Energy crises in perspective

Estimates of US energy resources and projections of future energy consumption show that the country has enough fossil fuel to last 500 years and enough nuclear fuel to last for a million years.

John C. Fisher

How real and long lasting is the current energy crisis? There is reason to believe that domestic fossil fuels will continue to be available, at slowly declining prices (in constant dollars), in adequate amounts to support total anticipated energy consumption of the US and the world for many centuries. There is also every reason to believe that domestic nuclear fuels will continue to be available, at slowly declining prices (in constant dollars), in adequate amounts to support total anticipated energy consumption for many millenia. If nuclear fuels or other energy sources take an increased proportion of the load, the fossil fuels will last correspondingly longer. Thus, the current energy crisis, although very real, should be viewed as a transient perturbation of the long-term trajectory of our energy economy.

Current energy crisis

The energy industries are managed by men whose decisions are based on anticipated future conditions; unexpected social or political upheavals can confound their plans and a crisis can ensue. The unanticipated closing of the Suez Canal in 1967 precipitated a crisis in Europe because a larger tanker fleet was suddenly and unexpectedly needed to carry oil around Africa to Europe. Within a few years, the tanker fleet was built and the crisis was over. The unanticipated environmental mass movement of the late 1960's and the early 1970's precipitated a crisis in the US because more petroleum products and more refinery capacity were suddenly and unexpectedly needed as consumers shifted to oil from coal and from planned uranium. Within a few years, the refinery capacity will be built and the petroleum products will be flowing.

A large part of the US energy crunch of the 1970's has been the result of unanticipated social factors, in particular the environmental movement. The demand for distillate oil turned out to be much higher than anticipated as coal-burning powerplants shifted to oil, as electric utilities substituted oil-burning gas turbines for delayed nuclear reactors, and as automobiles began burning more gasoline because of newly legislated safety and antipollution equipment.

Natural-gas price regulation was another contributing factor. In 1970 the owner of a gas well got only about a third the money from selling gas as did the owner of an oil well from selling oil with the same heating value. The motivation for developing new gas reserves eroded and the supply began to decline, while at the same time the increasing desirability of gas, relative to other fuels, caused demand to soar. With supply and demand decoupled from their customary meeting-ground in the marketplace, they moved so far out of balance that rationing, imports and synthetic gas have become necessary. But it appears that the underlying cause of much of the imbalance—the artificially low price set for interstate natural gas—is now more widely understood and appreciated, and the price of natural gas will be allowed gradually to seek its competitive level. With the price and market mechanism back at work, we can expect supply to increase and demand to decrease until after several years of adjustment the two again come into balance.

The uncertain viability of high-cost US crude oil and refined products in the face of a potential flood of low-cost imported crude oil and refined products inhibited US petroleum development and refinery construction, adding to the current crisis. Such uncertainty can only be dispelled, and action initiated, by a clear government policy for protecting US energy industry investment and infrastructure.

The energy crunch of the 1970's was caused by factors that are so clearly identifiable, so clearly understood, and so readily compensatable through the ordinary response mechanisms of government, industry and technology that there can be little doubt of its transitory nature. There are real shortages of distillate fuel now that the crunch is on, and there are sharp price rises associated with the shortages, but I expect that the crunch will be over in two or three years and that prices will drop back to lower levels. With this comment I would like to set aside the energy crunch, and consider some of the longer-range aspects of energy resources and consumption.

Projected energy consumption

In projecting energy consumption, let us first consider just the US, which consumes much of the world's energy and is to some extent representative of the industrialized regions of the world. And before projecting into the future, let us look at the past.

The pre-industrialized US appears never to have passed through a period of low *per capita* energy consumption once the European settlers arrived. The first settlers found a continent completely covered with virgin forest. This standing timber was available as fuel wood for the cutting, and the small population began consuming energy at a high *per capita* rate, far beyond the level of energy consumption in traditional societies, as soon as they stepped ashore. In 1850, for example, *per capita* energy consumption was nearly half as great as it is today. Fortunately for us, coal, oil and gas were discovered and put to use as the forests were cut down and the population grew, and the transition from fuel wood to fossil fuels was smooth.

