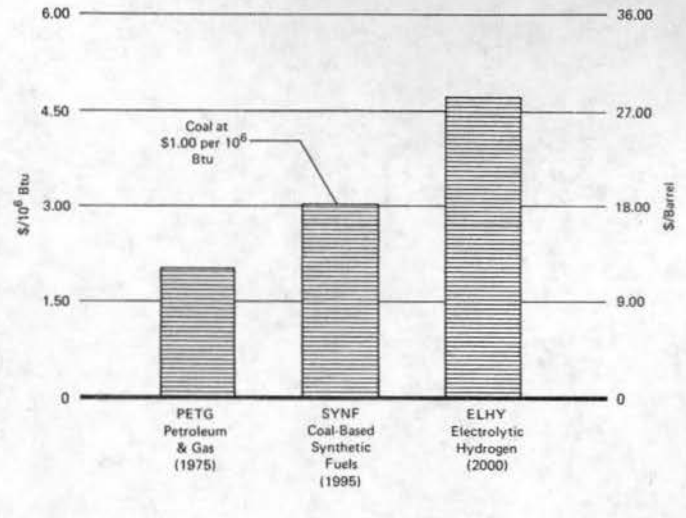


Figure 2 Nonelectric energy costs

ample, the value of today's dollar twenty-five years hence is only nine cents, if we use a 10 per cent annual discount rate.

What discount rate, then, is appropriate for measuring the costs and benefits of long-range projects? The present practice of the U. S. Office of Management and Budget is to use 10 per cent as the discount factor in federally sponsored energy research and development projects. But this rate seems far higher than the real returns to investors in the private sector of the economy. For example, Harvard economists L. R. Christensen and D. W. Jorgenson estimate that the real rate of compensation to property owners was 3 to 5 per cent in the years 1929-69, once allowance was made for the effects of inflation on both incomes and wealth. This would imply that, for example, a 10 per cent nominal discount rate would be consistent with a 4 per cent rate in *real* terms, coupled with a 6 per cent inflationary factor. Since the discount rate significantly affects the selection of future energy supply mix, we have used two and sometimes three alternative discount rates (5 per cent, 7.5 per cent, and 10 per cent, expressed in terms of "constant" dollars) in order to study the sensitivity of this important factor.

Demand

In the analysis, the energy demand projections are not extrapolations of historical trends but are derived instead from an economic model that incorporates the effects of aggregate national income growth and energy supply price changes. For the latter effects, through the use of own-price and cross-price elasticities, a higher price of one energy source would induce conservation of that source and prompt its substitution by another.

Using this model, projections of the demand growth for electric energy could be on the low side because historically, with consumers' preference for electricity over other forms of energy, new technological applications of electricity have stimulated increased demand. However, demand projections calculated for cases studied in the analysis have all fallen well within the bounds of historical extrapolations and the forecasts of other major studies, such as the Ford Foundation Energy Policy Project.

Resource Base

The availability and cost of petroleum, natural gas, and their derivatives (designated here collectively as PETG) will have profound effects on the benefits of competing energy sources. We assume, for planning purposes, that a realistic base figure for the ultimately producible PETG resources in the United States is two quintillion Btu (= 2×10^{18} Btu), corresponding approximately to a 40-year lifetime supply at *current* domestic consumption rates. This estimate falls well within the confidence range of recent official estimates. In order to test sensitivity, we also treat the more optimistic case that the ultimate domestic PETG reserves will turn out to be three quintillion Btu (3Q). In order to simulate a policy aimed at energy independence, import levels are held constant at 7 million barrels per day (oil equivalent) even though realistically we recognize that they are likely to be more than this in the near term. As long as resources are available, it is assumed that PETG costs will remain constant at the 1975 oil import price of $2 per million Btu. This is more than actual 1975 domestic prices, averaged over the mix of new and old oil, regulated and unregulated gas. However, it represents a plausible assumption, unless one is inclined to believe that OPEC will soon collapse and world oil prices will plunge.

