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Bulletin of the
Association of Engineering Geologists
Vol. XIII, No. 2, 1976

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Energy Resources: A Scientific and Cultural Dilemma

ABSTRACT

The present large-scale use of energy and power by the human species represents a unique event in the billions of years of geologic history. Furthermore, in magnitude, most of the development has occurred during the present century. In the United States, the peak in the rate of petroleum production occurred in 1970 and that for natural gas in 1973. The peak in the world production of crude oil is expected to occur at about the year 2000 and that for coal production at about 2150 or 2200. Other sources of energy and power—water power, geothermal power and tidal power—are inadequate to replace power from fossil fuels. Nuclear power, based on the breeder reactor and utilizing low-grade deposits of uranium and thorium, has a larger potential than the fossil fuels, but it also constitutes a large and perpetual hazard.

The largest source of energy available to the earth is solar radiation. This source has a life-expectancy of a geologic time scale, is nonpolluting and is larger in magnitude than any likely requirements of the human species.

In consequence of the large supplies of available energy, the period since 1800 has been one of an unprecedented exponential industrial growth. This also has been accompanied by a world-wide ecological disturbance, including that of the human population growth. It can easily be seen that such a period of growth must be ephemeral in character and, in fact, is now almost over.

One aspect of this transition from a state of exponential growth to a state of nongrowth is the present alarm over an "energy crisis." Actually, the world's present problems are by no means unmanageable in terms of present biological and technological knowledge. The real crisis confronting us is, therefore, not an energy crisis but a cultural crisis. During the last two centuries, we have evolved what amounts to an exponential-growth culture, with institutions based on the premise of an indefinite continuation of exponential growth. One of the principal consequences of the cessation of exponential growth will be an inevitable revision of some of the tenets of that culture.

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INTRODUCTION

It has become generally recognized that the world's present civilization differs fundamentally from all earlier civilizations in both the magnitude of its operations and the degree of its dependence on energy and mineral resources—particularly energy from the fossil fuels. Energy is involved in everything that occurs on the earth—everything that moves. Succinctly, the earth's surface is composed of the 92 naturally occurring chemical elements, all but a minute radioactive fraction of which obey the laws of conservation and of nontransmutability of classical chemistry. Into and out of this system is a continuous flux of energy, in consequence of which the material constituents undergo either continuous or intermittent circulation.

The principal energy inputs into this system are three (fig. 1): (1) 174,000 $\times$ 10^{12} thermal watts from the solar radiation intercepted by the earth's diametrical plane; (2) 32 $\times$ 10^{12} thermal watts conducted and convected to the earth's surface from inside the earth; and (3) 3 $\times$ 10^{12} thermal watts of tidal power from the combined kinetic and potential energy of the earth-moon-sun system. Of these inputs of thermal power, that from solar energy is overwhelmingly the largest, exceeding the sum of the other two by a factor of more than 5,000.

Of the solar input, about 30 percent, the earth's albedo, is directly reflected and scattered into outer space, leaving the earth as short-wavelength radiation; about 47 percent is directly absorbed and converted into heat; and about 23 percent is dissipated in circulating through the atmosphere and the oceans, and in the evaporation, precipitation and circulation of water in the hydrologic cycle. Finally, a minute fraction, about 40 $\times$ 10^{12} watts, is absorbed by the leaves of plants and stored chemically by the process of photosynthesis whereby the inorganic substances, water and carbon dioxide, are synthesized into organic carbohydrates according to the approximate equation

$$\text{Light energy} + CO_2 + H_2O \rightarrow [CH_2O] + O_2.$$

Small though it is, this fraction is the energy source for the biological requirements of the earth's entire populations of plants and animals.

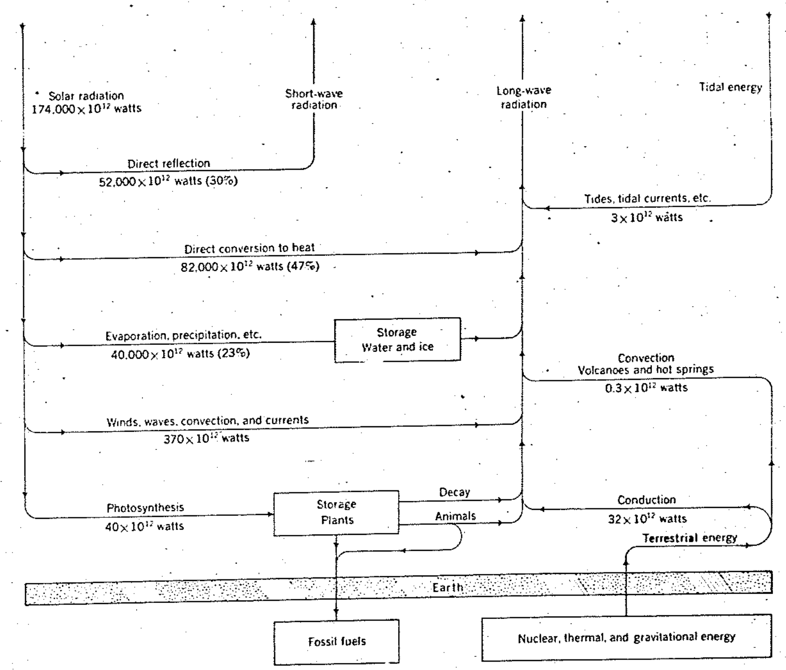

FIGURE 1. World energy flowsheet

From radioactive dating of meteorites, the astronomical cataclysm that produced the solar system is estimated to have occurred about 4.5 billion years ago and microbial organisms have been found in rocks as old as 3.2 billion years. During the last 600 million years of geologic history, a minute fraction of the earth's organisms have been deposited in swamps and other oxygen-deficient environments under conditions of incomplete decay, and eventually buried under great thicknesses of sedimentary muds and sands. By subsequent transformations, these have become the earth's present supply of fossil fuels: coal, oil and associated products.

About 2 million years ago, according to recent discoveries, the ancestors of modern man had begun to walk upright and to use primitive tools. From that time to the present, this species has distinguished itself by its inventiveness in the progressive control of an ever-larger fraction of the available energy supply. First, by means

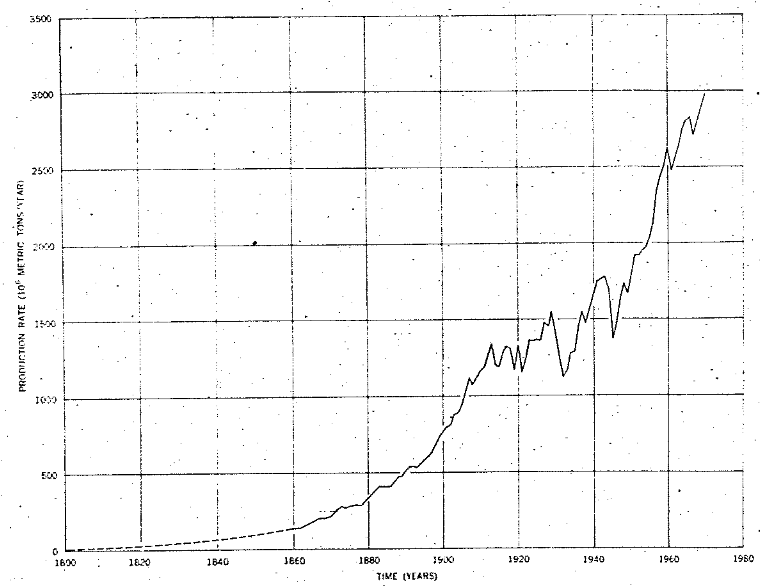

FIGURE 2. World production of coal and lignite (Hubbert, 1974, fig. 3)

of tools and weapons, the invention of clothing, the control of fire, the domestication of plants and animals and use of animal power, this control was principally ecological in character. Next followed the manipulation of the inorganic world, including the smelting of metals and the primitive uses of the power of wind and water.

Such a state of development was sufficient for the requirements of all pre-modern civilizations. A higher-level industrialized civilization did not become possible until a larger and more concentrated source of energy and power became available. This occurred when the huge supply of energy stored in the fossil fuels was first tapped by the mining of coal, which began as a continuous enterprise about 9 centuries ago near Newcastle in northeast England. Exploitation of the second major fossil-fuel supply, petroleum, began in 1857 in Romania and 2 years later in the United States. The tapping of an even larger supply of stored energy, that of the atomic nucleus, was first achieved in a controlled manner in 1942, and now the production of nuclear power from plants in the 1,000-megawatt range of capacity is in its early stages of development.

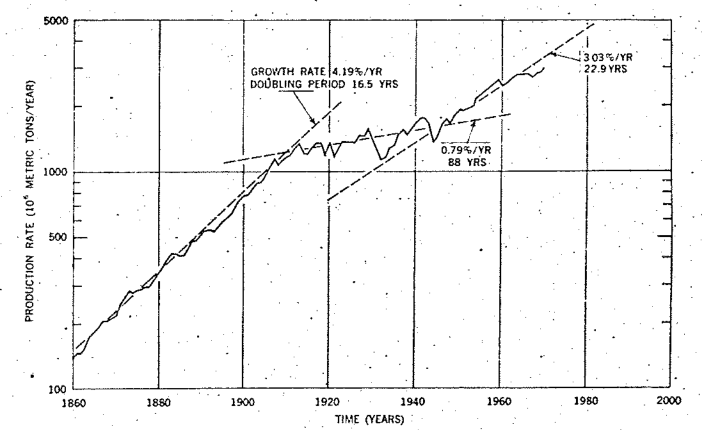

FIGURE 3. World production of coal and lignite (semilogarithmic scale) (Hubbert, 1974, fig. 4)

In addition to increased energy sources, energy utilization was markedly enhanced by two technological developments near the end of the last century: the development of the internal-combustion engine, utilization petroleum products for mobile power, and the development of electrical means for the generation and distribution of power from large-scale central power plants. This also made possible for the first time the large-scale use of water power. This source of power derived from the contemporary flux of solar energy has been in use to some degree since Roman times, but always in small units—units rarely larger than a few hundred kilowatts. With electrical generation and distribution of hydropower, first accomplished at Niagara Falls about 1895, progressively larger hydropower stations have been installed with capacities up to several thousand megawatts.

ENERGY FROM FOSSIL FUELS

To the present the principal sources of energy for industrial uses have been the fossil fuels. Let us therefore review the basic facts concerning the exploitation and utilization of these fuels. This can best be done by means of a graphical presentation of the statistics of annual production.

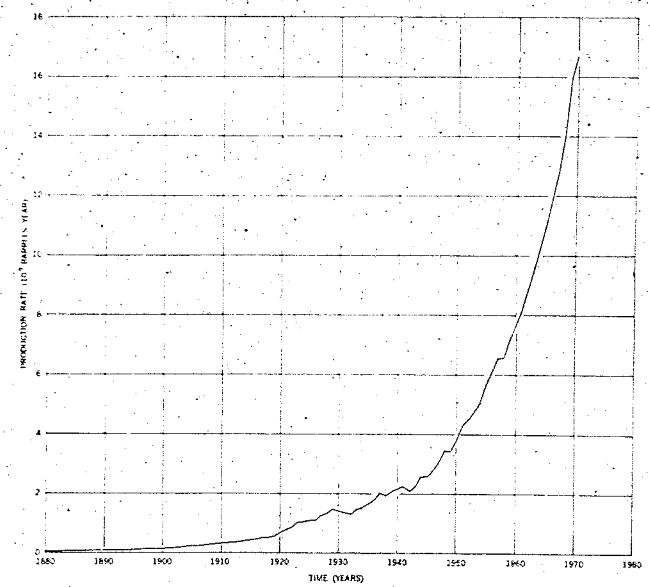

FIGURE 4. World production of crude oil (Hubbert, 1974, fig. 5)

World Production of Coal and Oil

Figure 2 shows the annual world production of coal and lignite from 1860 to 1970, and the approximate rate back to 1800, on an arithmetic scale. Figure 3 shows the same data on a semilogarithmic scale. The significance of the latter presentation is that straight-line segments of the growth curve indicate periods of steady exponential growth in the rate of production.

