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Exponential Growth as a Transient Phenomenon in Human History

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In this bicentennial year of American history, it is useful for us to reflect that the two-hundred-year period from 1776 to 1976 marks the emergence of an entirely new phase in human history. This is the period during which our industrial civilization has arisen and developed. It is also the period during which there has occurred a transition from a social state whose material and energy requirements were satisfied mainly from renewable resources to our present state that is overwhelmingly dependent upon nonrenewable resources. In 1776 our material requirements for food, housing, clothing, and industrial equipment were principally satisfied by renewable vegetable and animal products. Nonrenewable mineral products, clay products, lime, sand, and metals, were used in such small amounts that the available supplies, at that rate of consumption, seemed almost inexhaustible.

The energy requirements two centuries ago were likewise met principally by renewable resources. Vegetable and animal products were used for food and warmth; human and animal labor and wind and water power for mechanical work. The only nonrenewable energy source then used was coal, which was consumed in such small amounts per year that the total supply at this rate would likewise have seemed almost inexhaustible.

During the ensuing two centuries, the development of the world's present highly industrialized society has occurred. The magnitude and significance of this transition can most readily be appreciated if we consider the graphs showing the growth in the world's annual

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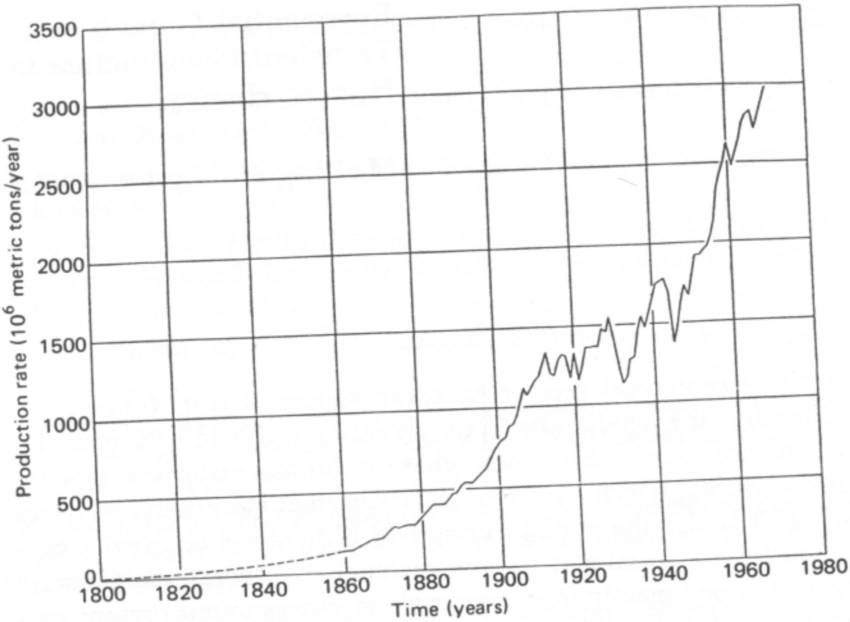

Figure 5.1
World production of coal and lignite (Hubbert, 1974a, fig. 3).

production of the principal sources of industrial energy, coal and petroleum.

Figure 5.1 shows the annual world production of coal and lignite from 1860 to 1970; figure 5.2 shows the corresponding growth in the annual world production of crude oil from 1880 and 1970.

The mining of coal as a continuous industrial enterprise began nine centuries ago near the town of Newcastle upon Tyne in northeast England. Annual statistics of world coal production are difficult to assemble before 1860, but by that time the annual production rate had reached 138 million metric tons per year. From the earlier history of coal mining and from scattered statistics it can be estimated that during the eight centuries from 1060 to 1860, the average growth rate in annual coal production was about 2.3 percent per year with an average doubling period of about 30 years. From this it can be estimated that the production of coal in 1776 was about 20 million metric tons. As of this year, the annual coal production rate has reached about 3.3 billion metric tons—a 165-fold increase during the two centuries since 1776. This has been at an average growth rate of