The magnitude of the ultimately producible domestic coal reserves is not at issue because of the limited time span of our planning horizon (only seventy-five years). What is of some concern, however, is the future rate of coal utilization. The rises in the price of coal since 1973 are not assumed to be significant in determining long-term benefits, but we are largely ignorant of what shape the coal supply curve would take under conditions where annual coal production would have to increase ad infinitum. Consequently, we have assumed two simple alternative cases: one in which coal costs remain constant at the current value of $1 per million Btu, independent of production volumes; and one in which the unit costs remain constant until annual production reaches twice the current level and thereafter rise linearly with the amount produced. Thus, coal costs would reach $2 per million Btu when annual production had become four times the present level and $3 per million Btu at six times the current production volume. (These cost increases could arise from a variety of factors; for example, the need for more stringent environmental controls in the presence of a greater density of coal-burning plants.) It should not be surprising that the relative benefits of coal and nuclear technologies are quite sensitive to whether coal costs remain level or rise with increasing use. This question should be given far more careful scrutiny than in the past.

It is well-known that the projected benefits of advanced nuclear technologies, whether plutonium recycle, high-conversion reactors or breeders, are quite sensitive

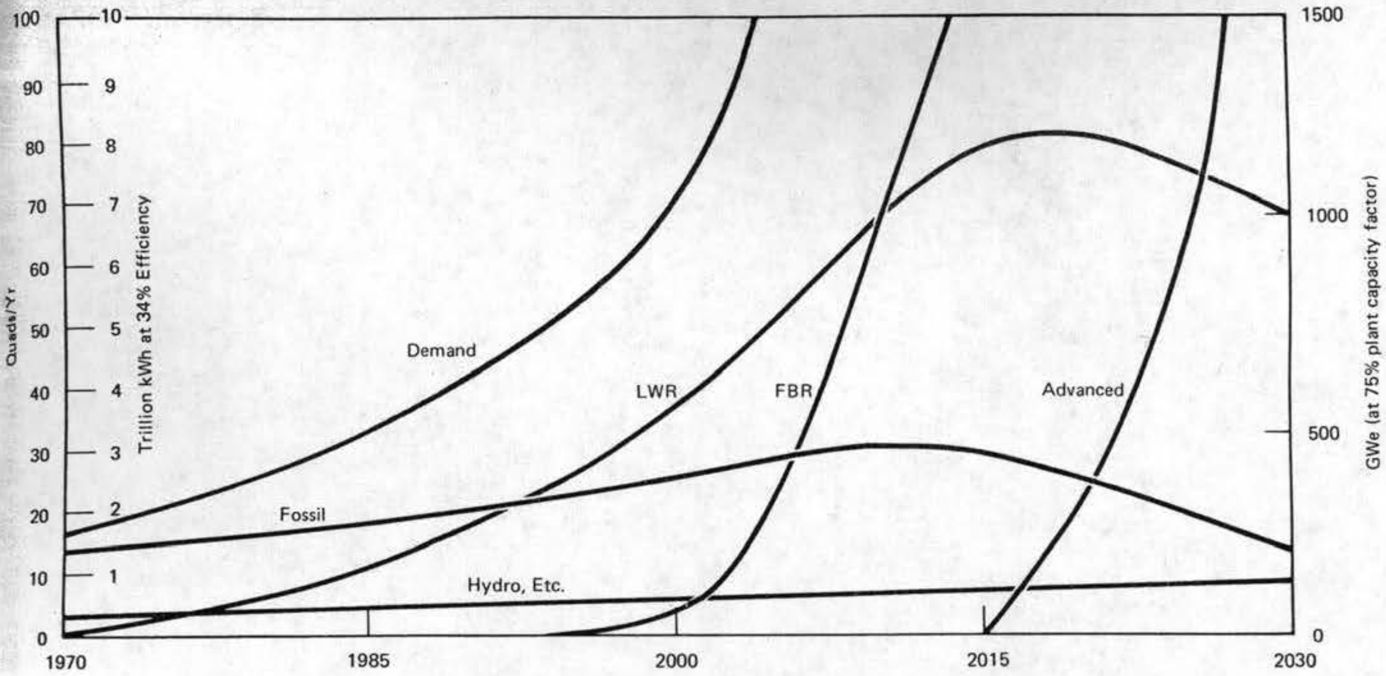


Figure 3 Electric energy demand and production through the year 2030

to the assumed quantities of uranium fuel available at a given price. We do not pretend to add any new information to the often-debated question of how much uranium of a given richness remains to be discovered and exploited within the United States. Instead, we rely on the official estimates given by the Energy Research and Development Administration in its most recent report on breeder benefits. From this we have extracted a base case and a "pessimistic" supply curve. The two differ in that the former predicts 5 million short tons of U_3O_8 available at $100 per pound, while the latter predicts only 3 million short tons at that cost. One should note, however, that official figures for identified reserves of economically recoverable U_3O_8 are currently quoted at 700,000 short tons.

Technological Options

As PETG supplies for the nonelectric energy sector dwindle, they will be replaced by oil shale, synthetic gaseous and liquid fuels from coal (SYNF), or hydrogen produced by electrolysis (ELHY). It can be argued that biomass derived from solar energy is another source that should be included in this category, although we have not done so explicitly.

The development of shale oil products by existing mining and surface-retorting technology is apt to be limited by the availability of water and the problems of disposing of spent shale waste. We have allowed for shale's initial commercial appearance in 1985, a production of one million barrels per day (oe) by 1990, and a constant increase of production by one million barrels per day (oe) in each five-year period thereafter.