Annual statistics of coal production earlier than 1860 are difficult to assemble, but from intermittent earlier records it can be estimated that from the beginning of coal mining about the 12th century A.D. until 1800, the average growth rate of production must have been about 2 percent per year, with an average doubling period of about 35 years. During the 8 centuries to 1860 it is estimated that cumulative production amounted to about 7×10^9 metric tons. By 1970, cumulative production reached 140×10^9 metric tons. Hence, the coal mined during the 110-year period from 1860

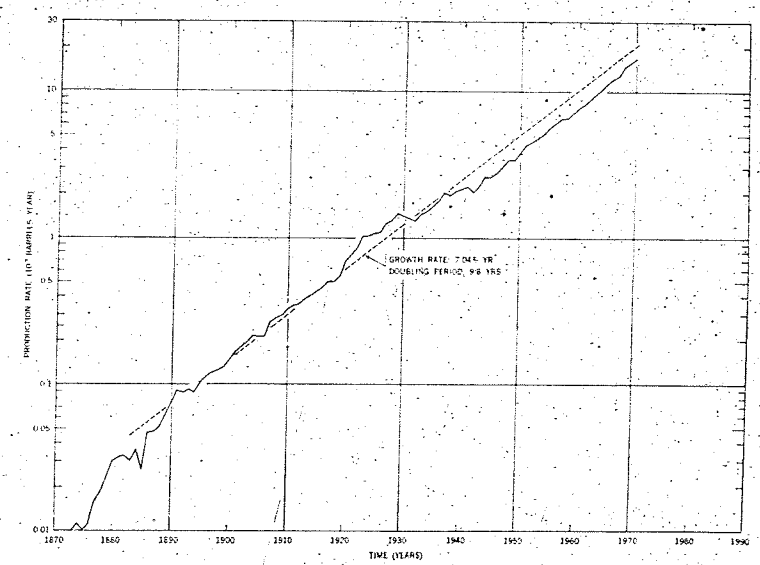

FIGURE 5. World production of crude oil (semilogarithmic scale) (Hubbert, 1974, fig. 6)

to 1970 was approximately 19 times that of the preceding 8 centuries. The coal produced during the last 30-year period from 1940 to 1970 was approximately equal to that produced during all preceding history.

The rate of growth of coal production can be more clearly seen from the semilogarithmic plotting of figure 3. The straight-line segment of the production curve from 1860 to World War I indicates a steady exponential increase of the rate of production during this period at about 4.19 percent per year, with a doubling period of 16.5 years. Between the beginning of World War I and the end of World War II, the growth rate slowed down to about 0.79 percent per year and a doubling period of 88 years. Finally, after World War II a more rapid growth rate of 3.03 percent per year and a doubling period of 22.9 years was resumed.

Figure 4 shows, on an arithmetic scale, the annual world crude-oil production from 1880 to 1970. Figure 5 shows the same data plotted semilogarithmically. After a slightly higher initial growth

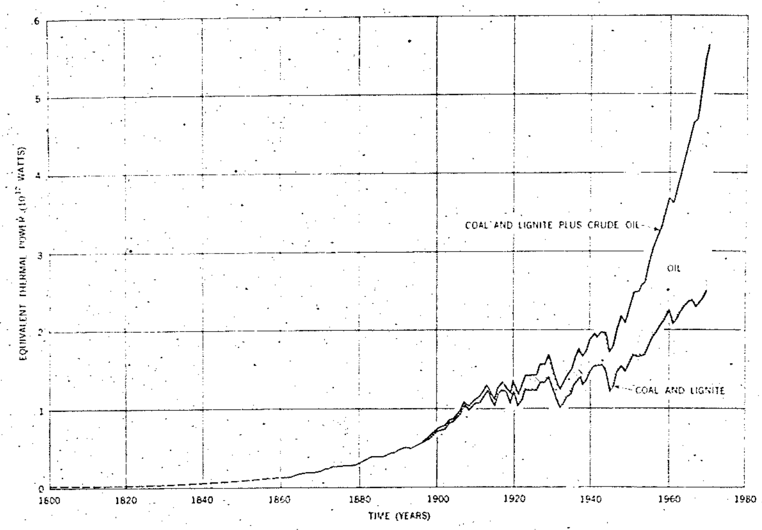

FIGURE 6. World production of thermal energy from coal and lignite plus crude oil (Hubbert, 1974, fig. 7)

rate, world petroleum production from 1890 to 1970 has had a steady exponential increase at an average rate of 7.04 percent and a doubling period of 9.8 years. Cumulative world production of crude oil to 1970 amounted to 233 $\times$ 10^9 barrels. Of this, the first half required the 103-year period from 1857 to 1960 to produce, the second half only the 10-year period from 1960 to 1970.

When coal is measured in metric tons and oil in U.S. 42-gallon barrels, a direct comparison between coal and oil cannot be made. Such a comparison can be made, however, by means of the energy contents of the two fuels as determined by their respective heats of combustion. This is shown in figure 6, where the energy produced per year is expressed in power units of 10^{12} thermal watts. From this it is seen that until after 1900 the energy contributed by crude oil was barely significant as compared with that of coal. By 1970, however, the energy from crude oil had increased to 56 percent of that from coal and oil combined. Were natural gas and natural-gas liquids also to be included, the energy from petroleum fluids would represent about two-thirds of the total.

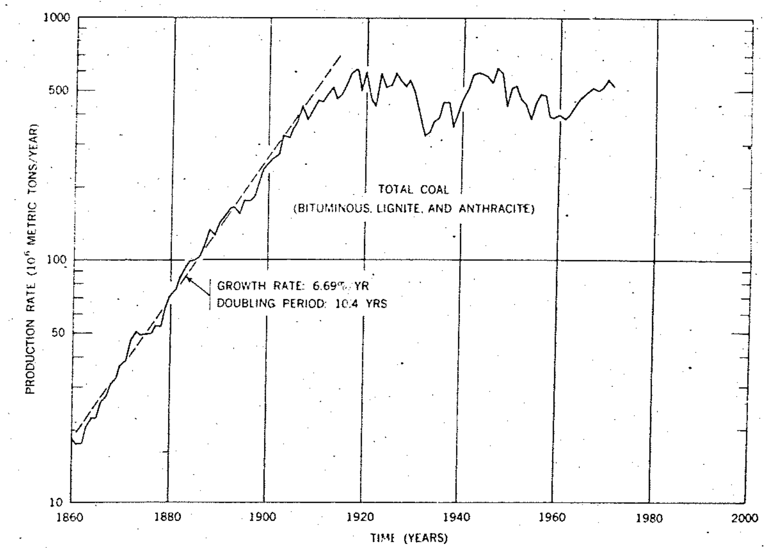

FIGURE 7. U.S. production of coal (semilogarithmic scale) (Hubbert, 1974, fig. 10)

U.S. Production of Fossil Fuels

The corresponding growths in the production of coal, crude oil and natural gas in the United States are shown graphically in figures 7 to 9. From 1860 to 1907 annual U.S. coal production increased at a steady exponential rate of 6.69 percent per year, with a doubling period of 10.4 years. After 1907, due largely to the increase in oil and natural-gas production, coal production fluctuated about a production rate of approximately 500 $\times$ 10^6 metric tons per year. After an initial higher rate, U.S. crude-oil production increased steadily from 1873 to 1929 at about 8.27 percent per year, with a doubling period of 8.4 years. After 1929, the growth rate steadily declined to a 1970 value of approximately zero. From 1905 to 1957 the U.S. production of natural gas increased at an exponential rate of 6.73 percent per year, with a doubling period of 10.3 years; after 1957 the growth rate declined steadily to to a 1973 value of zero.

Finally, figure 10 shows the annual production of energy in the

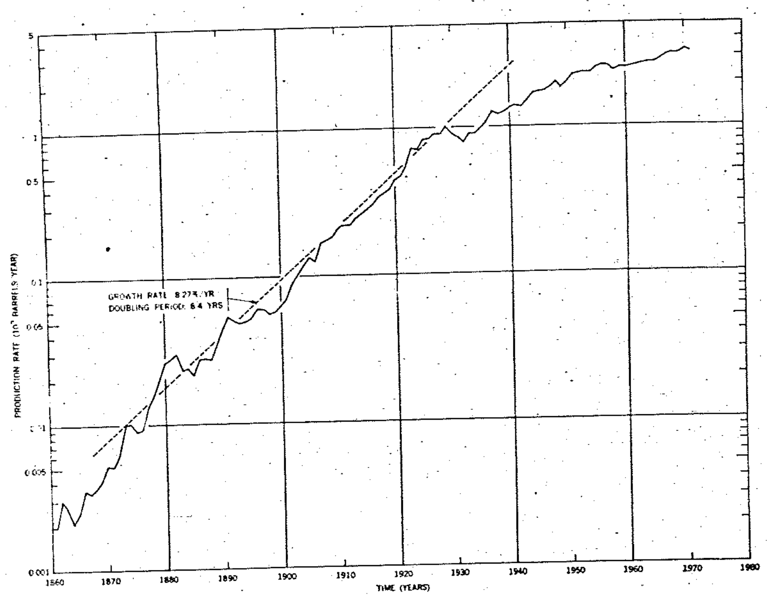

FIGURE 8. U.S. production of crude oil, exclusive of Alaska (semilogarithmic scale) (Hubbert, 1974, fig. 12)

United States from coal, oil, natural gas and hydro- and nuclear power from 1850 to 1970. From 1850 to 1907, this increased at a steady growth rate of 6.9 percent per year and doubled every 10.0 years. At about 1907, the growth rate dropped abruptly to an average value from 1907 to 1960 of about 1.77 percent per year, with a doubling period of 39 years. Since 1960, the growth rate has increased to about 4.25 percent per year, with the doubling period reduced to 16.3 years.

Degree of Advancement of Fossil-Fuel Exploitation

The foregoing are the basic historical facts pertaining to the exploitation of the fossil fuels in the world and in the United States. In the light of these facts we can hardly fail to wonder: How long can this continue? Several different approaches to this problem will now be considered.