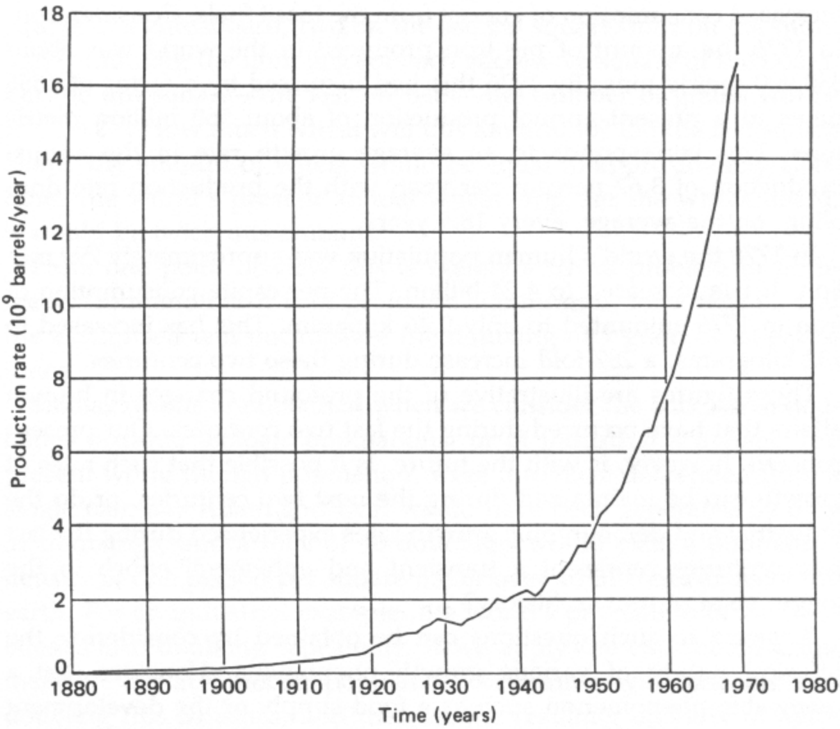

Figure 5.2
World production of crude oil (Hubbert, 1974a, fig. 5).

about 2.55 percent per year, or an average period of doubling of 27 years.

Although very small amounts of oil were produced in China and Burma at earlier times, the world's production of crude oil as a continuous industrial enterprise was begun in Romania in 1857 and in the United States two years later. As figure 5.2 shows, from 1880 until 1970 the growth in annual crude oil production increased smoothly and spectacularly. During this period the growth rate averaged 7.04 percent per year and the production rate doubled, on the average, every 9.8 years. The cumulative production also doubled about every 10 years. For example, the amount of oil produced during the decade 1960–1970 was almost exactly equal to all the oil produced from 1857 to 1960.

The increase in the consumption of and dependence upon the industrial metals during the last two centuries is comparable to the increased consumption of energy from the fossil fuels. Consider iron. In 1776 the amount of pig iron produced in the world was about 360,000 metric tons. By 1976 this had increased by a factor of 1556 times to a present annual production of about 560 million metric tons. This corresponds to an average growth rate in the annual production of 3.67 percent per year, with the production rate doubling, on the average, every 18.9 years.

In 1776 the world's human population was approximately 790 million. It has increased to 4.24 billion. The per capita consumption of iron in 1776 amounted to only 0.46 kilogram. This has increased to 132 kilograms, a 287-fold increase during these two centuries.

These figures are illustrative of the profound changes in human affairs that have occurred during the last two centuries. Our present concern, however, is with the future. Is it possible that such rates of growth can be maintained during the next two centuries, or do the industrial and demographic growth rates experienced during the last two centuries represent a transient and ephemeral epoch in the longer span of human history?