Growth in energy consumption still continues. Five key factors affecting the growth rate can be identified and quantified; they are listed with their current annual growth rates:

- Total population, 1.3%.
- *Per capita* residential energy, 2.8%.
- Energy content per unit goods and services, 0.9% (for example, the energy required to manufacture a modern au-

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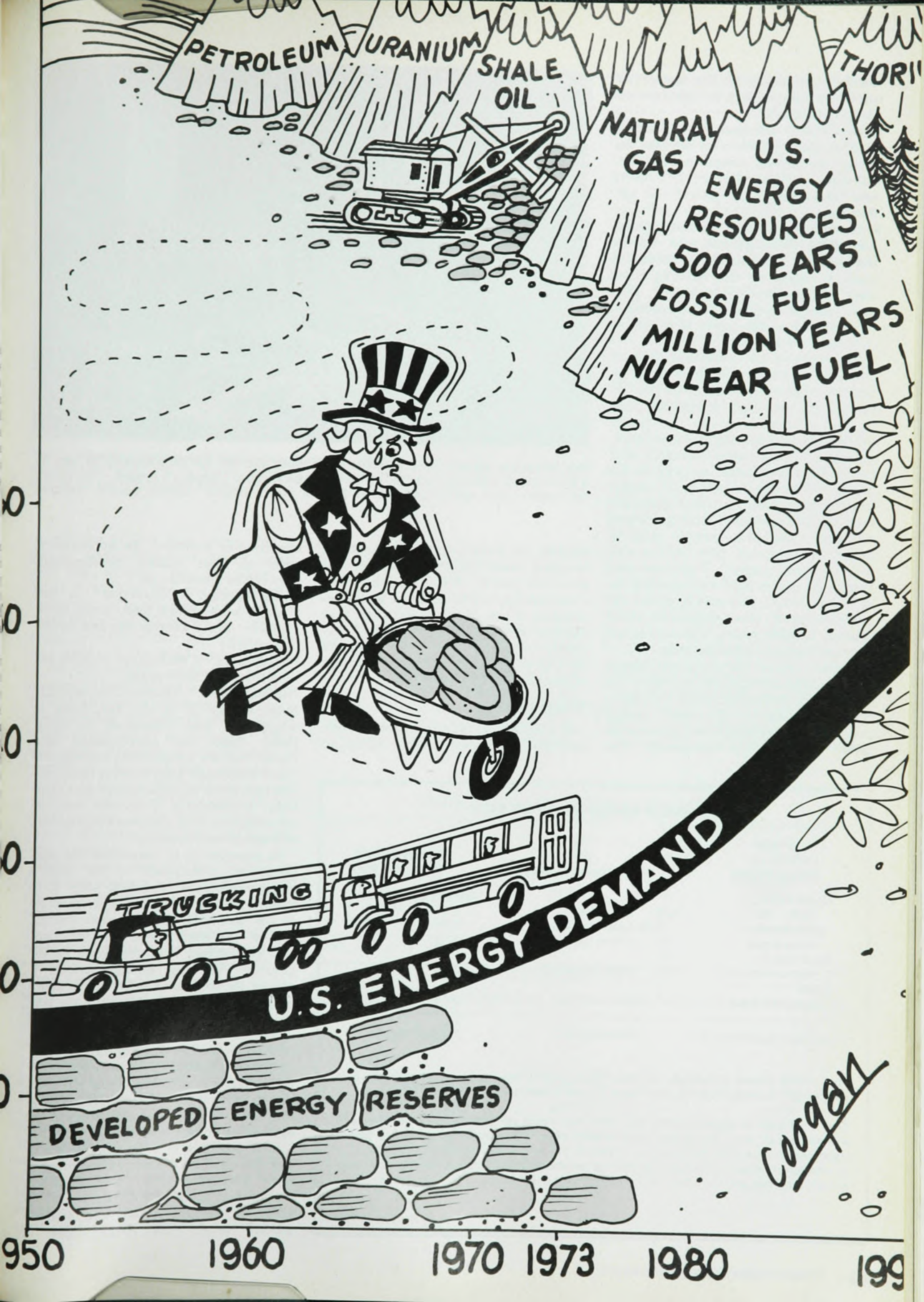
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tomobile compared to the energy required to manufacture its lighter, simpler predecessor).