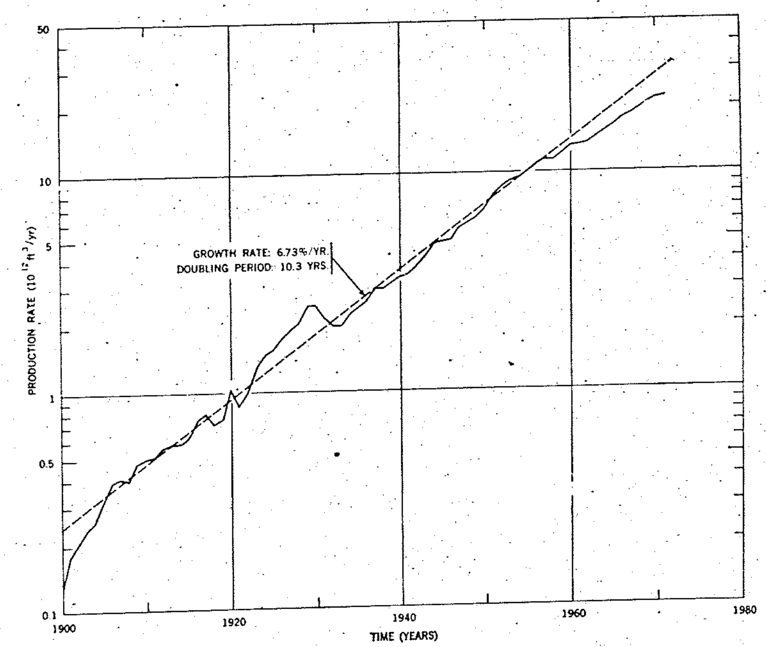

FIGURE 9. U.S. net production of natural gas (semilogarithmic scale) (Hubbert, 1974, fig. 14)

Method of Donald Foster Hewett

In 1929, geologist Donald Foster Hewett delivered a very important paper, entitled "Cycles in Metal Production" (Hewett, 1929). In 1926, Hewett had made a trip to Europe during which he visited 28 mining districts, of which about half were then or had been outstanding sources of several metals. These districts ranged from England to Greece and from Spain to Poland. Regarding the purpose of this study, Hewett states: "I have come to believe that many of the problems that harass Europe lie in our path not far ahead. I have therefore hoped that a review of metal production in Europe in the light of its geologic, economic and political background may serve to clear our vision with regard to our own metal production."

In this paper, extensive graphs were presented of the production of separate metals from these various districts showing the rise, and

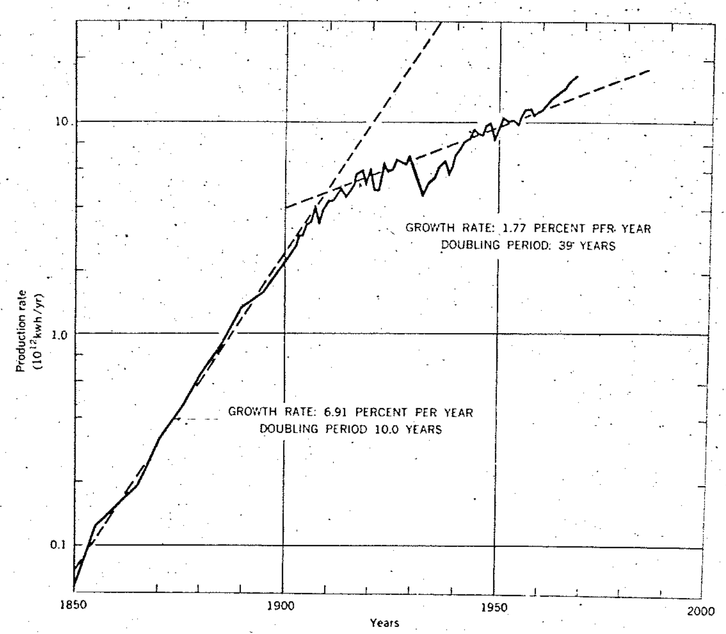

FIGURE 10. U.S. production of thermal energy from coal, oil, natural gas, water power and nuclear power (semilogarithmic scale)

in many cases the decline, in the production rates as the districts approached exhaustion of their ores. After having made this review, Hewett generalized his findings by observing that mining districts evolve during their history through successive stages analogous to those of infancy, adolescence, maturity and old age. He sought criteria for judging how far along in such a sequence a given mining district or region had progressed, and from his study he suggested the successive culminations shown in figure 11. These culminations were: (1) the quantity of exports of crude ore; (2) the number of mines in operation; (3) the number of smelters or refining units in operation; (4) the production of metal from domestic ore; and (5) the quantity of imports of crude ore.

Although not all of Hewett's criteria are applicable to the production of the fossil fuels, especially when world production is considered, the fundamental principle is applicable; namely, that like the metals, the exploitation of the fossil fuels in any given area

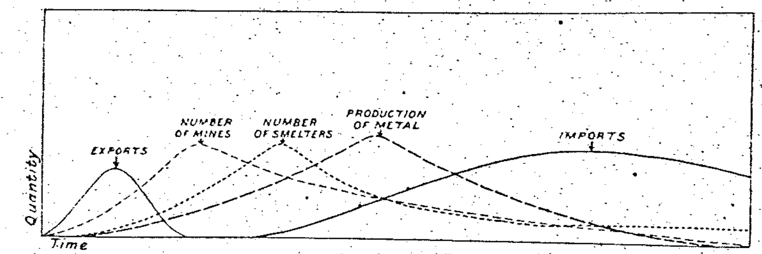

FIGURE 11. Figure 7 from D. F. Hewett's paper, "Cycles in Metal Production" (1929)

must begin at zero, undergo a period of more or less continuous increase, reach a culmination and then decline, eventually to a zero rate of production. This principle is illustrated in figure 12, in which the complete cycle of the production rate of any exhaustible resource is plotted arithmetically as a function of time. The shape of the curve is arbitrary within wide limits, but it still must have the foregoing general characteristics.

An important mathematical property of such a curve may be seen if we consider a vertical column of base Δt extending from the time axis to the curve itself. The altitude of this column will be the production rate

$$P = \Delta Q/\Delta t$$

at the given time, where ΔQ is the quantity produced in time Δt. The area of the column will accordingly be given by the product of its base and altitude:

$$P \times \Delta t = (\Delta Q/\Delta t) \times \Delta t = \Delta Q.$$

Hence, the area of the column is a measure of the quantity produced during the time interval Δt, and the total area from the beginning of production up to any given time t will be a measure of the cumulative production up to that time. Clearly, as the time t increases without limit, the production rate will have gone through its complete cycle and returned to zero. The area under the curve after this has occurred will then represent the ultimate cumulative production, Q_∞. In view of this fact, if from geological or other data the producible magnitude of the resource initially present can be

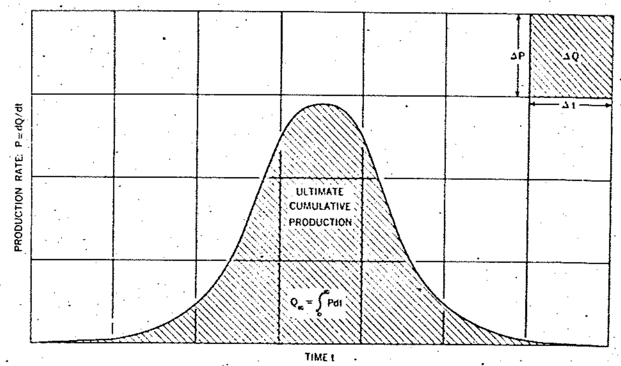

FIGURE 12. Mathematical properties of arithmetical graph of production P versus time t for the complete production cycle of an exhaustible resource (after Hubbert, 1956, fig. 11)

estimated, then any curve drawn to represent the complete cycle of production *must be consistent with that estimate.* No such curve can subtend an area greater than the estimated magnitude of the producible resource.

Utilization of this principle affords a powerful means of estimating the time scale for the complete production cycle of any exhaustible resource in any given region. As in the case of animals where the time required for the complete life cycle of, say, a mouse is different from that of an elephant, so in the case of minerals, the time required for the life cycle of petroleum may differ from that of coal. This principle also permits a reasonably accurate estimate of the most important date in the production cycle of any exhaustible resource, that of its culmination. This date is especially significant because it marks the dividing point in time between the initial period during which the production rate almost continuously increases and the subsequent period during which it almost continuously declines. It need hardly be added that there is a significant difference between operating an industry whose output increases at a rate of 5 to 10 percent per year and one whose output declines at such a rate.

Complete Cycle of Coal Production

Because coal deposits occur in stratified seams which are continuous over extensive areas and often crop out on the earth's surface,

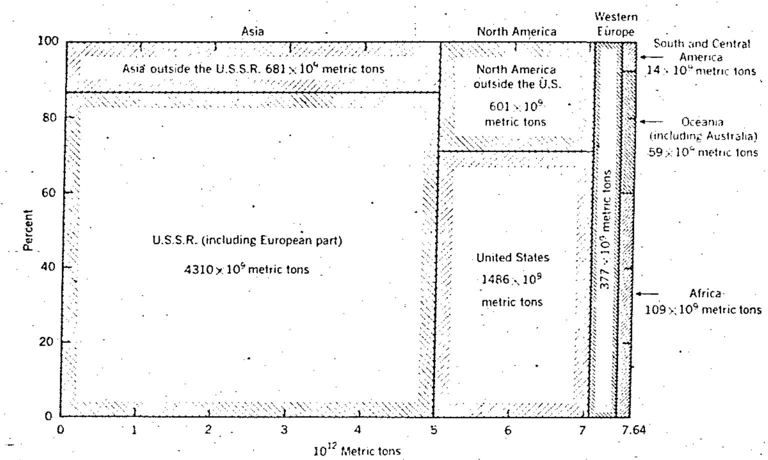

FIGURE 13. Averitt (1969) estimate of original world recoverable coal resources (Hubbert, 1969, fig. 8.24)

reasonably good estimates of the coal deposits in various sedimentary basins can be made by surface geological mapping and a limited amount of drilling. A summary of the current estimates of the world's initial coal resources has been published by Averitt (1969). These estimates comprise the total amounts of coal (including lignite) in beds 12 inches (30 cm) or more thick and at depths as great as 4,000 feet (1,200 m), and in a few cases as great as 6,000 feet. Averitt's estimates as of January 1, 1967, for the initial producible coal, allowing 50 percent loss in mining, are shown graphically in figure 13 for the world's major geographical areas. As seen in this figure, the original recoverable world coal resources amounted to an estimated 7.64×10^{12} metric tons. Of this, 4.31×10^{12}, or 56 percent, were in the USSR, and 1.49×10^{12}, or 19 percent, in the United States. At the other extreme, the three continental areas, Africa, South and Central America, and Oceania, together contained only 0.182×10^{12} metric tons, or 2.4 percent of the world's total.

In view of the depths and thinness of the seams, the foregoing coal estimates may be unrealistically large. A seam of coal 12 inches thick and 4,000 feet deep is not a very attractive target for a coal-mining operation. Consequently, more recently Averitt (cited by

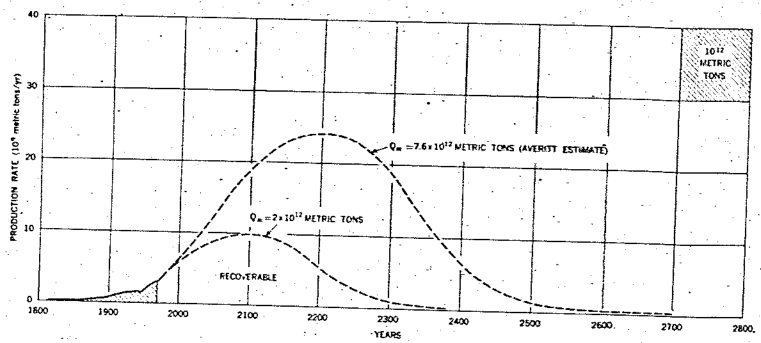

FIGURE 14. Two complete cycles of world coal production based upon Averitt's higher and lower estimates of initial resources of recoverable coal (Hubbert, 1974, fig. 21)

Theobold, Schweinfurth and Duncan, 1972) has estimated the amount of recoverable coal in the United States occurring in seams not less than 28 inches (0.7 meter) thick for bituminous coal and anthracite, and not less than 5 feet (1.5 meters) thick for subbituminous coal and lignite, and at depths of not more than 1,000 feet (300 meters). The estimate for the initial amount of recoverable coal in this category in the United States was 390×10^9 metric tons, which is only 26 percent of the larger estimate of 1,486 metric tons. Assuming the same ratio for the world coal, the larger estimate of 7.6×10^{12} metric tons would be reduced to but 2.0×10^{12} metric tons.