SYNF production could begin to grow significantly in the early 1990's. We assume it to be available at a cost of $3 per million Btu, with a conversion efficiency of 67 per cent and a coal cost of $1 per million Btu. Under base case assumptions, we project the combined output from shale and SYNF to be eight million barrels per day (oe) by the year 2000, almost equal to the 1975 levels of domestic crude oil production.

ELHY is assumed to be available at about $5 per million Btu, assuming that electrolyzers will achieve 100 per cent efficiency and that on an equivalent-energy basis the value of hydrogen is no different from that of any other fuel. With these assumptions, ELHY does not become economically competitive with SYNF until coal costs rise above $2 per million Btu, or unless the cost of nuclear base-load electricity is decreased by future developments. Eventually, thermochemical processes may lead to reduced costs for hydrogen production. We do not allow for this explicitly in our calculations, however, because of the uncertain state of this technology.

We combine the production of electricity from geothermal sources and from wind and waste products, together with hydroelectric generation, and refer to them all as hydro. In 1970 this category accounted for 16 per cent of the electricity generated. It is assumed that the hydro component will grow steadily at 2 per cent annually.

Fossil-fired plants will continue to produce electricity in the future for at least two reasons. As of 1970, about 45 per cent of these plants used oil or gas. Even if no additional PETG-consuming plants has been built after 1970, those in service would continue to operate through their useful lifetimes, thus requiring a significant amount of PETG input to the electric sector until the end of the century. Coal-fired plants are expected to provide a minimum of 40 per cent of all new electric energy supplies until the year 2000, in order to accommodate cycling and peak-load requirements. After 2000, it is assumed that these requirements can be reduced linearly to zero in twenty years. By 2020, for example, low-cost storage technologies are likely to become available. This would then make it economical for nuclear plants to meet the cycling and peak loads of a system, in addition to the base loads.

Light-water reactors (LWR's) appear at present to be, on a national average, the lowest cost plants for base-load generation. Operations with and without plutonium recycle are included in our model. Our calculations indicate that stockpiling plutonium for future breeders is the economically advantageous choice, providing the FBR becomes available by the year 2000 and its breeding gain is limited to the low value assumed here. The model also allows for a variation in the tails assay at which future enrichment plants will operate. We generally find it preferable to aim for a 0.2 per cent rather than 0.3 per cent tails assay as uranium ore costs increase.