- New energy consumed by all sectors of the economy, 8.5% (this includes the energy needed for computers, air conditioning, clothes drying; it reflects new invention and growth of affluence).
- Growth of non-farm working population, 2.9% (This growth rate reflects the fact that more energy is needed to support people in the working force than people who stay at home. This extra energy provides for transportation and the maintenance of people at their places of work).

Estimates of the evolution of these growth rates allow one to project the future consumption of energy in the US. Implicit in any such projection must be an assumption as to the future availability and price of the basic energy sources. For many decades, with occasional fluctuations one way or the other, the prices of all basic energy sources have been declining gradually relative to the prices of other goods and services. The past growth rates of energy consumption must reflect this fact to some degree. I assume that this trend of the past will continue far into the future: that energy prices will continue their slow downward trend relative to other prices, with occasional fluctuations one way or the other.

Table I gives the projected energy consumption for the US as 300 C for the period 1970–2000 ($C \equiv 10^{16}$ Btu). The projection for the world energy consumption, although not quite as reliable, is 1300 C for this period. Extending the projection for the next one hundred years, I find that the US consumption will be 1600 C and the world consumption will be 5000 C. In the remainder of this article, I will show that current reserves and estimated resources of fuel are not only adequate for this period but for many hundreds of years beyond the year 2000.

The Waterside Station in mid-Manhattan supplies 900 000 kW of electricity as well as 4.2×10^6 lbs steam per hour to the Consolidated Electric Company's system. The plant's ten boilers burn natural gas and oil but not coal. (Photo: Edison Electric Institute)

Energy sources

A number of different sources have provided significant energy inputs at one time or another. In approximate order of their historic development, they can be classified as:

Solar energy. Conversion via fuel wood, work-animal feed, direct windpower, direct waterpower and hydroelectricity

Fossil fuels. Combustion of coal, petroleum and natural gas

Nuclear fuels. Fission of U and Th.

Solar energy is dilute, but large in magnitude and unlimited in time. Fossil fuels are concentrated and cheap, but are exhaustible and can become exhausted after several centuries. Nuclear fuels are practically inexhaustible, particularly if breeder reactors are able to utilize the common isotopes of uranium and thorium.

In attempting to determine the adequacy or inadequacy of the world's energy resources, the first step is to make as good an estimate as possible of the available flux of solar energy, and of the fossil fuels, nuclear fuels, and geothermal heat reservoirs in the ground. The flux of solar energy is easiest to estimate, as it comes down from the sky and has been fairly well measured. Hydropower, as a special aspect of solar energy, is equally easy to estimate. The subterranean energy resources present more difficult problems, as they are usually hidden from direct view until reached by drilling, and many of the promising areas of the earth have not yet been drilled.

The quantity of solar energy reaching the earth at the upper boundary of the atmosphere is well known, amounting to 530 000 C per year. Of this, on average about half reaches ground level: As rough rules of