Answers to such questions can be obtained by considering the physical nature of various growth phenomena. Consider first a renewable phenomenon such as a food supply or the development of water power. Human food supply is derived almost entirely from plant or animal products. Therefore, the problem of the increase of food supply, or of the human population itself, reduces to the basic problem of how much the population of any biologic species can be increased on the earth. The basics of this problem are well understood. Biologists discovered a couple of centuries ago that the population of any biologic species, plant or animal, if given a favorable environment, will increase exponentially with time. That is, the population will double and redouble in the successive ratios of 1, 2, 4, 8, etc. during successive equal intervals of time. The period required for the population to double is different for different species. For elephants and humans the doubling period is a few decades, but for some bacteria it is as short as 20 minutes. Such a manner of growth obviously cannot continue indefinitely, but the significant question is this: About how many successive doublings on a finite earth are possible?

An approximate answer can be obtained when we consider the magnitudes obtained by successive doublings. Consider, for example, the classical problem of placing one grain of wheat on the first square of a chessboard, two on the second square, four on the third, and continuing the doubling for each successive square of the board. On the *n*th square—the last, or 64th—the number of grains will be 2^{n-1} or 2^{63}. How much wheat will this amount to? On the last square alone, the amount of wheat would be equal to approximately 1,000 times the world's present annual wheat crop; for the whole board, it would be twice this amount.

From one point of view this is merely a trivial problem in arithmetic; from another it is of profound significance, for it tells us that the earth itself will not tolerate the doubling of 1 grain of wheat 64 times.

Similar results are obtained when we consider the successive doublings of other biologic populations, or of industrial activities. The present world human population, were it to have descended from a single pair, say Adam and Eve, would have been generated by only 31 doublings, and a total of 46 doublings would yield a population density of one person per square meter over all the land areas of the earth. For an industrial example, the world's population of automobiles is also doubling repeatedly. If we apply the chessboard arithmetic to the automobile population, beginning with one car and doubling this 64 times, and then let the resulting quantity of automobiles be stacked uniformly on all the land surfaces of the earth, how deep would be the layer formed? About 1,200 miles or 2,000 kilometers.

From such considerations it becomes evident that the maximum number of doublings that any biological population or industrial component can experience is but a few tens. Therefore, any rapid rate of growth of such a component must be a transient phenomenon of temporary duration. The normal state of a biologic population, when averaged over a few years, must be one of an extremely slow rate of change—a near steady state. For example, the maximum possible number of times the human population could have doubled during the last million years is 31. Consequently, the minimum value of the average period of doubling during that time would have been 32,000 years, as contrasted with the present period of but 32 years.

The growth curve that characterizes a rapid increase of any biologic population or the exploitation of any renewable nonbiologic resource such as water power must accordingly be similar to that shown in figure 5.3. Beginning at a near steady state of a constant biologic population, or at zero as in the case of water power, the quantity

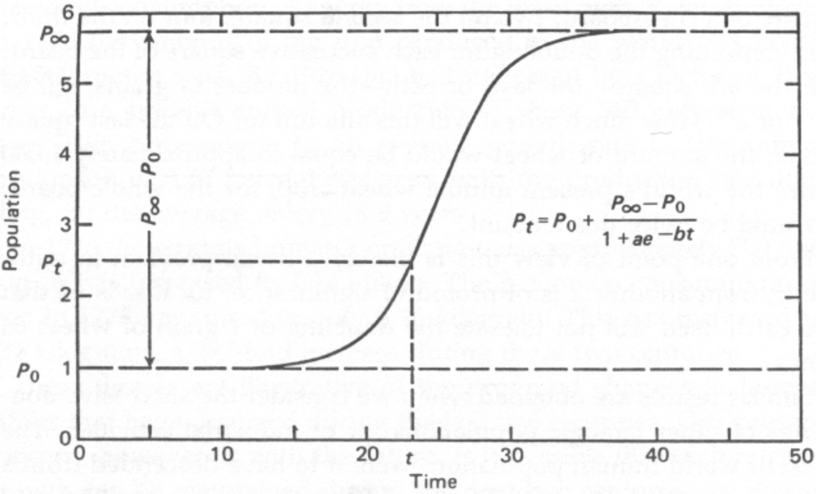

Figure 5.3
Logistic curve of population growth.

considered increases exponentially—that is, it doubles in equal intervals of time—for a while, and then, in response to retarding influences, gradually levels off to a constant figure, characterized by a state of nongrowth.