The high-temperature gas-cooled reactor (HTGR) has been introduced into some of these calculations in order to test the sensitivity of breeder benefits to the existence of a high-performance converter. Thus, somewhat unrealistically, we assume HTGR capital costs to be equal to those of the LWR and fuel cycle costs to be only somewhat higher for HTGR than for the LWR with plutonium recycle. We also assume the HTGR can appear in substantial numbers commercially by 1990, a full ten years before the FBR, although at the moment it still lacks sufficient industrial backing. The high-temperature advantages of the HTGR for process heat generation or thermochemical hydrogen production are not specifically taken into account. Only its potential advantage in conserving expensive uranium is included in our analysis.

The FBR assumptions here are decidedly conservative. We postulate that indecision will continue to slow down the U. S. program and that no significant commercial introduction of the FBR will occur before 1995; that FBR's will constitute no more than 20 per cent of the new plants installed and operating in the year 2000 and no more than 40 per cent of the new plants installed in 2005; and that the number of FBR's installed will be unlimited beyond 2005. Capital costs of the FBR are assumed to be $100 per kilowatt-electric higher than those of the LWR, implying that in order for the FBR to be competitive with the LWR it will be necessary for uranium costs to exceed $30 per pound. We assume a net breeding gain of 4 per cent (corresponding to a simple doubling time of twenty-five years). Any improvements in FBR performance or reductions in capital cost are ascribed to advanced technology (ADV, defined below). The small breeding gain limits the rate of breeder introduction, thus making plutonium quite valuable. We find that its incremental value rises from $10 per gram in 1985 to $45 per gram in the year 2000.

In order to allow for potential major technological breakthroughs, we have included an advanced technology (ADV) category in our model. This may be solar, fusion, improved breeders, or yet some other advanced technology. Its cost is assumed to be appreciably less than the FBR used in the model. The only constraint we place on the ADV is that it appear commercially no sooner than twenty years after the FBR.

Cost estimates for these technology options are summarized in Figures 1 and 2 (pages 29 and 30).

An Example of Transition, Using Base Case Results

The shift from the present PETG-dominated energy economy to one dependent on nuclear or coal, or both, may occur along various paths. For purposes of illustration, we present one mode of transition, obtained from the base case calculations. In this case, the uranium supply curve has its nominal value, coal costs are assumed to rise with increasing use, and the nuclear reactor mix consists only of LWR's and FBR's. Figure 3 (page 31) indicates the gradual transition in electricity generation from fossil fuels to LWR to FBR to ADV, along with a