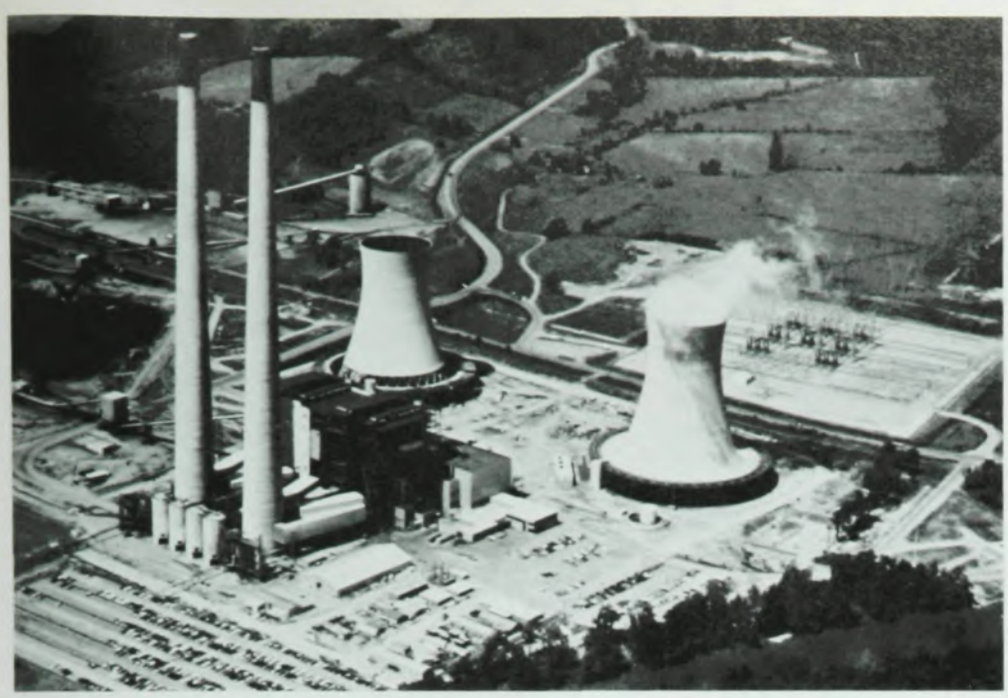
Sources of Energy for the US 1970

Energy Source	Conventional Quantity	Energy content ($C \equiv 10^{16}$ Btu)	
		Units of C	Percent
Fossil fuel			
Coal	525 million tons	1.28	20
Petroleum	5.36 billion barrels	2.65	41
Natural gas	21.4 trillion cubic feet	2.13	33
Solar energy			
Hydroelectricity	253 billion kilowatt-hours	0.26	4
Other			
Miscellaneous		0.13	2
		6.45	100

The United States consumes so much energy that the annual number of Btu's is very large. In order to bring such large numbers down to size, I define a C-unit as

$$1C = 10^{16}\ \text{Btu}$$

One C of heat is approximately the heat that would be generated by burning 400 million tons of coal, the approximate amount of coal consumed in the United States each year for the past half century. (Hence the use of the letter C for the unit.) It is also approximately the heat required to warm up lake Michigan one degree Fahrenheit, for there are just about 10^{16} pints of water in the lake.



The coal-burning Conemaugh Generation Station in western Pennsylvania consists of two 850 000 kW units. It is jointly owned by nine utility companies that supply power throughout the mid-Atlantic states. (Photo: Edison Electric Institute)

thumb, the highest solar energy flux at ground level, found in desert lands near the equator, can be taken as about a million Btu per square foot each year. The average flux over the lower 48 United States can be taken as about ½ million Btu per square foot each year. If the total energy supply of the US in 1970, amounting to 6.45 C, were to be obtained from solar energy with an overall conversion efficiency of 10 percent, an area of about 50 000 square miles would be required. This area seems large, but it is only about 3 percent of the land now devoted to farms. It is clear that solar-energy resources are far more than adequate for supplying the world with energy, although of course they may not be the least expensive.

Hydropower resources are limited to rivers and streams wherever they happen to be or wherever they can be diverted to. The total resource base—if all potentially developable falling water were turned to hydroelectricity—amounts to about 1 C annually in North America and 9 C annually in the world. This is not enough to make up the US or world totals for energy, but is enough to allow hydroelectricity to grow for some time at its historic rate, amounting to four percent of US energy input and six percent of world energy input (on a fuel-equivalent basis).

Next consider the various mineral fuels of current significance: coal, petroleum, natural gas, uranium and thorium; and the mineral fuels of potential future significance: oil shale and tar sand. These minerals are not distributed uniformly throughout the earth, but are concentrated to varying degrees, in deposits of varying size, at different depths, in different regions of the world.