Figure 14 shows two complete-cycle curves for the world coal production, based upon the two figures, 7.6×10^{12} and 2.0×10^{12} metric tons for the ultimate cumulative production, Q_∞. Utilizing the principle illustrated in figure 13, the quantity ΔQ represented by one grid square in figure 14 is given by

$$\begin{aligned}\Delta Q &= (10^{10} \text{ met ton/yr}) \times 10^2 \text{ yr} \\ &= 10^{12} \text{ metric tons.}\end{aligned}$$

Therefore, the complete-cycle curve corresponding to 7.6×10^{12} metric tons would encompass just 7.6 grid squares; that for the estimate of 2.0×10^{12} metric tons would encompass only 2.0 grid squares.

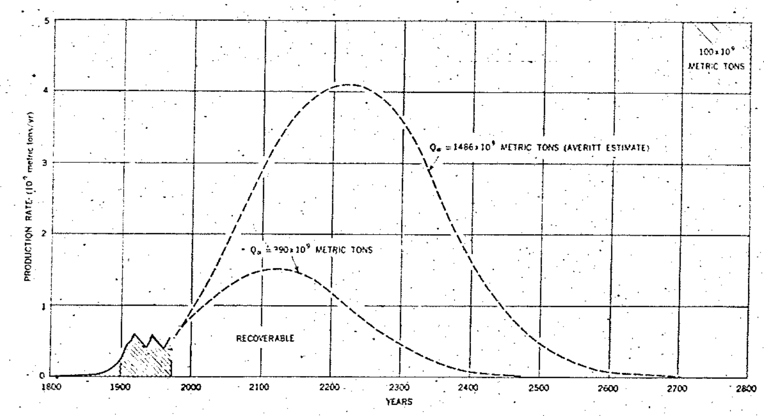

FIGURE 15. Two complete cycles of U.S. coal production based upon Averitt's higher and lower estimates of initial resources of recoverable coal (Hubert, 1974, fig. 22)

The curve corresponding to 7.6×10^{12} metric tons is also drawn on the basis of the assumption that the production rate will double only three more times, or increase 8-fold, before the culmination is reached. The lower curve shows only a 4-fold increase in the present production rate. Were the maximum rate to be larger, the time-span curve would correspondingly shorten.

A significant time span for these complete-cycle curves is obtained when we disregard the long times required to produce the first and last 10-percentiles of the cumulative production and consider only the time for the middle 80 percent From figure 14, it appears that this will probably fall within a range of about two to three centuries, with the peak in the production rate occurring within the period 2100 to 2200. For a round number, it appears that the time required to consume the middle 80 percent of the world's initial coal will probably not be more than about three centuries.

Figure 15 shows two complete-cycle curves for U.S. coal production, corresponding to the high and low Averitt estimates of $1,486 \times 10^{12}$ and 390×10^{12} metric tons for Q_∞. The time scales for the U.S. consumption of the middle 80 percent are approximately the same as those for the world.

Estimates of Petroleum Resources

Because oil and gas occur in limited volumes of space underground in porous sedimentary rocks and at depths ranging from a few hundred feet to 5 or more miles, the estimation of the ultimate quantities of these fluids that will be obtained from any given area is much more difficult and hazardous than for coal. For the estimation of petroleum, essentially two methods are available: (1) estimation by geological analogy; and (2) estimation based on cumulative information and evidence resulting from exploration and productive activities in the region of interest.

The method of estimating by geological analogy is essentially the following. A virgin undrilled territory, Area *B*, is found by surface reconnaissance and mapping to be geologically similar to Area *A* which is already productive of oil and gas. It is inferred, therefore, that Area *B* will eventually produce comparable quantities of oil and gas per unit of area or unit of volume of sediments to those of Area *A*.

Although this is practically the only method available initially for estimating the oil and gas potential of an undrilled region, it is also intrinsically hazardous, with a very wide range of uncertainty This is illustrated in table 1, in which the estimates made in 1953 for the future oil discoveries on the continental shelf off the Texas and Louisiana coasts are compared with the results of subsequent drilling.

In 1953, the U.S. Geological Survey, on the basis of geological analogy between the onshore and offshore areas of the Gulf Coast and the respective areas of the continental shelf bordering Texas and Louisiana, estimated future discoveries of 9 billion barrels of oil on the Texas continental shelf and 4 billion on that of Louisiana. After approximately 20 years of petroleum exploration and drilling, discoveries of crude oil on the Louisiana continental shelf have amounted to approximately 5 billion barrels; those on the continental shelf off Texas have been negligible.

An even more dramatic example is afforded by the recent experience in the drilling of the Destin anticline in the offshore waters just southeast of Pensacola, Florida. This is a large anticline about 50 miles long and 20 miles wide extending east and west. Onshore, on the north boundary of the Florida panhandle is the Jay field, one of the largest oil discoveries in the lower 48 states within the last decade. By geological analogy, the probability amounted almost to a certainty that the Destin anticline would become a very large oil field. On the basis of such reasoning three companies, Exxon, Mobil, and Champlin, paid $632,377,950 for the lease of the eastern half of the anticline (the western half was not offered for lease). Seven deep wells have subsequently been drilled on the structure, all dry.

TABLE 1. *Petroleum Estimates by Geological Analogy: Louisiana and Texas Continental Shelves*

(crude oil, 10^9 bbls)

	U.S. Geological Survey estimates, 1953	Cumulative discoveries to 1971
Louisiana	4	ca. 5
Texas	9	Negligible

The second technique of petroleum estimation involves the use of various aspects of the Hewett criterion that the complete history of petroleum exploration and production in any given area must go through stages from infancy to maturity to old age. Maturity is plainly the stage of production culmination, and old age is that of an advanced state of discovery and production decline.

In March 1956, this technique was explicitly applied to crude-oil production in the United States by the present author (Hubbert, 1956) in an invited address, "Nuclear Energy and the Fossil Fuels," given before an audience of petroleum engineers at a meeting of the Southwest Section of the American Petroleum Institute at San Antonio, Texas. At that time the petroleum industry in the United States had been in vigorous operation for 97 years, during which 52.4 billion barrels of crude oil had been produced. A review of published literature in conjunction with inquiries among experienced petroleum geologists and engineers indicated a concensus that the ultimate amount of crude oil to be produced from the conterminous 48 states and adjacent continental shelves would probably be within the range of 150 to 200 billion barrels. Using these two limiting figures, the curves for the complete cycle of U.S. crude-oil produc-

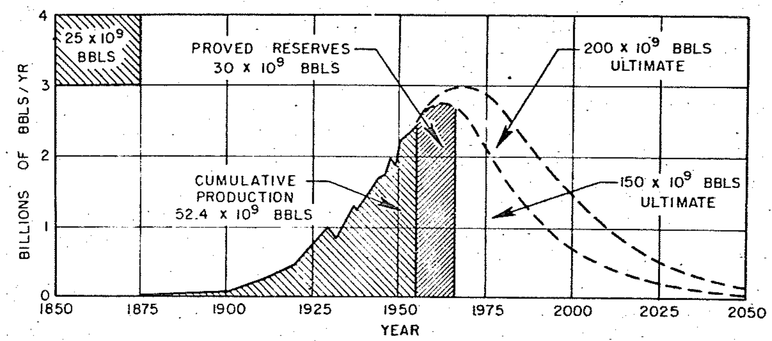

FIGURE 16. 1956 prediction of the date of peak in the rate of U.S. crude-oil production (Hubbert, 1956, fig. 21)

tion shown in figure 16 (Hubbert, 1956) were constructed. This showed that if the ultimate cumulative production, Q_∞, should be as small as 150×10^9 bbls, the peak in the rate of production would probably occur about 1966—about 10 years hence. Should another 50×10^9 bbls be added, making $Q_\infty = 200 \times 10^9$ bbls, the date of the peak of production would be postponed by only about 5 years. It was accordingly predicted on the basis of available information that the peak in U.S. crude-oil production would occur within 10–15 years after March 1956.

This prediction proved to be both surprising and disturbing to the U.S. petroleum industry. The only way it could be avoided, however, was to enlarge the area under the curve of the complete cycle of production by increasing the magnitude of Q_∞. As small increases of Q_∞ have only small effects in retarding the date of peak production, if this unpleasant conclusion were to be avoided, it would be necessary to increase Q_∞ by larger magnitudes. This was what happened. Within the next 5 years, with insignificant amounts of new data, the published values for Q_∞ were rapidly escalated to successively higher values—204, 250, 372, 400 and eventually 590 billion barrels.

In view of the fact that values of Q_∞ used in figure 16 involved semisubjective judgments, no adequate rational basis existed for showing conclusively that a figure of 200×10^9 bbls was a much more reliable estimate than one twice that large. This led to the

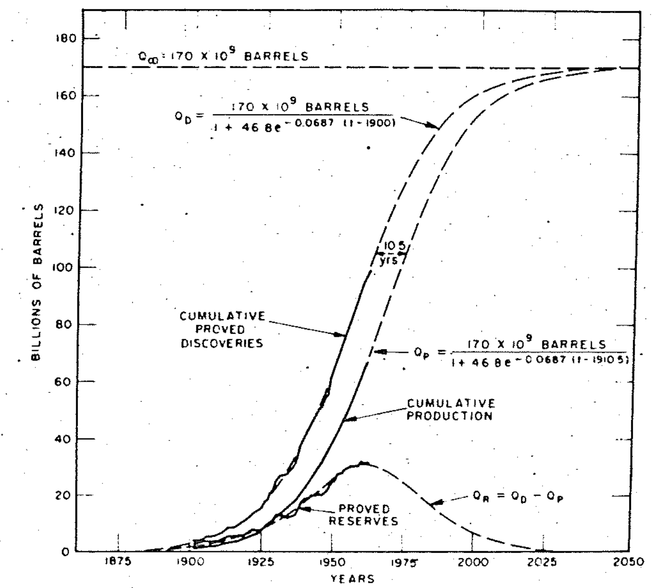

FIGURE 17. Curves of cumulative proved discoveries, cumulative production and proved reserves of U.S. crude oil as of 1962 (Hubbert, 1962, fig. 27)

search for other criteria derivable from objective, publicly available data of the petroleum industry. The data satisfying this requirement were the statistics of annual production available since 1860, and the annual estimates of proved reserves of the Proved Reserves Committee of the American Petroleum Institute, begun in 1937. From these data cumulative production from 1860 could be computed, and also cumulative proved discoveries defined as the sum of cumulative production and proved reserves after 1937.