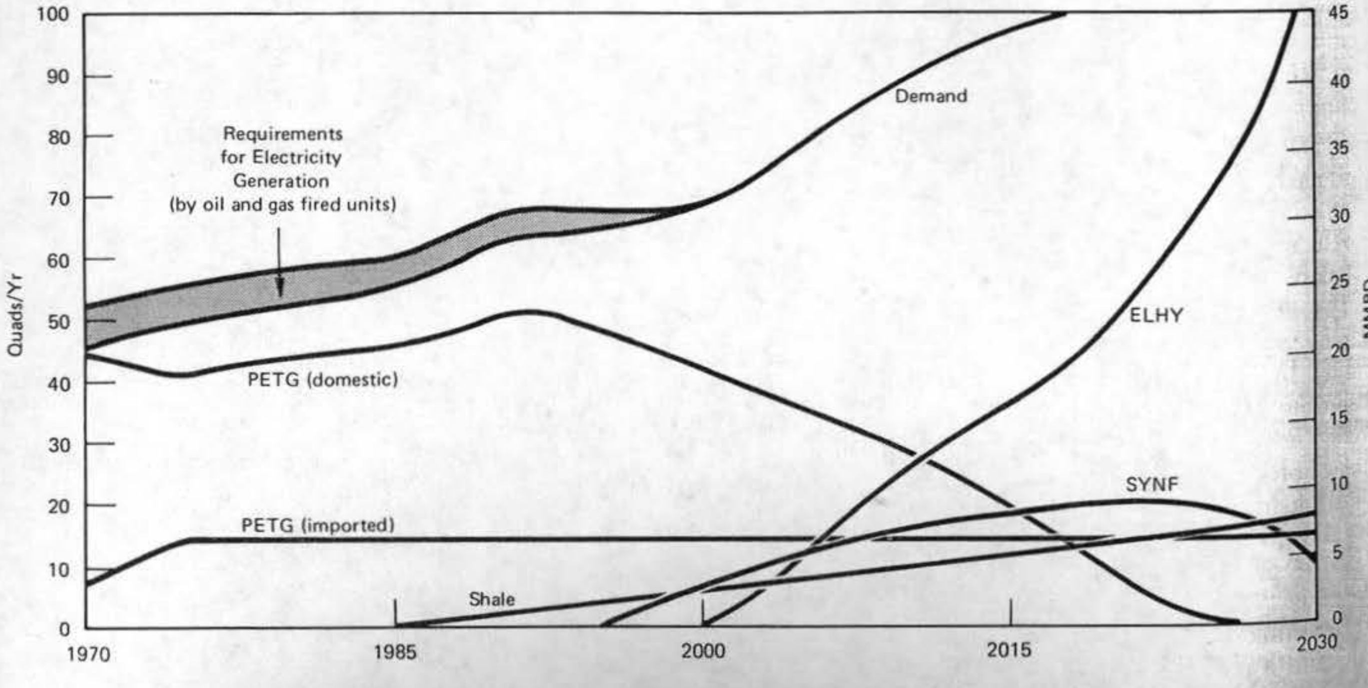


Figure 4 Nonelectric energy demand and production through the year 2030

relatively small but steady contribution from hydro between 1970 and 2030. The units of measure are quadrillions of Btu, or quads (1 quad = one-thousandth of a Q = 10^{15} Btu). This can also be expressed as gigawatts-electric of base-load capacity equivalent, at a 75 per cent capacity factor, or in kilowatt-hours of electricity generated at a given (34 per cent) conversion efficiency. Figure 4 (page 32) shows the corresponding shifts in the nonelectric sector, from PETG to shale and SYNF and then to ELHY. The area under the domestic PETG curve corresponds to the two-quad resource base. The units of measure are quads or million barrels per day (oe). Note that the shaded area represents the requirements for old oil- and gas-fired generating units.

Figures 3 and 4 may be literally interpreted as showing a gradual shift to a "hydrogen economy." Alternatively, one could interpret them as indicating a rapid shift toward an "all-electric economy." Needless to say, the transition indicated is sensitive to the comparative costs of nuclear-generated and coal-generated electricity. Electricity demand would change from the base case if the FBR were delayed indefinitely and coal costs remained constant. Such an extreme departure from the base case would have major consequences. Under those conditions, coal consumption in 2015 would rise dramatically from 75 quads (under base case assumptions) to 180 quads if coal costs remained constant and the FBR were absent.

By presenting the base case results in some detail, it is not our intent to argue that a firm commitment is warranted at this time to an all-electric or an all-hydrogen economy. Rather, it is to underscore the fact that in the foreseeable future a much greater reliance on both coal and nuclear energy will be required to sustain the general economy.

Finally, we wish to observe that the rising energy prices given by the base case calculations lead to energy demand growth rates significantly lower than those of the past. This is shown in Figure 5 (page 33), where for the sake of comparison we have included points obtained by the Ford Foundation Energy Policy Project. Interestingly enough, our model suggests that the uncertainty of knowing whether our ultimate domestic PETG reserves will be two quads or three quads has little effect upon demand projections until shortly before the year 2000. Presumably, in the interval, continued effort in exploration and production will indicate more reliably which of these two assumptions lies closer to the truth. In the absence of relief from rising real energy prices, we expect strong market responses in the direction of energy conservation. Technological advances that promise energy savings (such as solar-assisted heating and cooling, and improved auto efficiencies) are likely to be adopted by the public if energy prices continue to rise.