Resources and reserves

We must distinguish between total resources and reserves. A lack of clear thinking in this regard has led to much misunderstanding of the current energy crisis. At any given time, some of the known mineral deposits have been well mapped and have been developed for production, while others remain undeveloped. A deposit is developed when the necessary investment has been made in whatever capital equipment is required to produce the mineral from the deposit and to move it to market. For example in the coal industry this means acquisition of mining rights, investment in mining equipment, and installation of transportation equipment to move the coal to the nearest existing railroad or waterway. Investments of this nature are made in anticipation and expectation of profitable production. The minerals that have been developed for profitable production are called "reserves." This definition of reserves is followed most closely in the oil, gas and uranium industries, and perhaps less closely in the coal industry where well-known easily developable deposits may be counted as reserves.

Reserves amount to current inventory of minerals in the ground. As mineral production proceeds, material is withdrawn from inventory and reserves are diminished. At the same time, as investments are made in developing additional deposits, new inventory is created and reserves are increased. Current reserves at any given time reflect the interplay of these opposing tendencies. Reserves can be measured in terms of the reserve-to-annual-production ratio, which equals the number of years that the inventory would last if production continued at its present rate (and if no new inventory were developed). Economic forces keep the reserve-to-production ratio for many minerals at 10 to 20 years.

Should the reserve-to-production

Table 1. Projected Energy Consumption

Region	30-year total* (1970–2000)	100-year total* (1970–2070)	Quality of projection
United States	300	1600	Highest
Other industrialized	800	2800	Lower
Non-industrialized	200	800	Poor
World total	1300	5000	Intermediate

* *Units of C ≡ 10^{16} Btu*

Table 2. US fossil-fuel and nuclear-fuel reserves and resources

Energy source	US reserves*	US additional resources*
Fossil fuels		
Coal	900	6 600
Petroleum	30	1 640
Natural gas	30	640
Shale oil	—	15 000
Total	960	24 000
Nuclear fuels		
Uranium	22	22 000 000
Thorium	—	34 000 000
Total	22	56 000 000

* *Units of C ≡ 10^{16} Btu*

ratio for some mineral drop from 12 years supply to 10 years supply over some period of time, we need not necessarily assume that ultimate mineral depletion is approaching. It may reflect only prudent trimming of inventory at a time of rising interest rates, or perhaps it may reflect growing uncertainty about a potential flood of low-cost imports.

Known undeveloped deposits are often called "submarginal," because they cannot be developed to produce minerals at a profit with today's technology, today's costs, and today's prices. Yet as the *economy of scale* reduces costs, and as *new technology* reduces costs, submarginal deposits tend progressively to be developed and are transformed into reserves. As an example, when oil is withdrawn from an oilfield, it flows easily at first, then less easily, then must be pumped, and finally, with whatever state of technology exists at the time, the cost of getting it out exceeds the price that it will bring. The inventory of recoverable oil has been exhausted. The reserves are gone. Yet 70 percent or so of the original oil in place in the field still remains there as a submarginal resource. As new recovery technology is developed, a time usually comes when it pays to redevelop the same field for additional production by waterflood, fire-sweep or some other technology.

New reserves are created whenever an old oil field or coal mine is redeveloped, and in principle, the process can be continued time after time until the oil and coal are completely developed.

In addition to reserves and known submarginal deposits, there are additional deposits not yet discovered. And (particularly for oil and gas) there is substantial worldwide activity devoted to discovering them. Once discovered, some will prove to be easily developable for low-cost production, and these may be classified as unknown deposits of economically recoverable minerals. Others will prove not to be profitably developable, and these may be classified as unknown submarginal deposits. The quantities of undiscovered resources clearly are the most difficult to determine, but geological and geophysical experts have learned to make respectable estimates.

Resource and reserve estimates

US Geological Survey specialists have compiled[1] estimates of US fossil-fuel resources including coal, petroleum liquids, natural gas, and oil from shale. Their estimates are generally made on geological projections of favorable rocks and on anticipated frequency of the energy resource in the favorable rocks. The estimates of submarginal resources of oil from shale include only relatively rich deposits that might be recoverable with today's technology at less than two or three times today's oil prices, and exclude much larger quantities of lower-grade shale. I believe these Geological Survey estimates are the best objective estimates available for the U.S.