This type of analysis was used in the report, *Energy Resources* (Hubbert, 1962), of the National Academy of Sciences Committee on Natural Resources, advisory to President Kennedy. The principal results of this study are shown in figures 17 and 18, in which it was found that the rate of proved discoveries of crude oil had already passed its peak about 1957, proved reserves were estimated to be at their peak in 1962, and the peak in the rate of crude-oil production was predicted to occur at about the end of the 1960 decade. The ultimate amount of crude oil to be produced from the lower

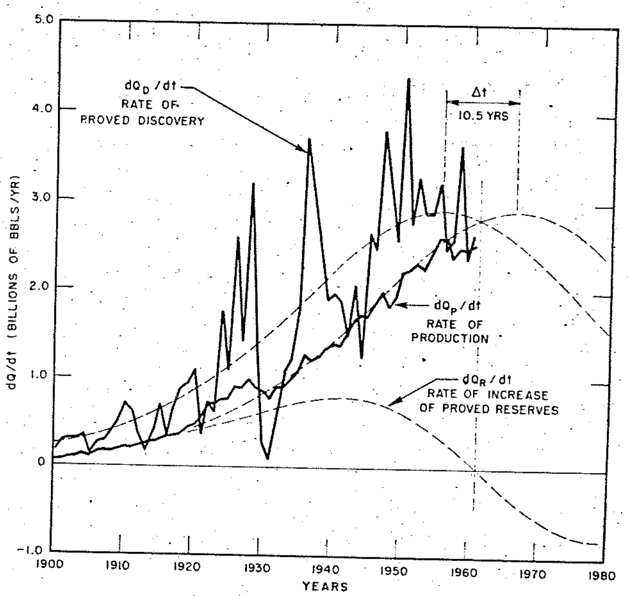

FIGURE 18. Curves showing the rates of proved discovery and of production, and rate of increase of proved reserves of U.S. crude oil as of 1961. Note prediction of peak of production rate near the end of 1960 decade (Hubbert, 1962, fig. 28)

48 states and adjacent continental shelves was estimated to be about 170 to 175 billion barrels.

The corresponding estimates for natural gas are shown in figures 19 and 20 (Hubbert, 1962). From these figures it will be seen that the rate of proved discoveries was estimated to be at its peak at about 1961. Proved reserves of natural gas were estimated to reach their peak ($dQ_r/dt = 0$) at about 1969, and the rate of production about 1976.

At the time the study was being made, the U.S. Geological Survey, in response to a Presidential directive of March 4, 1961, presented to the Academy Committee estimates of 590×10^9 bbls for crude oil and 2650 ft^3 for natural gas as its official estimates of the ultimate amounts of these fluids that would be produced from the lower 48 states and adjacent continental shelves.

These estimates were, by a wide margin, the highest that had

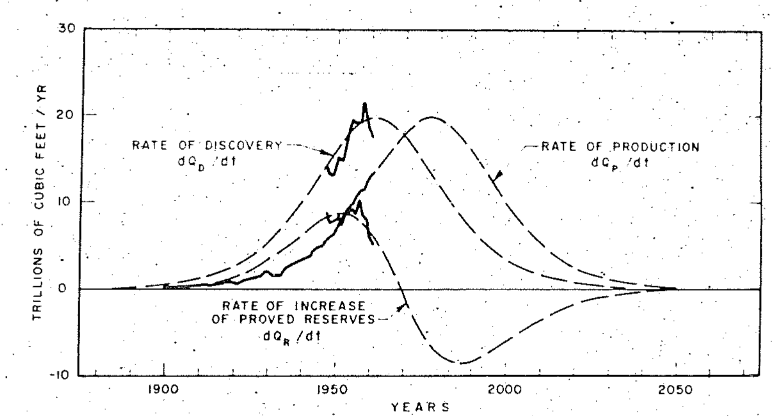

FIGURE 19. 1962 estimates of the dates of the peaks of rate of proved discovery, rate of production and proved rate of increase of reserves of U.S. natural gas (Hubbert, 1962, fig. 46)

ever been made up until that time. Moreover, had they been valid, there would have been no grounds for the expectation of an oil or gas shortage in the United States much before the year 2000. These estimates were cited in the Academy Committee report, but because

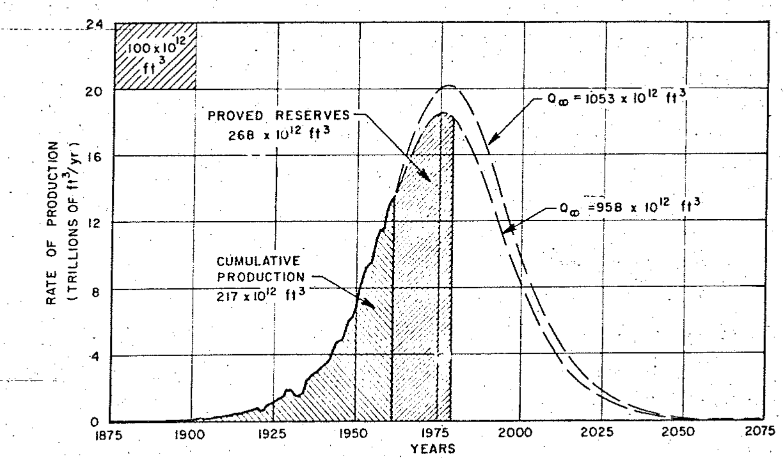

FIGURE 20. 1962 estimates of ultimate amount of natural gas to be produced in conterminous United States, and estimates of date of peak production rate (Hubbert, 1962, fig. 47)

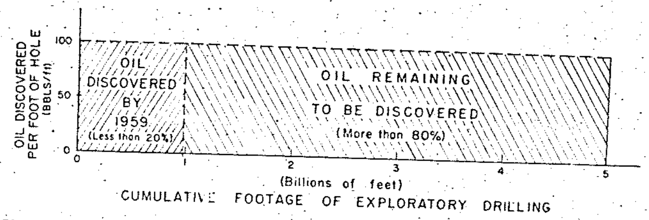

FIGURE 21. Zapp (1962) hypothesis of oil discoveries per foot versus cumulative footage of exploratory drilling for conterminous United States and adjacent continental shelves (Hubbert, 1969, fig. 8.18)

of their wide disparity with any available evidence from the petroleum industry, they were also rejected.

As only became clear sometime later, the basis for those large estimates was an hypothesis introduced by the late A. D. Zapp (1962) as illustrated in figure 21 (Hubbert, 1969). Zapp postulated that the exploration for petroleum in the United States would not be completed until exploratory wells with an average density of one well per each 2 square miles had been drilled either to the crystalline basement rock or to a depth of 20,000 ft in all the potential petroleum-bearing sedimentary basins. He estimated that to drill this pattern of wells in the petroliferous areas of the conterminous United States and adjacent continental shelves would require about 5×10^9 feet of exploratory drilling. He then estimated that, as of 1959, only 0.98×10^9 feet of exploratory drilling had been done and concluded that at that time the United States was less than 20 percent along in its ultimate petroleum exploration. He also stated that during recent decades there had been no decline in the oil found per foot of exploratory drilling, yet already more than 100×10^9 barrels of oil had been discovered in the United States. It was implied, but not expressly stated, that the ultimate amount of oil to be discovered would be more than 500×10^9 bbls.

This was confirmed in 1961 by the Zapp estimate for crude oil given to the Academy Committee. At that time, with cumulative drilling of 1.1×10^9 feet, Zapp estimated that 130×10^9 bbls of crude oil had already been discovered. This would be at an average rate of 118 bbls/ft. Then, at this same rate, the amount of oil to be discovered by 5×10^9 feet of exploratory drilling should be 590×10^9 bbls, which is the estimate given to the Academy Committee.

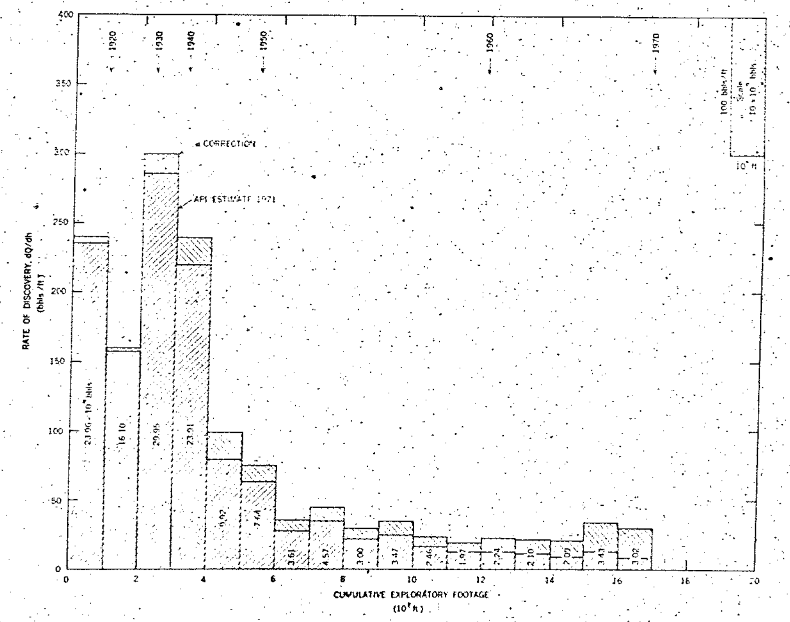

FIGURE 22. Average discoveries of crude oil per foot for each 10^8 feet of exploratory drilling in the conterminous United States from 1860 to 1971 (Hubbert, 1974, fig. 49)

This constitutes the "Zapp hypothesis." Not only is it the basis for Zapp's own estimates, but with only minor modifications it has been the principal basis for most of the subsequent higher estimates by the U.S. Geological Survey.

The most obvious test for the validity of this hypothesis is to apply it to past petroleum discoveries in the United States. Has the oil found per foot of exploratory drilling been nearly constant during the past? The answer to this is given in figure 22 (Hubbert, 1974), which shows the quantity of oil discovered and the average amount of oil found per foot for each 10^8 ft of exploratory drilling in the United States from 1860 to 1972. This shows an initial rate of 240 bbls/ft for the first unit from 1860 to 1920, a maximum rate of 300 bbls/ft for the third unit extending from 1929 to 1935 and then a precipitate decline to about 30 bbls/ft by 1972. This is approximately an exponential decline curve, the integration of which for

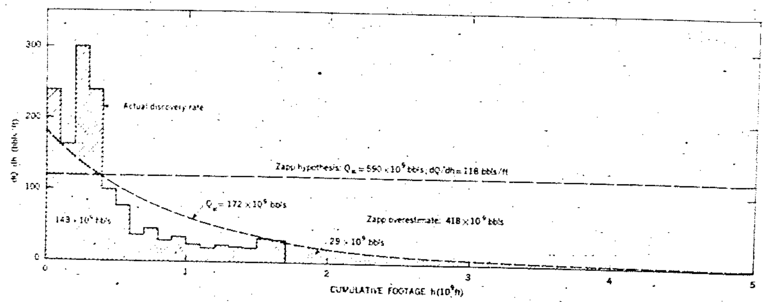

FIGURE 23. Comparison of U.S. crude-oil discoveries according to Zapp hypothesis with actual discoveries. The difference between the areas beneath the two curves represents an overestimate of about 418 billion barrels (Hubbert, 1974, fig. 50)

unlimited future drilling gives an estimate of about 172×10^9 for Q_∞, the ultimate discoveries.

The superposition of the actual discoveries per foot shown in figure 22 on the discoveries per foot according to the Zapp hypothesis of figure 21 is shown in figure 23 (Hubbert, 1974). The difference between the areas beneath the two curves represents the difference between the two estimates—an apparent overestimate of about 418×10^9 bbls.

To recapitulate, in the Academy Committee report of 1962, the peak in U.S. proved crude-oil discoveries, excluding Alaska, was estimated to have occurred at about 1957, the peak in proved reserves at about 1962, and the peak in production was predicted for about 1968–1969. The peak in proved reserves did occur in 1962, and the peak in the rate of production occurred in 1970. Evidence that this is not likely to be exceeded is afforded by the fact that since March 1972, the production rates of both Texas and Louisiana, which together account for 60 percent of the total U.S. crude-oil production, have been at approximately full capacity, and are now declining.