In the biologic case the inverse can also happen. The disturbance may be unfavorable and the population may undergo a decline or a negative growth. It then must stabilize at a lower level, or else become extinct.

The long-term behavior of the exploitation of the nonrenewable resources such as the fossil fuels or the ores of metals differs from that of the renewable resources in a very fundamental respect. Nonrenewable resources are absolutely exhaustible. Figure 5.4 is a flow diagram of the mining and utilization of a fossil fuel. The fuel is taken from the earth, and, in burning, is combined chemically with atmospheric oxygen. The materials, in the form of gaseous compounds CO_2, H_2O, and SO_2 and of asheous solids, remain on the earth, but the energy content released initially as heat, after undergoing successive degradations, eventually leaves the earth as spent low-temperature radiation.

The exploitation of metallic ores is illustrated in figure 5.5. Here, an ore body consisting of a naturally occurring rock containing an

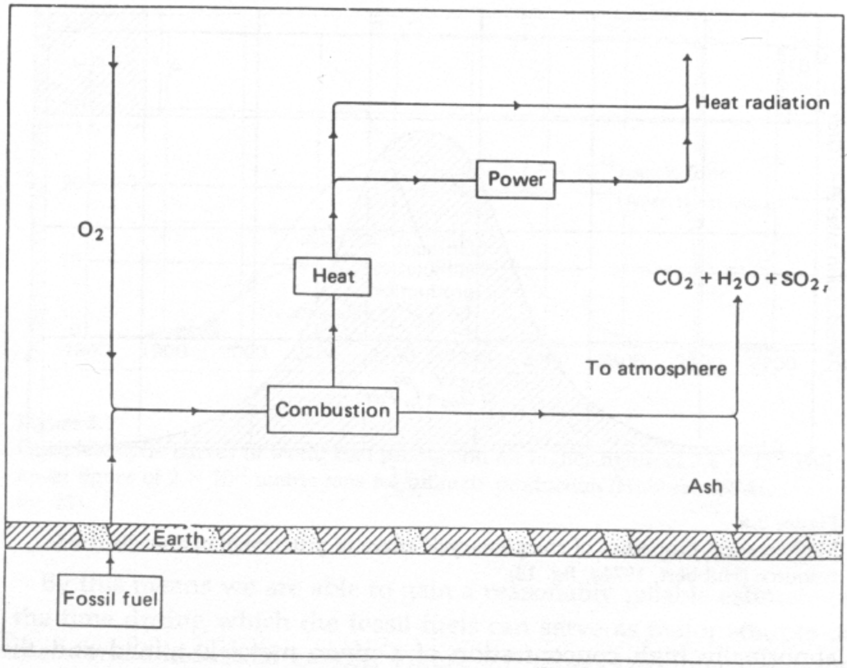

Figure 5.4
Flow diagram of matter and energy in combustion of fossil fuel for power production (Hubbert, 1974a, fig. 15).

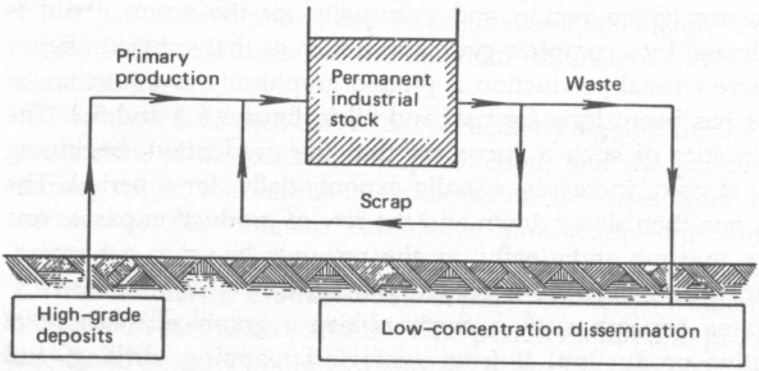

Figure 5.5
Flow diagram for the production and use of an industrial metal (Hubbert, 1972, fig. 26).