Big Rock Point Nuclear Power Plant is one of 15 boiling-water reactors currently in use. It has been producing 75 000 kW since December 1962 and recently set a record by giving 198 consecutive days of service. (Photo: Edison Electric Institute)

Total cumulative US consumption of fossil fuels has amounted to about 200 C through 1970, and 1970 consumption amounted to about 6.5 C. The data in table 2 show that the US has abundant fossil fuel reserves and resources. Present fossil-fuel reserves are more than adequate to supply the 300 C of energy required for the balance of this century. If we accept the projections that annual *per capita* energy consumption will level off at 450 million Btu *per capita* and that annual *per capita* fossil-fuel consumption for non-energy purposes such as asphalt tiles, road oil and petrochemical feed-stocks will level off at 50 million Btu per year; then, in an economy totally energized by fossil fuel, the annual *per capita* fossil-fuel consumption would level off at 500 million Btu. If we assume in addition that the US population will stabilize at about a billion people within the next few centuries, it follows that annual fossil-fuel consumption (energy uses plus non-energy uses) will level off at about 50 C per year. Under these conditions, in an economy where all energy was derived from fossil fuels, US fossil-fuel reserves and resources would be enough to last about 500 years

$$\frac{25\ 000\ \text{C reserves} - \text{resources}}{50\ \text{C per year}} \approx 500\ \text{yrs}$$

Uranium and thorium contain so much energy per pound that it makes good sense to consider very low-grade ores in estimating resources. The most comprehensive estimates have been made by an Interdepartmental Study[2] with participation by nine Federal departments and agencies. The uranium reserves shown in table 2 correspond to utilization of 1.5 percent of the potential energy of the uranium, as is appropriate for today's light-water reactors. The nuclear resources correspond to utilization of 80 percent of the potential energy of uranium and thorium as may become possible with the new technologies of breeder reactors. Although nuclear fuel reserves available with current technology are not particularly large in relationship to projected energy consumption, nuclear fuel resources are adequate for millions of years.

So far our consideration of fossil and nuclear fuels has focussed on the United States. The Interdepartmental Study[2] considered world resources as well as US resources, and using data available in 1962, they estimated that in terms of total resources "the United States is endowed with approximately one-fourth of the coal, one-seventh of the oil, possibly one-tenth of the natural gas, one-twelfth of shale oil, and one seventeenth of uranium and thorium." Since the United States has about one seventeenth of the world's land area, it appears that it may have somewhat more than its share of fossil fuels, particularly coal. I expect that as better data become available, the overall energy resources of the world will prove to be more or less uniformly distributed. Most major countries should have their proportion-

technical difficulty.

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ate share, with a few exceptions such as Japan having none, the Mideast having more than its share of oil, and the US having more than its share of coal.

In summary, we find that fossil-fuel reserves alone are adequate for 70 years. Fossil-fuel reserves and resources alone are adequate for 500 years, and nuclear resources for a million years; provided, of course, that these reserves and resources can be utilized within the bounds of environmental acceptability. Solar energy is even more abundant: the energy reaching ground level in the US amounts to about 10 000 C annually and is assured indefinitely. World energy resources are substantially larger, in approximate ratio of the world's land area to the US land area.

Although it is true that nuclear and solar resources exceed fossil-fuel resources by a wide margin, there is no immediate treat of fossil-fuel depletion to cause us to shift to nuclear fuel or solar energy. The United States supply of coal and shale oil is sufficient to last for many centuries if we choose to use it, and the same is true for the rest of the world. It is the overall socio-economics of energy supply and utilization that will determine which fuels are actually used, and on what timetable.

Future of fuels and technologies

Non-economic factors are of fundamental significance to the future of the energy industries. Every forecast of fuel availability, energy consumption, conversion technologies and electrification must be based implicitly or explicitly upon an assessment of political and social forces that provide the overall environment—the basic ground rules—within which economics and technology operate. For example, unrestricted international competition in petroleum would drop the price of crude oil five-fold or more in the United States, ruining the nation's oil and coal industry infrastructures and ruining the world's nuclear and high-performance steam-turbine infrastructures. In such a world, economics and technology would lead to the simple gas turbine as prime mover for electric power generation. Thus it is political and social factors, in large part, that determine the overall environment in which the technological and economic struggles for position among fuels and energy conversion technologies will be fought out in the US.