As for natural gas, the Academy report estimated that the peak in proved reserves would occur at about 1969 and the peak in the rate of production about 1976. The peak of proved reserves for the conterminous 48 states actually was reached in 1967, 2 years ahead of the predicted date, and the peak in natural-gas production was reached in 1973, 3 years earlier than predicted. In the 1962

Academy report, the ultimate production of natural gas was estimated to be about 1000×10^{12} ft^3. Present estimates by two different methods give a low figure of 1000×10^{12} and a high figure of $1,100 \times 10^{12}$, or a mean of 1050×10^{12} ft^3.

Because of its early stage of development, the petroleum potential of Alaska must be based principally on geological analogy with other areas. The recent Prudhoe Bay discovery of a 10-billion-barrel field—the largest in the United States—has been a source of excitement for an oil-hungry U.S. petroleum industry, but it still represents only a 2-year supply for the United States. From present information, a figure of 43×10^9 bbls is about as large an estimate as can be justified for the ultimate crude-oil production from the land and offshore areas of Alaska. Adding this to a present figure of about 170×10^9 bbls for the conterminous 48 states gives 213×10^9 bbls as the approximate amount of crude oil ultimately to be produced in the United States.

Canada's Resources

For the present paper, it has not been possible to make an analysis of the oil and gas resources of Canada. However, figure 24, from R. E. Folinsbee's Presidential Address before the geological section of the Royal Society of Canada (1970), provides a very good appraisal of the approximate magnitude of Canadian crude-oil resources. According to this estimate, the ultimate production of crude oil from Western Canada south of latitude 60° will be about 15×10^9 barrels, of which 12.5×10^9 have already been discovered. The peak in the production rate for this area is estimated at about 1977. This figure also shows a maximum estimate of 86×10^9 barrels of additional oil from the frontier areas of Canada. Should this be exploited in a systematic manner from the present time, a peak production rate of about 3×10^9 bbl/yr would probably be reached by about 1995.

However, the proved reserves for Canadian crude oil and natural-gas liquids both reached their peaks in 1969, those for natural gas had reached their peak by 1974. Therefore, unless development and transportation of oil and gas from the frontier provinces begins soon, there may be a temporary decline in total Canadian production of oil and gas toward the end of the present decade.

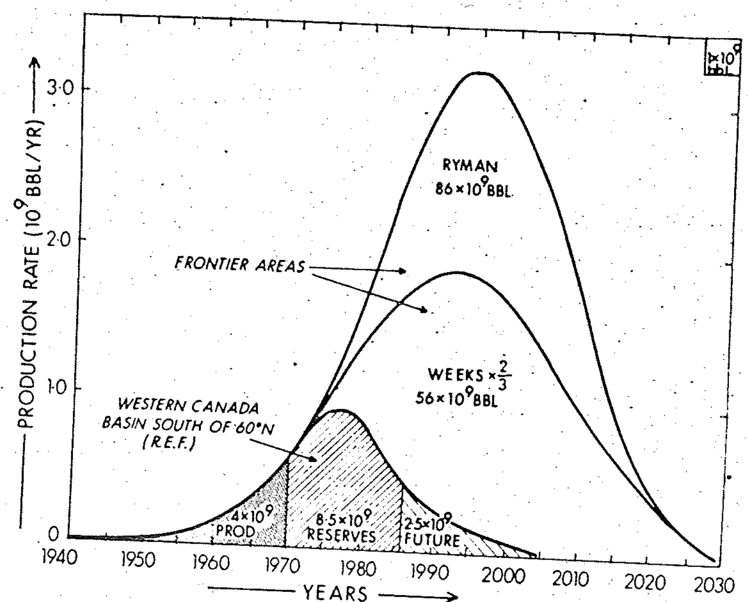

FIGURE 24. Complete cycles of crude-oil production in Canada (Folinsbee, 1970, with permission)

World Crude-Oil Production

~~In the present brief~~ review, only a summary statement can be made for the petroleum resources of the world as a whole. Recent estimates by various major oil companies and petroleum geologists have been summarized by H. R. Warman (Warman, 1971), who gave 226×10^9 bbls as the cumulative world crude-oil production and 527×10^9 bbls for the proved reserves at the end of 1969. This totals 753×10^9 bbls as the world's cumulative discoveries. For the ultimate recoverable crude oil, Warman cited the following estimates published during the period 1967–1970:

Year	Author	Quantity (10^9 bbls)
1967	Ryman (Esso)	2090
1968	Hendricks (USGS)	2480
1968	Shell	1800
1969	Hubbert (NAS-NRC)	1350–2100
1969	Weeks	2200
1970	Moody (Mobil)	1800

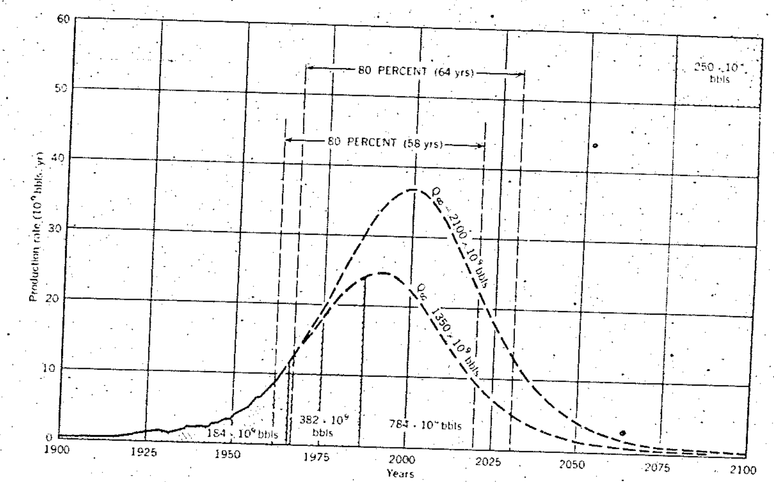

FIGURE 25. Complete cycle of world crude-oil production for two values of Q_∞ (Hubbert, 1969, fig. 8.23)

To this, Warman added his own estimate of $1200–2000 \times 10^9$ bbls. A recent unpublished estimate by the research staff of another oil company is in the mid-range of $1900–2000 \times 10^9$ bbls.

From these estimates, there appears to be a convergence toward an estimate of 2000×10^9 bbls, or slightly less. The implication of such a figure to the complete cycle of world crude-oil production is shown in figure 25 (Hubbert, 1969), using two limiting values of 1350×10^9 and 2100×10^9 bbls. For the higher figure, the world will reach the peak in its rate of crude-oil production at about the year 2000; for the lower figure, this date would be about 1990.

Another significant figure for both the U.S. and the world crude-oil production is the length of time required to produce the middle 80 percent of the ultimate production. In each case, the time is about 65 years, or less than a human lifetime. For the United States, this subtends the period from about 1937 to 2003; for the world, from about 1967 to 2032.

Another category of petroleum liquids is that of natural-gas liquids which are produced as a by-product of natural gas. In the United States (excluding Alaska), the ultimate amount of natural-gas liquids, based on an ultimate amount of crude oil of 170×10^9 bbls, and 1050×10^{12} ft of natural gas, amounts to about 34×10^9

bbls. Corresponding world figures, based on an estimate of 2000×10^9 bbls for crude oil, would be about 400×10^9 bbls for natural-gas liquids, and $12{,}800 \times 10^{12}$ ft^3 for natural gas.

Other Fossil Fuels

In addition to coal, petroleum liquids and natural gas, the other principal classes of fossil fuels are the so-called tar, or heavy-oil, sands and oil shales. The best known and probably the largests deposits of heavy-oil sands are in the "Athabasca Tar Sands" and two smaller deposits in northern Alberta containing an estimated 300×10^9 bbls of potentially producible oil. One large-scale mining and extracting operation was begun in 1966 by a group of oil companies, and others doubtless will follow as the need for this oil develops.

Unlike tar sands, the fuel content of which is a heavy, viscous crude oil, oil shales contain hydrocarbons in a solid form known as *kerogen*, which distills off as a vapor on heating and condenses to a liquid on cooling. The extractible oil content of oil shales ranges from as high as 100 U.S. gallons per short ton for the richest grades to near zero as the grades diminish. When all grades are considered, the aggregate oil content of the known oil shales is very large. However, in practice, only the shales having an oil content of about 25 gallons or more per ton and occurring in beds 10 feet or more thick are considered to be economical sources at present. According to a world inventory of known oil shales by Duncan and Swanson (1965), the largest known deposits are those of the Green River Formation in Wyoming, Colorado, and Utah. From these shales, in the grade range from 10 to 65 gallons per ton, the authors estimate that only 80×10^9 bbls are recoverable under 1965 economic conditions. Their corresponding figure for oil shales outside the United States is 110×10^9 bbls.

The absolute magnitude of the world's original supply of fossil fuels recoverable under present technological and economic conditions and their respective energy contents in terms of their heats of combustion are given in table 2. The total initial energy represented by all of these fuels amounted to about 84×10^{21} thermal joules, or 23×10^{15} thermal kilowatt-hours. Of this, 63 percent was represented by coal and lignite, 33 percent by petroleum liquids

TABLE 2. *Approximate Magnitudes and Energy Contents of the World's Original Supply of Fossil Fuels Recoverable under Present Conditions*

Fuel	Quantity	Energy Content: 10^{21} thermal joules	Energy Content: 10^{15} thermal kwh	Percent
Coal and lignite	2.35×10^{12} metric tons	53.2	14.78	63.11
Petroleum liquids	2400×10^9 bbls	14.2	3.95	16.84
Natural gas	$12{,}800 \times 10^{12}$ ft^3	14.0	3.88	16.61
Tar-sand oil	300×10^9 bbls	1.8	0.50	2.14
Shale oil	190×10^9 bbls	1.1	0.31	1.30
TOTALS		84.3	23.42	100.00

and natural gas combined, and about 3 percent for tar sand and oil shale taken together. Although the total amount of coal and lignite in beds 14 or more inches thick and occurring at depths less than 3,000 feet, as estimated by Averitt, is very much larger in terms of energy content than the initial quantities of oil and gas, the coal practically recoverable under present conditions is only about twice the magnitude of the initial quantities of gas and oil in terms of energy content. Therefore, at comparable rates of production, the time required for the complete cycle of coal production will not be much longer than that for petroleum—an order of a century or two for the exhaustion of the middle 80 percent of the ultimate cumulative production.

To appreciate the brevity of this period in terms of the longer span of human history, the historical epoch of the exploitation of the fossil fuels is shown graphically in figure 26, plotted on a time scale extending from 5,000 years in the past to 5,000 years in the future—a period well within the prospective span of human history. On such a time scale, it is seen that the epoch of the fossil fuels can be only a transitory or ephemeral event—an event, nonetheless, which has exercised the most drastic influence on the human species during its entire biological history.

OTHER SOURCES OF INDUSTRIAL ENERGY

The remaining sources of energy suitable for large-scale industrial uses are principally the following:

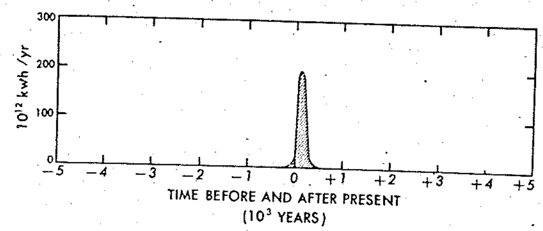

FIGURE 26. Epoch of fossil-fuel exploitation in perspective of human history from 5000 years in the past to 5000 years in the future (Hubbert, 1974, fig. 69)

1. Direct use of solar radiation.
2. Indirect uses of solar radiation.
   (a) Water power.
   (b) Wind power.
   (c) Photosynthesis.
   (d) Thermal energy of ocean water at different temperatures.
3. Geothermal power.
4. Tidal power.
5. Nuclear power.
   (a) Fission.
   (b) Fusion.