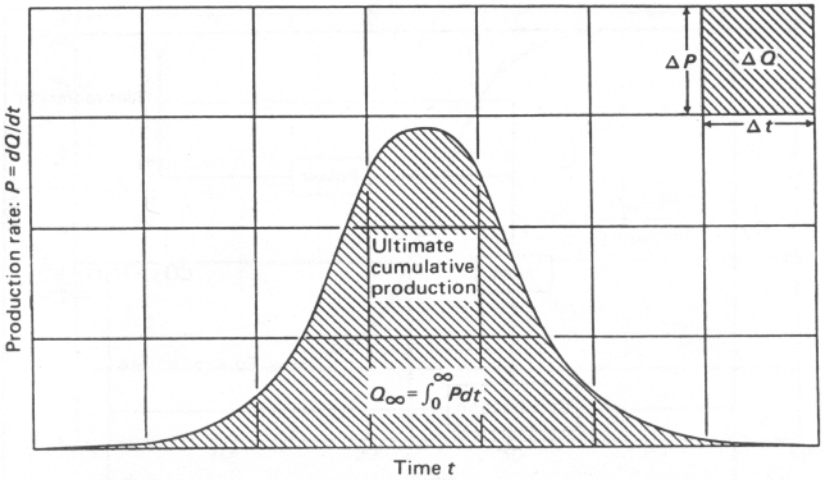

Figure 5.6
Mathematical properties of complete-cycle curve of production of an exhaustible resource (Hubbert, 1974a, fig. 18).

abnormally high concentration of a given metal is mined and the metal extracted by smelting. This then goes into the industrial stock from which it eventually is removed—lead in gasoline, for example, is irretrievably scattered.

Thus the production history of the fossil fuels or of the metallic ores, in any given region and eventually for the entire earth, is characterized by a complete-cycle curve such as that shown in figure 5.6, where annual production is plotted graphically as a function of time, as has been done for coal and oil in figures 5.1 and 5.2. The characteristics of such a curve are that the production, beginning initially at zero, increases, usually exponentially, for a period. The growth rate then slows down and the rate of production passes one or more maxima and finally, as the resource becomes exhausted, goes into a long negative-exponential decline.

The area beneath such a curve is also a graphical measure of cumulative production. If from geological mapping, drilling, and other means, the total recoverable quantity of the resource considered can be estimated in the earlier stages of exploitation, the future of the production history can be estimated, because the complete-cycle curve can only encompass a total area corresponding to the estimate made.

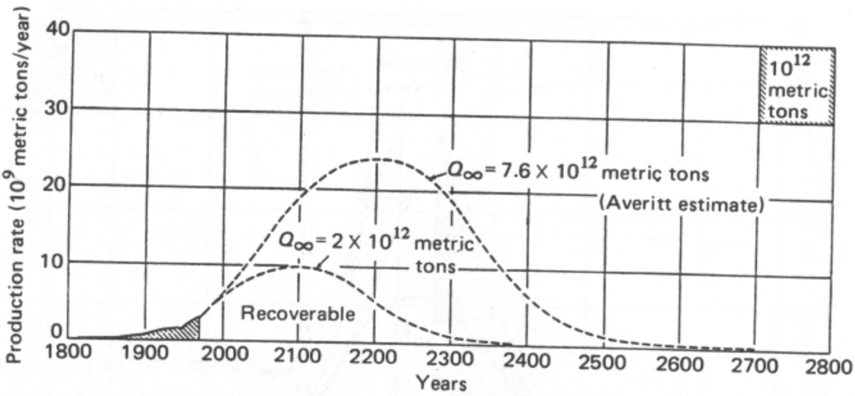

Figure 5.7
Complete-cycle curves of world coal production for higher figure of 7.6×12^{12} and lower figure of 2×10^{12} metric tons for ultimate production (Hubbert, 1974a, fig. 21).