Benefits of Future Technologies

We are concerned principally with two future technologies: SYNF, dependent on coal, and FBR, which essentially decouples the dependence of the nuclear option from the availability of uranium. In the table (page 34) on "Benefits of New Technologies" we show the interdependence between the economic benefits of these two technologies. The two center columns of figures in the table refer to the base case results, where we assume that two quads PETG are available and that coal costs rise with utilization. In the absence of the FBR, economywide energy costs would rise by \$26 billion at a 10 per cent annual discount rate and by \$435 billion at a 5 per cent annual discount rate. Including the FBR but excluding SYNF would result in a cost penalty of \$8 billion at a 10 per cent annual discount rate. The two technologies, however, are partial substitutes for each other. That is, total costs would increase by \$47 billion if neither were available during the time horizon of our analysis and the annual discount rate were 10 per cent.

Numbers in the two lefthand columns illustrate the extreme case, in which coal costs remain constant, independent of utilization rates. As expected, SYNF benefits in that case rise dramatically, while FBR benefits drop. Once more, the joint benefit of both technologies together exceeds the sum of the individual contributions. On the other hand, the benefits of SYNF are damped significantly if three quads PETG are assumed. (See the two righthand columns of the table.) In that case, the introduction of high-cost SYNF technology could be delayed by another decade after 1990. The basic message of these figures is that, in the absence of reliable knowledge of ultimate oil and gas reserves, of ultimate uranium reserves, and the cost of coal with increased use, both SYNF and FBR technologies represent valuable forms of insurance against future energy shortages.

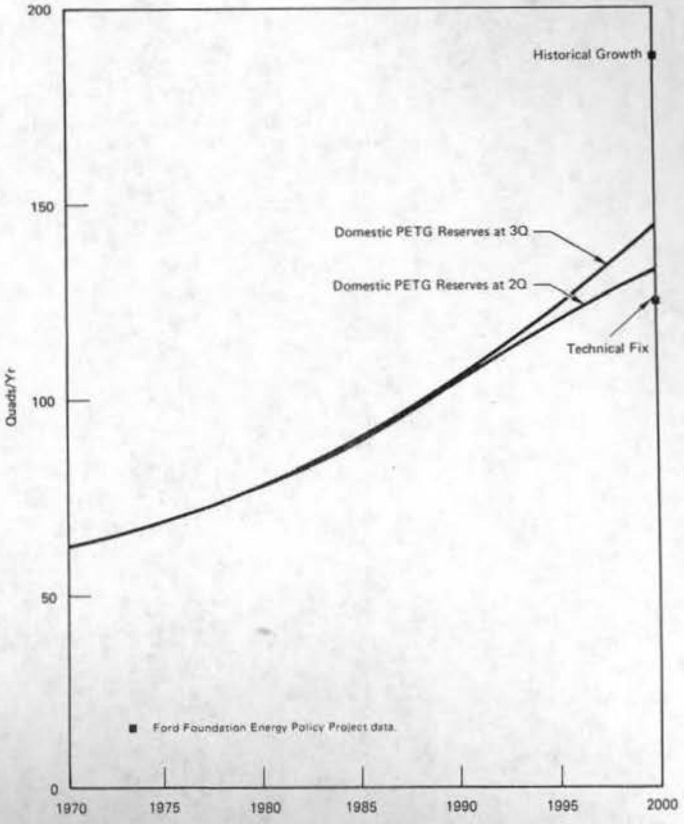


Figure 5 Total energy demand to the year 2000

Economic Costs of a Nuclear Moratorium

The model used for these benefit-cost analyses can also be applied to quantify the economic costs of a nationwide nuclear moratorium. This is done by calculating the difference between the economywide costs of meeting energy demands with and without nuclear power. We define a moratorium as a situation in which the total installed capacity of LWR's in the United States is limited to 50 gigawatts-electric, a level that will be reached before 1980.