Solar Power

By a large margin, the largest flux of energy occurring on the earth is that from solar radiation. The thermal power of the solar radiation intercepted by the earth, according to recent measurements of the solar constant, amounts to about $174{,}000 \times 10^{12}$ thermal watts. This is roughly 5,000 times all other steady fluxes of energy combined. It also has the expectation of continuing at about the same rate for geological periods of time into the future. For further comparison, the present rate of world consumption of energy for industrial purposes is about 7×10^{12} thermal watts.

The largest concentrations of solar radiation reaching the earth's surface occur in arid regions within about 35° of latitude north and south of the equator. The southwestern part of the United States is within this belt, as well as the plateau of Mexico, the Atacama

Desert along the Pacific coast in Chile, a 2,000 kilometer-wide zone across northern Africa, the Red Sea, the Arabian Peninsula, the Persian Gulf and beyond, and two-thirds of the continent of Australia. Recent measurements made by the Desert Research Institute of Nevada show that solar power incident on a square meter of horizontal surface at Las Vegas, Nevada, averaged day and night, and summer and winter, amounts to 250 thermal watts. By silicon photovoltaic cells 10 to 12 percent of incident radiation can be converted directly into electric power. There is promise that by means of steam-electric systems as much as 20 percent might be converted into electric power. At a 10 percent conversion rate and an incidence of solar power of 250 watts per square kilometer, a collection area of 1 square kilometer would produce an average of 25 megawatts of electric power. Then, for a 1,000 megawatt electrical power plant, the collection area required would be but about 40 square kilometers. At such an efficiency of conversion the collection area required for an electrical capacity of 400,000 megawatts, the aproximate capacity of the U.S. electrical utilities in 1975, would be 16,000 square kilometers or 6,200 square miles. This is only about 5.5 percent of the land area of Arizona.

Such a calculation indicates that large-scale generation of electric power from direct solar radiation is not to be ruled out on the grounds of technical infeasibility. It is also gratifying that a great deal of interest on the part of technically competent groups in universities and research institutions has risen during the last 6 years over the possibility of developing large-scale solar power.

Hydroelectric Power

Although there has been continuous use of water power since Roman times, large units were not possible until a means was developed for the generation and transmission of power electrically. The first large hydroelectric power installation was that made at Niagara Falls in 1895. There, ten 5,000-hp turbines were installed for the generation of A.C. power, which was transmitted a distance of 26 miles to the city of Buffalo. The subsequent growth of hydroelectric power in the United States is shown in figure 27 and that for the world in figure 28.

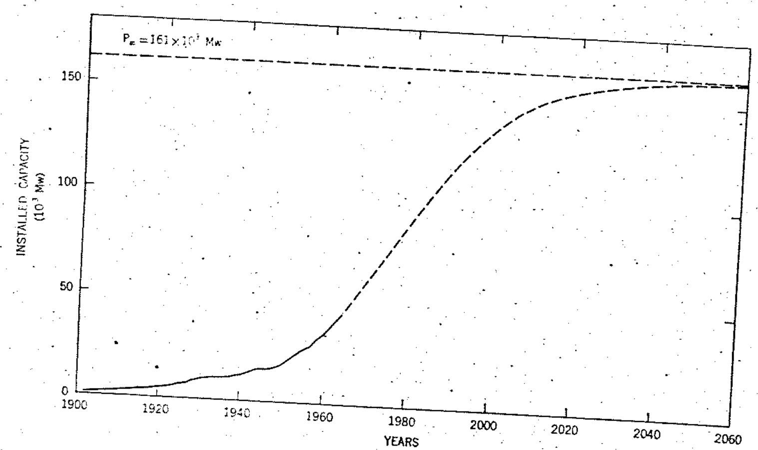

FIGURE 27. Installed and potential hydroelectric-power capacity of the United States (Hubbert, 1969, fig. 8.28)

In the United States, by 1970, the installed hydroelectric power capacity amounted to 53,000 megawatts, which is 32 percent of the ultimate potential capacity of 161,000 Mw as estimated by the Federal Power Commission. The world installation, by 1967, amounted to 243,000 Mw, which is 8.5 percent of the world's estimated potential hydroelectric power of 2,860,000 Mw. Most of this developed capacity is in the highly industrialized areas of North America, Western Europe and the Far East, especially Japan.

The areas with the largest potential water-power capacities are the industrially underdeveloped regions of Africa, South America and Southeast Asia, where combined capacities represent 63 percent of the world total.

The total world potential water power of approximately 3×10^{12} watts, if fully developed, would be about half the magnitude of the world's present rate of utilization of industrial power. It may also appear that this would be an inexhaustible source of power, or at least one with a time span comparable to that required to remove mountains by stream erosion. This may not be true, however. Most waterpower developments require the creation of reservoirs by the damming of streams. The time required to fill these reservoirs with sediments is only 2 or 3 centuries. Hence, unless a technical solution of this problem can be found, water power may actually be comparatively short-lived.

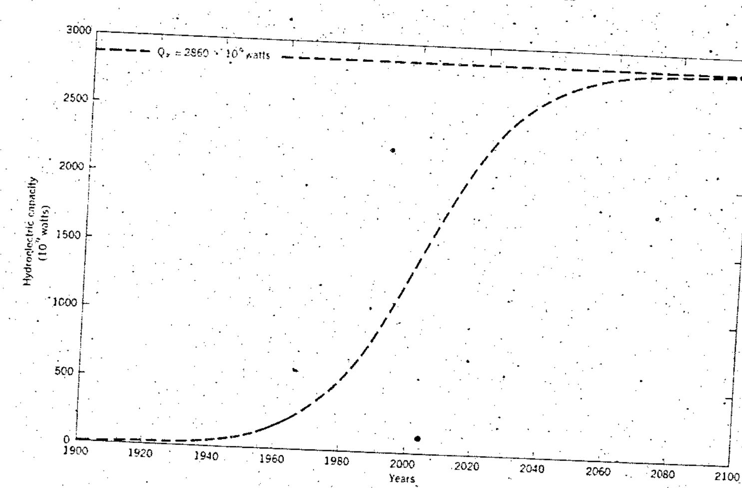

FIGURE 28. Installed and potential world hydroelectric-power capacity

Tidal Power

Tidal power is essentially hydroelectric power obtainable by damming the entrance to a bay or estuary in a region of tides with large amplitudes, and driving turbines as the tidal basin fills and empties. An inventory of the world's most favorable tidal-power sites gives an estimate of a total potential power capacity of about 63,000 Mw, which is about 2 percent of the world's potential water power capacity. At present, one or more small pilot tidal power plants of a few megawatts capacity have been built, but the only full-scale tidal plant so far built is that on the Rance estuary on the English Channel coast of France. This plant began operation in 1966 with an initial capacity of 240 Mw and a planned enlargement to 320 Mw.

One of the world's most favorable tidal-power localities is the Bay of Fundy region of northeastern United States and southeastern Canada. This has the world's maximum tides, with amplitudes up to 15 meters, and a combined power capacity of nine sites of about 29,000 Mw. Extensive plans have been made by both the United

States and Canada for the utilization of this power, but as yet no installations have been made.

Geothermal Power

Geothermal power is obtained by means of heat engines which extract thermal energy from heated water within a depth ranging from a few hundred meters to a few km beneath the earth's surface. This is most practical where water has been heated to high temperatures at shallow depths by hot igneous or volcanic rocks that have risen to near the earth's surface. Steam can be used to drive steam turbines. At present, the major geothermal power installations are in two localities in Italy with a total capacity in 1970 of about 600 Mw, the Geysers in California with a planned capacity by 1977 of 908 Mw, and at Wairakei in New Zealand with a capacity of 160 Mw. The total world installed geothermal power capacity at present is approximately 1,100 Mw.

What the ultimate capacity may be can be estimated at present to perhaps only an order of magnitude. Recently, a number of geothermal-power enthusiasts (many with financial interests in the outcome) have made very large estimates for power from this source. However, until better information becomes available, an estimation within the range of 60,000 to 600,000 Mw, or between 2 and 20 percent of potential water power, is all that can be justified. Also, as geothermal-power production involves "mining" quantities of stored thermal energy, it is likely that most large installations will also be comparatively short-lived—perhaps a century or so.

Nuclear Power

A last major source of industrial power is that of atomic nuclei. Power may be obtained by two contrasting types of nuclear reactions: (1) the fissioning of heavy atomic isotopes, initially uranium-235; and (2) the fusing of the isotopes of hydrogen into heavier helium. In the fission process, two stages are possible. The first consists of power reactors which are dependent almost solely on the rare isotope, uranium-235, which represents only 0.7 percent of natural uranium. The second process is that of breeding whereby either the common isotope of uranium, uranium-238, or alternatively thorium, is placed in a reactor initially fueled by uranium-235. In response to neutron bombardment, uranium-238 is converted into plutonium-239, or thorium-232 into uranium-233, both of which are fissionable. Hence by means of a breeder reactor, in principle, all of the natural uranium or thorium can be converted into fissionable reactor fuel.

Uranium-235 is sufficiently scarce that, without the breeder reactor, the time span of large-scale nuclear power production would probably be less than a century. With complete breeding, however, it becomes possible not only to consume all of the natural uranium, or thorium, but to utilize low-grade sources as well.

The energy released by the fissioning of a gram of uranium-235 or plutonium-239 or uranium-233 amounts to 8.2×10^{10} joules of heat. This is approximately equivalent to the heat of combustion of 2.7 metric tons of bituminous coal or 1[illegible].4 barrels of crude oil. For the energy obtainable from a source of low-grade uranium, consider the Chattanooga Shale, which crops out along the western edge of the Appalachian Mountains in eastern Tennessee and underlies, at minable depth, most of several mid-western states. This shale has a uranium-rich layer about 16 feet (5 meters) thick with a uranium content of 60 grams per metric ton, or 150 grams per cubic meter. This is equivalent to 750 grams per square meter of land area. Assuming only 50 percent extraction, this would be equivalent in terms of energy content to about 1,000 metric tons of bituminous coal or to 5,000 barrels of crude oil per square meter of land area, or to one billion metric tons of coal or 5 billion barrels of oil per square kilometer. In this region, an area of only 1,600 km² would be required for the energy obtainable from the uranium in the Chattanooga Shale to equal that of all the fossil fuels in the United States. Such an area would be equivalent to that of a square 40 km (25 miles) to the side, which would represent less than 2 percent of the area of Tennessee.

It thus appears that with a transition to the use of breeder reactors, the energy obtainable from the fissioning of plutonium-239, or uranium-233, derived from low-grade sources of uranium-238, or from thorium, respectively, is orders of magnitude larger than that from the world's supply of fossil fuels. However, before concluding that this is a sufficient answer to the world's energy needs, sight should not be lost of the unavoidable hazards associated with fission reactors. These hazards are three-fold. (1) The operation of such reactors produces continuously highly radioactive fission products which must be isolated from the earth's biological system, essentially in perpetuity. (2) The enormous concentration of energy in the small volume of a 1,000-megawatt fission reactor makes these reactors amenable to industrial accidents ranging in magnitude from trivial to catastrophic. For example, two large TVA reactors were recently put out of operation by an accident caused by a workman with a lighted candle. (3) In a world of social and political unrest, with terroristic activities occurring almost weekly, large fission reactors becomes "sitting ducks" for terroristic sabotage in peacetime, and doubly vulnerable in the case of international warfare.