By this means we are able to gain a reasonably reliable estimate of the time during which the fossil fuels can serve as major sources of the world's industrial energy. Figure 5.7 shows two interpretations of the complete cycle of world coal production, based upon a high estimate for the ultimate amount of coal to be produced of 7.6 trillion metric tons, and a low figure of 2 trillion. The high figure is based upon estimates, assuming 50 percent recovery, of beds as thin as 1 foot (0.3 meters) and to depths as great as 1,200 meters. The lower figure is for coal beds not thinner than 0.7 meters and not deeper than 300 meters.

Two aspects of such curves are particularly significant, the approximate date of the peak rate of production, and the period of time during which the cumulative production increases from 10 to 90 percent of the ultimate cumulative production—the time span required to produce the middle 80 percent. For the high estimate of 7.6 trillion tons the estimated date of peak production would be about 150 to 200 years hence, and the time period required to produce the middle 80 percent would be that from about the year 2000 to 2300 or 2400. For the lower figure of 2 trillion tons of ultimate production the peak in the production rate would occur earlier, about the year 2100, and the middle 80 percent of the ultimate coal would be consumed during the approximately 200 years from about 2000 to 2200.

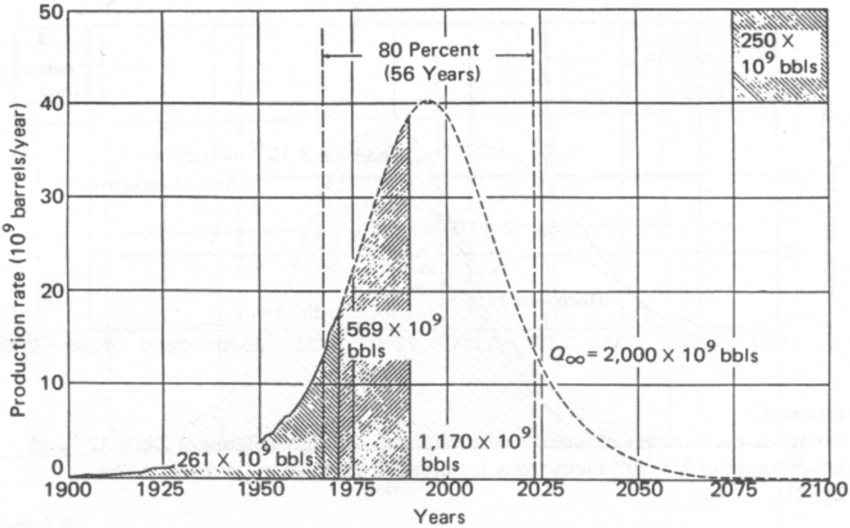

Figure 5.8
Complete-cycle curve for world crude oil production (Hubbert, 1974a, fig. 68).

The estimate of the complete cycle for the world production of crude oil is shown in figure 5.8. This is based upon an estimate of 2,000 billion barrels for the ultimate production, which is somewhat higher than the average of 15 estimates published since 1958 by international oil companies and leading international petroleum geologists. Using this figure, and assuming an orderly evolution of petroleum consumption, the peak in the production rate will probably occur during the decade 1990 to 2000, and the middle 80 percent will be consumed within the 60-year period from 1965 to 2025. Hence, children born within the last 10 years will see the world consume most of its oil during their lifetimes.

It is possible that oil production could be curtailed by the exporting nations to somewhat near the present rate. Were that to occur, the upper area under the curve in figure 5.8 would be displaced to the back slope and thus prolong the middle 80 percent period. Even so, this would be only about 10 to 15 years.