To offset a nuclear moratorium, it would not be realistic to rely upon the advanced technologies (solar or fusion or both) until the 21st century. Moreover, it would not be politically prudent to rely upon further increases in our imports of oil and gas. For the next twenty to forty years, this leaves us with just two alternatives to nuclear energy: (1) heavy reliance upon coal for the production of both electricity and synthetic fuels, and (2) conservation, induced by sharp rises in energy prices. Both routes are expensive.

The model automatically selects a minimal-cost *combination* of those energy supply and conservation options that are assumed to be available. In the base case, for example, it would be optimal for coal consumption to rise far more rapidly than it has in the past — quadrupling from 1970 to 2000. In the event of a nuclear moratorium, coal consumption would have to rise sixfold over this period, to reach 75 quads by the year 2000. It is highly doubtful that this could be accomplished in an environmentally and economically sound fashion.

Conservation could reduce energy demands, but it too has a cost — one that can be inferred indirectly from the price consumers are willing to pay for energy rather than do without it. For example, as shown in Figure 6 (page 35), with nuclear energy available (the base case assumption), in the year 2000 the price of electricity would be \$24 per 10^3 kilowatt-hours and the quantity demanded would be 6.6 trillion kilowatt-hours. With a moratorium, the cost of electricity would rise to \$38 per 10^3 kilowatt-hours. This price rise would induce conservation, and demand would be expected to drop by 19 per cent.

For the year 2000, the costs of a nuclear moratorium — the loss in "consumers' surplus," due to higher

BENEFITS OF NEW TECHNOLOGIES ($ BILLIONS)[a]

	Constant Coal Costs[b]		Rising Coal Costs[c]			
Total Amount of Oil and Gas Available Domestically	2Q[d]		2Q[d]		3Q[e]	
Annual discount rate	10%	5%	10%	5%	10%	5%
FBR benefits	4	123	26	435	15	270
SYNF benefits	103	176	8	0	3	0
FBR + SYNF (combined) benefits	127	587	47	449	22	277

a. Present values of the differences in economywide energy costs, with and without the specified technology, excluding R&D costs, discounted to 1975.

b. Coal costs remain $1/MM Btu, regardless of the amount consumed.

c. Coal costs remain constant at $1/MM Btu up to an annual consumption rate of 25 quads (twice the 1970 level). Thereafter, they rise linearly to $2 at 50 quads, $3 at 75 quads and so on. This is the base case assumption.

d. $Q = 10^{18}$ Btu. 2Q is equivalent to 45 years of supply at 1970 rate of production.

e. 3Q is equivalent to 68 years of supply at 1970 rate of production.