A particular hazard is associated with plutonium. Even the present generation of light-water reactors produce small amounts of plutonium as a by-product. A 1,000-megawatt light-water reactor produces 250 kilograms of plutonium per year, principally fissionable plutonium-239. Plutonium-239, with a half-life of 24,400 years, together with other plutonium isotopes, emerges from the reactors as a part of the spent-fuel products, and its presence renders these products hazardous for a half-million years. However, plutonium, being a chemical element, is separable from the other wastes by chemical processes. According to an estimate by the U.S. Atomic Energy Commission (1973, table 3–9), the fissile plutonium to be produced in 1974 by U.S. reactors would be about 1,000 kilograms. By 1978 this would increase to 10,000 and by 1985 to 36,900 kilograms per year. The cumulative production by 1985 was estimated to amount to 199,800 kilograms.

The hazards posed by this amount of fissile plutonium, which must be transported over long distances and stored in many widely separated places, become evident when it is considered that only slightly more than 5 kilograms of plutonium were required for the bomb detonated over Nagasaki in 1945, and according to Theodore B. Taylor, formerly a leading bomb designer for the AEC, an amateur bomb could be constructed by terrorists with as little as 2 kilograms of plutonium (Willrich and Taylor, 1974; McPhee, 1974).

In view of these ominous hazards in the burgeoning proliferation of nuclear-fission electric-power plants and concomitant real and

potential spread of nuclear weapons, it becomes increasingly urgent to develop some less hazardous means of meeting the world's future energy requirements.

The fusion of hydrogen into helium is known to be the source of the enormous amount of energy radiating from the sun. Fusion has also been achieved by man in an uncontrolled or explosive manner in the thermonuclear or hydrogen bomb. As yet, despite intensive efforts in several countries, controlled fusion has not been achieved. Researchers, however, are hopeful that it may be within the next few decades.

Should fusion be achieved, eventually the principal raw material will probably be the heavy isotope of hydrogen, deuterium. This occurs in sea water at an abundance of 1 deuterium atom to each 6,700 atoms of hydrogen. The deuterium-deuterium, or D-D, reaction involves several stages, the net result of which is:

$$5\,{}_1^2D \rightarrow {}_2^4He + {}_2^3He + H + 2n + 24.8\ \text{Mev};$$

or, in other words, 5 atoms of deuterium, on fusion, produce 1 atom of helium-4, 1 atom of helium-3, 1 atom of hydrogen and 2 neutrons, and in addition release 24.8 million electron volts, or 39.8×10^{-13} joules.

It can be computed that 1 liter of water contains 1.0×10^{22} deuterium atoms, which upon fusion would release 7.95×10^{9} joules of thermal energy. This is equivalent to the heat of combustion of 0.26 metric tons of coal or 1.30 barrels of crude oil. Then, as 1 km^3 of sea water is equivalent to 10^{12} liters, the heat released by the fusion of the deuterium contained in 1 km^3 of sea water would be equivalent to that of the combustion of 1,300 billion barrels of oil or 260 billion tons of coal. The deuterium in 33 km^3 of sea water would be equivalent to that of the world's initial supply of fossil fuels.

ECOLOGICAL ASPECTS OF EXPONENTIAL GROWTH

From the foregoing review, what stands out most clearly is that our present industrialized civilization has arisen principally during the last 2 centuries. It has been accomplished by the exponential growth of most of its major components at rates commonly in the range of 4 to 8 percent per year, with periods of doubling from 8 to

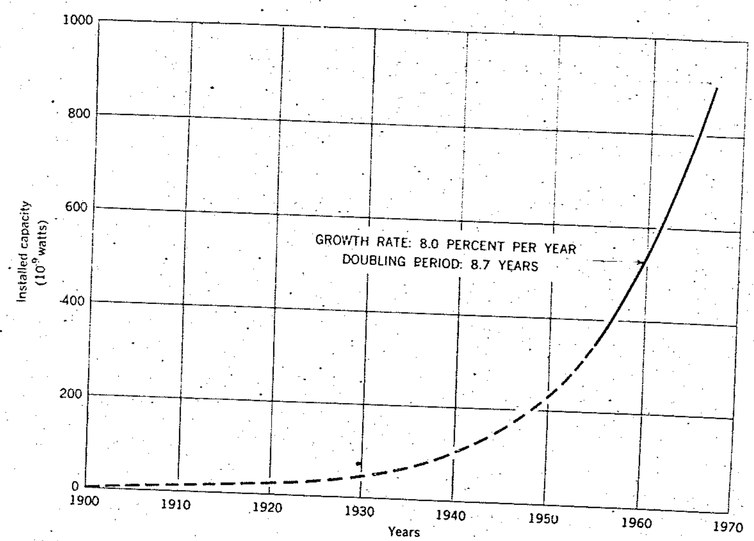

FIGURE 29. World electric generating capacity as an example of exponential growth (Hubbert, 1971, fig. 2)

16 years. The question now arises: What are the limits to such growth, and what does this imply concerning our future?

What we are dealing with are the principles of ecology. It has long been known by ecologists that the population of any biologic species, if given a favorable environment, will increase exponentially with time; that is, that the population will double repeatedly at roughly equal intervals of time. From our previous observations, we have seen that this is also true of industrial components. For example (fig. 29), the world electric-power capacity is now growing at 8 percent per year and doubling every 8.7 years. The world automobile population and the miles flown per year by the world's civil-aviation scheduled flights are each doubling every 10 years. Also, the human population is now doubling in 35 years (fig. 30).

The second part of this ecological principle is that such exponential growth of any biologic population can only be maintained for a limited number of doublings before retarding influences set in. In the biological case, these may be represented by restriction of food supply, by crowding, or by environmental pollution. The

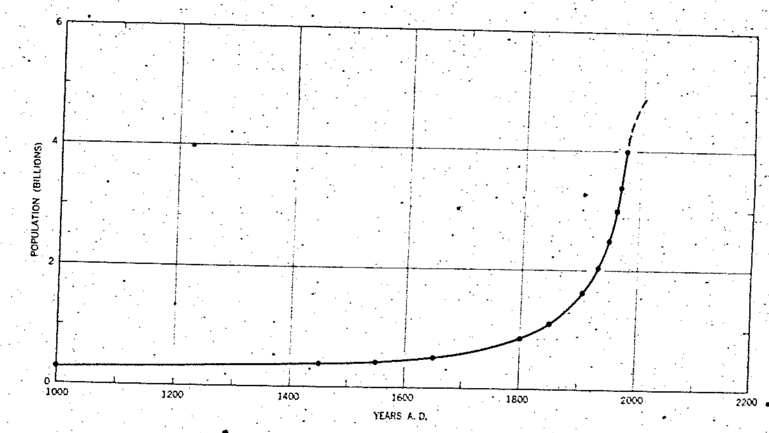

FIGURE 30. Growth of human population since the year 1000 A.D. as an example of an ecological disturbance

complete biologic growth curve is represented by the logistic curve of figure 31.

That there must be limits to growth can easily be seen by the most elementary arithmetic analysis. Consider the familiar checkerboard problem of placing 1 grain of wheat on the first square, 2 on the second, 4 on the third and doubling the number for each successive square. The number of grains on the nth square will be 2^{n-1}, and on the last or 64th square, 2^{63}. The sum of the grains on the entire board will be twice this amount less one grain, or $2^{64} - 1$.

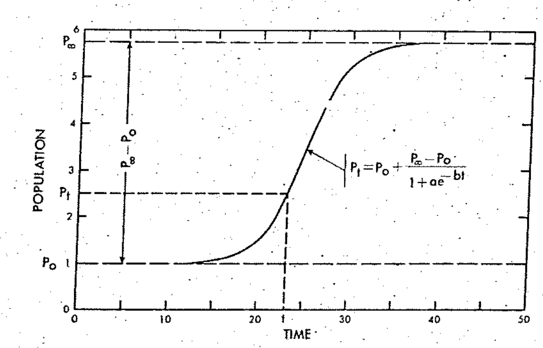

FIGURE 31. The logistic growth curve showing both the initial exponential phase and the final slowing down during a cycle of growth

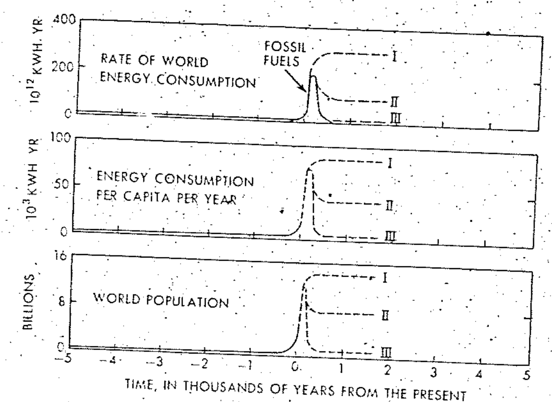

FIGURE 32. Epoch of current industrial growth in the context of a longer span of human history

When translated into volume of wheat, it turns out that the quantity of wheat required for the last square would equal approximately 1,000 times the present world annual wheat crop, and the requirement for the whole board would be twice this amount.

It follows, therefore, that exponential growth, either biological or industrial, can be only a temporary phenomenon because the earth itself cannot tolerate more than a few tens of doublings of any biological or industrial component. Furthermore, most of the possible doublings have occurred already.

After the cessation of exponential growth, any individual component has only three possible futures: (1) it may, as in the case of water power, level off and stabilize at a maximum; (2) it may overshoot and, after passing a maximum, decline and stabilize at some intermediate level capable of being sustained; or (3) it may decline to zero and become extinct.

Applied to human society, these three possibilities are illustrated graphically in figure 32. What stands out most clearly is that our present phase of exponential growth based on man's ability to control ever larger quantities of energy can only be a temporary period of about 3 centuries' duration in the totality of human history. It represents but a brief transitional epoch between two very much longer periods, each characterized by rates of change so slow as to be regarded essentially as a period of non-growth. Although the

forthcoming period poses no insuperable physical or biological difficulties, it can hardly fail to force a major revision in those aspects of our current culture the tenets of which are dependent on the assumption that the growth rates which have characterized this temporary period can somehow be sustained indefinitely.

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Bulletin of the
Association of Engineering Geologists
Vol. XIII, No. 2, 1976

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The Role of Coal in Future U.S. Energy Development

Introduction

Much has been said lately about attaining domestic energy self-sufficiency, but to date, little has been done. Oil tankers from Caracas, Abu Dhabi, and Al Kuwait continue to glide across the seas to meet our increasing energy needs. Meanwhile, our principal domestic energy resources—oil and natural gas reserves in the Outer Continental Shelf, the oil shale deposits and the coal lands of the West—remain untapped.

Help, however, appears to be on the way. In a forceful address in October 1974, President Ford called for the elimination of a large portion of the nation's oil-fired power plants by 1980. He also urged the accelerated leasing of federal lands on the Outer Continental Shelf, the resumption of coal leasing on federal lands, and the development of a new energy conservation policy.

There are, of course, many details left to be worked out. Language must be developed to put statutory flesh on the conceptual bones spelled out by the President. Congress must act. Regulations must be approved and tested, if need be, in court.

Toward A National Energy Policy

But the point is that consensus has emerged on many energy issues and the leadership needed to forge a coherent national energy policy is now being exerted. Positive action should soon result.

What will this action be? Early indications are that federal

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