In parallel with the energy resources, modern industry, as we have seen, is also dependent upon the industrial metals. One of the most abundant of these is iron, the known ores of which are estimated to amount to about 250 trillion metric tons and the ultimate amount to

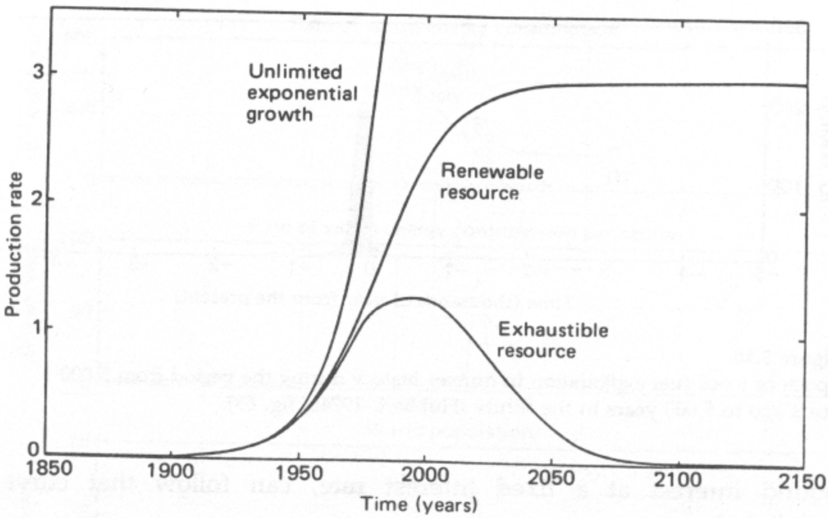

Figure 5.9
Three types of growth (Hubbert, 1974b, fig. 1).

possibly as much as 750 trillion. Based upon these figures in conjunction with the record of past production, the time span for iron production would be about the same as that for coal, the peak in the production rate occurring one or two centuries hence, and the middle 80 percent span extending about two to four centuries.

The known and estimated ores of most other industrial metals, copper, tin, lead, zinc, and others, are in very much shorter supply, with the time until the peak production rate occurs and the time span for the middle 80 percent being measurable in decades rather than in centuries.

Three types of growth phenomena with which an industrial society must deal are shown graphically in figure 5.9. Here, the lower curve represents the rise, culmination, and decline in the production rate of any nonrenewable resource such as the fossil fuels or the ores of metals. The middle curve represents the rise and leveling off of the production of a renewable resource such as water power or a biological product. The third curve is simply the mathematical curve of exponential growth. No physical quantity can follow this curve for more than a brief period of time. However, a sum of money, being of a nonphysical nature and growing according to the rules of com-

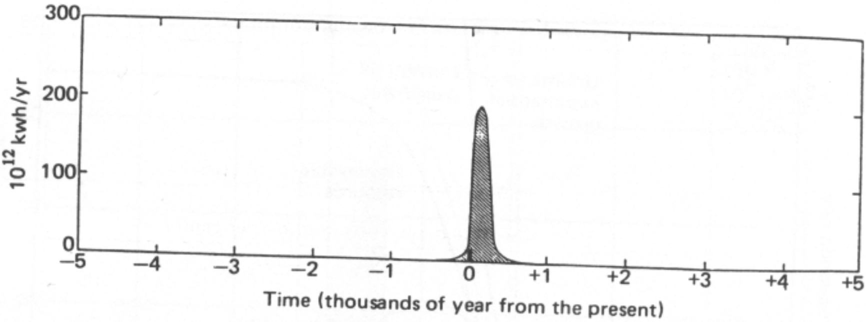

Figure 5.10
Epoch of fossil fuel exploitation in human history during the period from 5,000 years ago to 5,000 years in the future (Hubbert, 1974a, fig. 69).

pound interest at a fixed interest rate, can follow that curve indefinitely.

In their initial phases, the curves for each of these types of growth are indistinguishable from one another, but as industrial growth approaches maturity, the separate curves begin to diverge from one another. In its present state the world industrial system has already entered the divergence phase of these curves but is still somewhat short of the culmination of the curve of nonrenewable resources.