Fuel price levels within the US are projected to continue their historic decline (in constant dollars). For electric utility generation (but not for transportation or space heating, which already use relatively expensive clean fuel), the cost of all forms of fossil fuel is likely to double. Natural gas price at the wellhead—near where most gas-burning utilities get it—may approximately double when natural gas finds its competitive level. (Owing to relatively large transportation and distribution costs, doubling the wellhead price in the Southwest increases the price to a residential consumer in the Northeast by only about 20 percent.) The cost of utility coal may approximately double, because of increased transportation required to bring low-sulfur coal from long distances or because of the necessity for refining coal to purify it. The cost of utility oil may approximately double as utilities shift from high-sulfur residual oil (the dregs of refining) to the more expensive low-sulfur oil used by others.

The approximate doubling of fossil-fuel prices is a competitive boon to nuclear power, for it increases the cost of electricity from fossil fuel relative to electricity from nuclear fuel. There is a tendency among nuclear-power advocates to hope that one doubling will be followed by others, and to project much higher fossil fuel prices in the future; but I believe this view mistaken. Social factors are requiring the utility industry to join the rest of the country in burning clean fuel purchased at competitive prices. The price of clean fuel itself is likely to continue its historic downward trend.

When measured in constant dollars per kilowatt of capacity, the cost of constructing a nuclear power plant increased by perhaps 50 percent between 1965 and 1975, during which time the cost of a fossil steam plant increased slightly and the cost of a gas turbine power plant declined. The increase in nuclear power-plant construction costs has dealt a competitive blow to nuclear power, in effect cancelling the competitive advantage conferred by doubled fossil-fuel prices.

Advocates of fossil fuel may tend to hope that one 50-percent increase in nuclear plant construction costs will be followed by others, and to project much higher nuclear-plant costs in the future; but I believe this view mistaken. The field-construction cost lesson appears to have been learned, and there is an increasing trend toward standardization and assembly-line construction of major nuclear power-plant components. The requirements of the new licensing procedures are being better anticipated now that they are more familiar, and licensing delays may diminish. Overall, competition between nuclear power and fossil-fuel power is likely to remain vigorous.

We note that both fossil-fuel and nuclear-fuel conversion technologies are under increased pressure to improve efficiency for generating electricity. Fossil-fuel conversion efficiency is more important than before because the refined fuel required today is more costly than the formerly acceptable unrefined fuel. Nuclear-fuel conversion efficiency is more important than before because construction costs are higher, and cost per unit electrical output can be decreased by raising the output from a plant of a given size. Both technologies are moving ahead rapidly, and from the overall standpoint of electrification, one or the other or both in combination are expected to enable electrification to progress for decades. Interest is intense in the fut-