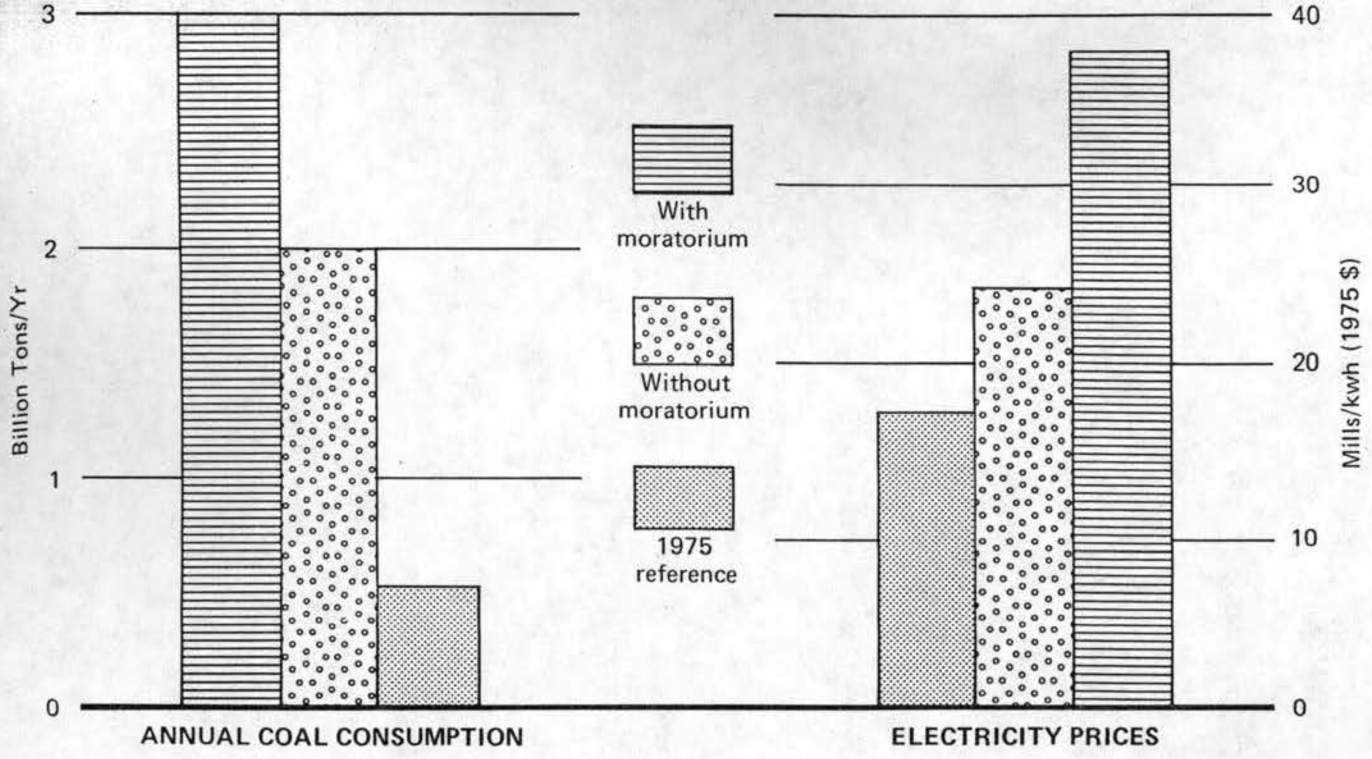


Figure 6 Projected consequences of a nuclear moratorium in year 2000

electricity prices — would be approximately $80 billion. Discounting and summing over all future years, the total costs would amount to more than $300 billion at a 10 per cent annual discount rate and $2,500 billion at a 5 per cent annual discount rate. This is our best estimate of the cost of shifting to a predominantly coal-based and conservation-oriented economy. Nearly half of these costs would be reflected in each month's residential electricity bills. The remainder would be paid in the form of higher prices for all goods and services that consume electricity.

Two additional remarks should be made. First, since our model assumes a given rate of income growth, the damping effect of rising energy prices on the general economy is not considered. If it were, the overall economic cost of a moratorium could be still higher. Second, one should also compare our numbers with estimates that have been made of possible damages resulting from a catastrophic accident following a core meltdown. In this manner, one could then begin to compare the costs and benefits of a national nuclear moratorium.

The Past as Prologue

For some time now, Washington bureaucrats have been holding staff meetings in an attempt to find methods for conserving energy by cutting waste. According to a memorandum that followed one such meeting, "It is estimated that 20 per cent (of the fuel consumed) can be saved if carburetors are properly adjusted, if cars are started more slowly, and if their rate of speed is such as to get the fullest possible use out of the gasoline.

"I also wanted to ascertain whether people driving back and forth to work could not double up with others who use their automobiles for this purpose. Questionnaires have been distributed through the department ... We may be able to improve parking conditions ..."

The memo came from the Secretary of the Interior, Harold Ickes. It was dated June 13, 1941.

According to Marcus Aurelius, "That which comes after ever conforms to that which has gone before."