A better appreciation of the brevity and exceptional character of the epoch of the fossil fuels can be gained if we view it in the perspective of a longer time span of human history that we have considered heretofore. In figure 5.10 the complete cycle of exploitation of the world's total supply of fossil fuels, coal and petroleum, is shown on a time scale extending from 5,000 years in the past to 5,000 years in the future. On such a scale, the Washington Monument–like spike in the middle of this range, with a middle 80 percent spread of about three centuries, represents the period of exploitation of the fossil fuels in the much longer span of human history. Brief as this period is, having arisen, as we have seen, principally within the last century, it has already exercised one of the most disturbing influences ever experienced by the human species in its entire biological existence.

The position in which human society now finds itself in this longer span of history is depicted in figure 5.11. What we see there is that we are now in a period of transition between a past characterized by a much smaller population, a low level of technology, of energy

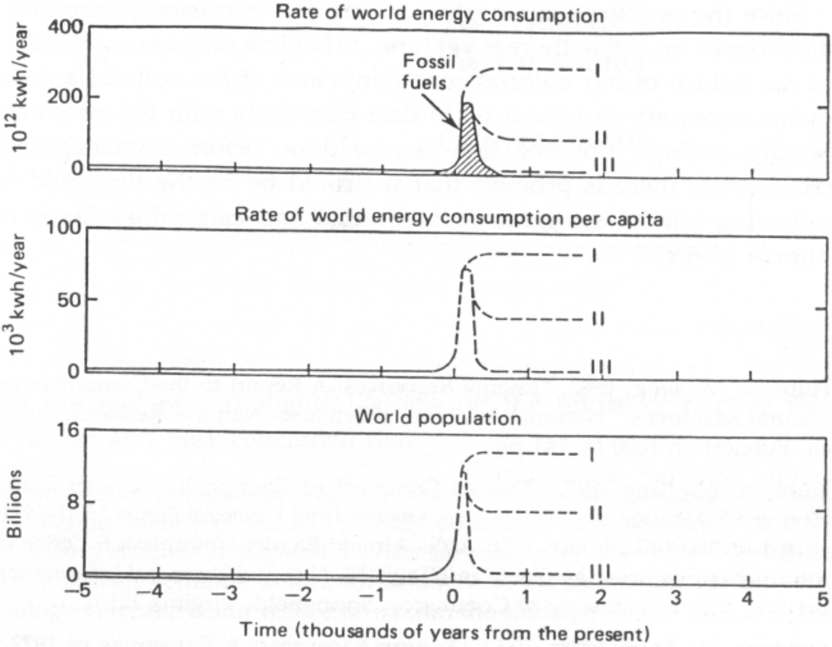

Figure 5.11
Human affairs in historical perspective from 5,000 years in the past to 5,000 years in the future (after Hubbert, 1962, fig. 61).

consumption, and of dependence upon nonrenewable resources, and by very slow rates of change, and a future also characterized by slow rates of change, but by means of utilization of the world's largest source of energy, that of inexhaustible sunshine, capable of sustaining a population of optimum size at a very comfortable standard of living for a prolonged period of time.

It appears therefore that one of the foremost problems confronting humanity today is how to make the transition from the precarious state that we are now in to this optimum future state by a least catastrophic progression. Our principal impediments at present are neither lack of energy or material resources nor of essential physical and biological knowledge. Our principal constraints are cultural. During the last two centuries we have known nothing but exponential growth and in parallel we have evolved what amounts to an exponential-growth culture, a culture so heavily dependent upon the continuance of exponential growth for its stability that it is incapable of reckoning with problems of nongrowth.

Since the problems confronting us are not intrinsically insoluble, it behooves us, while there is yet time, to begin a serious examination of the nature of our cultural constraints and of the cultural adjustments necessary to permit us to deal effectively with the problems rapidly arising. Provided this can be done before unmanageable crises arise, there is promise that we could be on the threshold of achieving one of the greatest intellectual and cultural advances in human history.

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