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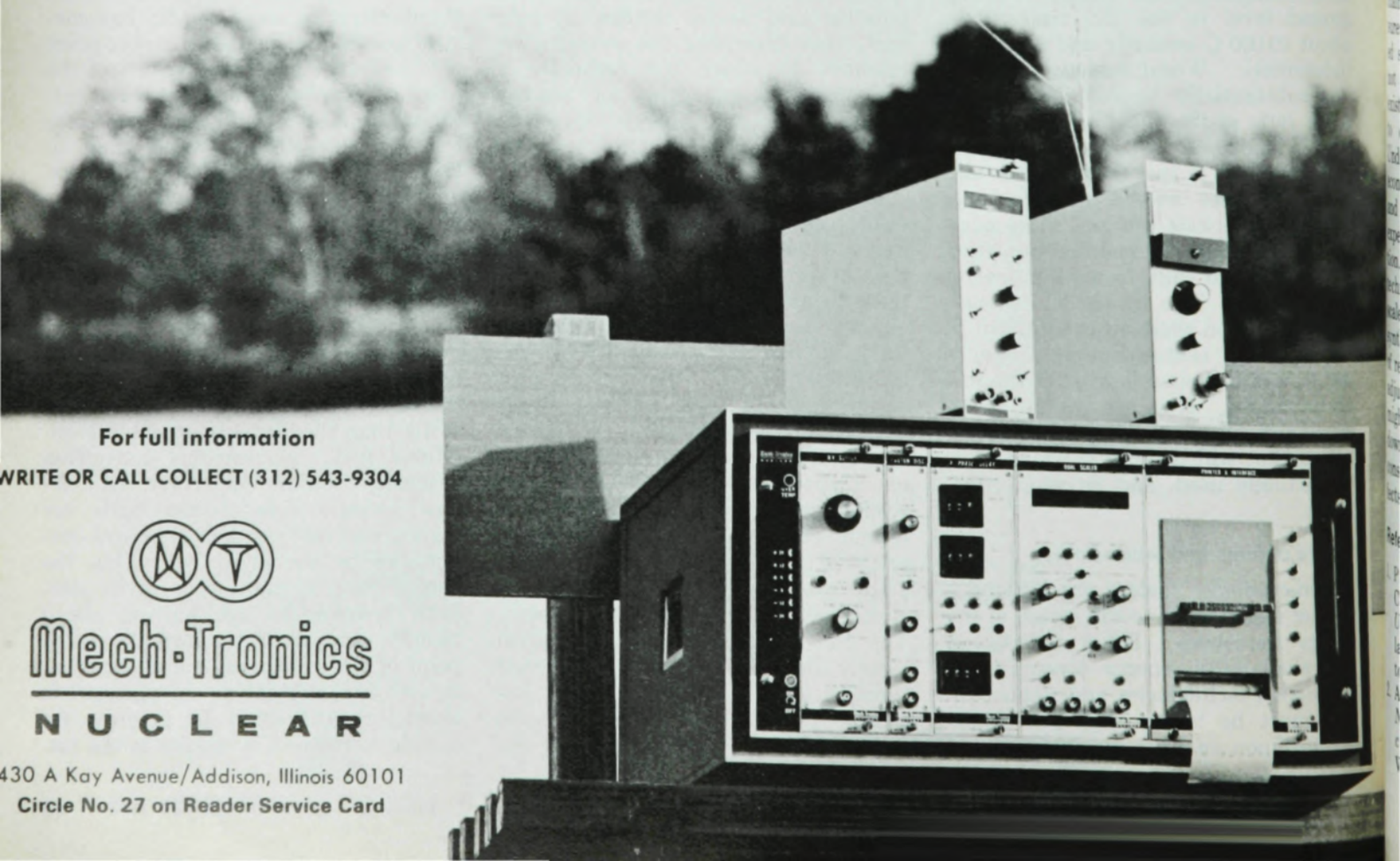

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ure market shares that will be achieved by nuclear and fossil fuels and technologies, but prudence suggests that a detailed forecast not be made. I am content to forecast continued electrification, and to watch with interest the competitive battle among the various fuels and technologies.

Long-range perspective

Although it is not possible from this vantage point to determine what combination of fuels and technologies will be leaders in the next century, we are as fortunate with technologies as with fuels in having many viable alternatives. We possess the technologies that will enable the cost of electricity to be reduced, the efficiency of generation to be increased, and electrification to proceed.

Although crises may be expected from time to time, the fundamentals of the energy industries are sound. Fossil fuels, nuclear fuels and solar-energy resources are abundant. Improved technologies for generating and utilizing electricity can increase the extent of electrification. The greatest impondерables may be the future acceptability and price of the various forms of energy: acceptability as affected by ecological and environmental pressures, and price as affected by domestic and international political pressures.

Although no one can be sure what the future will bring, I would suggest a potential future for the United States in which environmental pressures require that all fuels be refined, and that all lands disturbed by mining be reclaimed; and in which political pressures require that oil imports be limited so that domestic production does not shrink, with the consequence that existing marginal producers continue to determine domestic fuel prices. Under these conditions the US energy economy, with its moderate fuel prices and high technology content, might be expected to continue its historic evolution. Through further progress of technology and further economies of scale, particularly with the advent of synthetic oil from coal or shale, prices of refined fuels (and of electricity after adjusting for the shift to refined fuel) might be expected to continue their downward trends, when measured in constant dollars to strip away the effects of inflation.

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