Brown, Bonner, and Weir

THE NEXT HUNDRED YEARS

by HARRISON BROWN, JAMES BONNER AND JOHN WEIR

This article has been extracted from the book, The Next Hundred Years: Man's Natural and Technological Resources, *by Harrison Brown, James Bonner and John Weir, copyright 1957 by The Viking Press, Inc., to be published in June. Dr. Brown is professor of geochemistry at Caltech; Dr. Bonner, professor of biology; Dr. Weir, professor of psychology.*

This extract, the first in a series of three, has been drawn largely from Dr. Brown's evaluation of our mineral and energy resources. Next month, Dr. Bonner reports on agricultural resources. In June, Dr. Weir discusses technical manpower sources.

DURING THE LAST 300 years man has achieved a degree of power over his environment which is unprecedented in the thousands of years of human history which preceded them and in the hundreds of thousands of years of human prehistory. Our rate of material progress and our rate of growth seem to be steadily accelerating, and one cannot help asking, for how long can this acceleration and this growth continue?

What is the future of our industrial civilization likely to be? Can we foresee the major problems that will confront us? Are these problems soluble? What kind of society could our science and our technology help us to create in a world at peace?

In this study we would like to take what we call "the long view" and attempt to make an assessment of the future of our scientific-technological-industrial civilization.

The reader should keep in mind that we are in . . . a period of rapid transition from a culture which has been predominantly agrarian to one which is predominantly industrial . . . Had we made a forecast at almost any time in the past, or perhaps were we writing at practically any time in the future, our chances of being correct would be considerably greater than they are today . . .

The transition from a culture which is primarily agrarian to one which is primarily urban-industrial, has proceeded unevenly in different parts of the world and brought with it no little confusion. The closest parallel in the past course of human existence is the transition from a food-gathering to an agrarian culture which took place some seven thousand years ago. . .

The contrasts which then existed between the wealthy agricultural minority and the poverty-stricken food-gathering majority are paralleled today by the contrasts between the wealthy industrialized minority and the poverty-stricken agricultural majority. Then the techniques of agriculture spread from one region to another, eventually to become world-wide. Today the techniques of industry are spreading from region to region, and it seems likely that, barring a world catastrophe, they too will become world-wide.

The spread of the agricultural revolution reached its eventual limit as the world's arable land became settled. As agriculture requires land, so industry requires huge quantities of raw materials—ores of iron, copper, aluminum, and a variety of other metals; quantities of non-metals such as sulphur, phosphate rock, and water; adequate sources of energy such as coal, petroleum, and water-power. To what degree can we expect the longevity of industrial civilization and the extent to which it spreads to be limited by the availability of these raw materials?

Raw materials

The factors which will determine the future supply of and demand for raw materials are numerous. In attempting to assess them, we can divide the broad question into several component parts. First we must inquire into the increasing per capita demands for raw materials in highly industrialized societies. Within the United States, for example, these have increased steadily during the course of the last century. With each new year more raw materials are required to support an individual within our society than were required the year before. For how long a time can we expect this trend to continue? Is there any foreseeable limit to the per capita requirements for raw materials within a highly industrialized society?

The second factor concerns the rate of spread of industrial civilization. During the course of the last three hundred years we have seen industrialization emerge in Western Europe and jump the Atlantic Ocean to the United States. More recently it has come to dominate Japan and the Soviet Union. Today we hear rumblings of impending industrialization in India, in China, in parts of Africa and in parts of South America. How quickly can we expect this process to take place? How rapidly can we expect the per capita demands for raw material in these at present underdeveloped areas to increase? And as they increase, are there sufficient raw materials in the world to satisfy, in such areas as India and China, demands which approach even remotely those which are now characteristic of the nations of the West?

Third, we must ask how large the population of human beings in the world is likely to become. Knowing the per capita demands for raw materials in the various regions of the world, by how many people must we multiply in order to determine the total drain upon the earth's resources? In order to determine this we must assess the number of people that we can feed.

The fourth factor is concerned with the amounts of raw materials available to man. What is a usable raw material? Certainly during the course of the last few decades we have seen our concepts changed drastically. We have seen that as industrialization spreads throughout the world the demands for raw materials will become enormous, and indeed will dwarf existing demands. As demands increase and as the world's high-grade resources are consumed, it will become necessary for us to process materials of lower grade, making our demand for raw materials increase still further as a result of the fact that more equipment, more energy, and more technology will be required for the processing.

What, if any, are the limits to the grades of ores which can be processed? Is it possible for the trend toward lower-and-lower-grade materials to be continued indefinitely? Or is there some limit of concentration below which processing will become impossible? Since the beginning of the present century the average grade of copper ore in use has dropped to one-sixth the concentration formerly processed—that is, to about 0.8 percent copper. Can we look toward the possibility of processing ores which contain as little as 0.1 percent, or perhaps as little as 0.01 percent copper?

When we examine this problem from the technological point of view, we see that fundamentally there is no lower limit to the grade of an ore which can be processed . . . If at some future time the average concentration of copper in copper ore were to drop to 0.01 percent, and if there were still an acute need for copper, there would be little question but that the metal could be extracted in high yield. To make this possible, two criteria must, however, be fulfilled. First, a satisfactory process must be developed—which means that scientists and engineers must work on the problem in the laboratory and in the pilot plant and conceive, develop, and test various methods for achieving the desired result. Second, energy must be available for the processing—for the mining and transport of vast quantities of ore, for the manufacture of the huge quantities of equipment which must be used in the processing and as a driving force in the process itself.

Potential resources

If we are given adequate supplies of energy, almost any material in the earth's crust can be looked upon as a potential resource . . . The ultimate resources of energy which are available to man are enormous—and indeed are sufficient to power a highly industrialized world for literally millions of years. This means that, given adequate brainpower, there is little doubt that the trend which has led us to process ores of steadily decreasing grade can continue until we reach the point where we are processing the very rocks of which the earth's crust is made.

If the energy consumption of the world were to increase no further, mankind could probably maintain its present level of productivity for an indefinitely long period of time—even after resources of fossil fuels had disappeared—simply by developing all potential water-power resources and by harvesting all the world's forests on a sustained-yield basis. But if rates of energy consumption continue to accelerate, and reach the levels we have seen to be probable, and if these rates are maintained beyond the time when our supplies of petroleum and coal are exhausted, it will be necessary for man to make use of new, less conventional sources of energy.

When we survey the energy sources which are potentially available, we find that forms such as earth heat, winds, and tides can be, at best, of limited usefulness. There are a few localities where such sources are being tapped today, and there are others where they might be tapped economically in the future. But when we assess the total energy output which might eventually be developed economically from such sources it turns out to be very small, compared to eventual world-wide demand.

Indeed, from a long-range point of view it is apparent that we must eventually depend more and more upon solar energy and nuclear energy. We now know that from the technological point of view both of these can be utilized. The question as to which will be most widely used is a question of economics. Which will require the least capital investment per unit of output? Which will have the lowest operating cost? On the basis of what we now know about the technologies of utilizing these two forms of energy it appears that, for the generation of mechanical power and electricity, nuclear energy will probably be less expensive than solar by a considerable margin.

Solar energy

A number of systems have been devised for transforming solar heat into electricity, but the capital costs per units of capacity have in all cases been extremely high. In hot regions the sun's energy might be used essentially to replace fossil fuels for the heating of water in an electrical generation plant. In order to accomplish this, the sun's rays are captured by special flat-plate collectors. Capital costs might run to $20,000 per acre; and the resultant power, depending upon the efficiency of the system, might cost several cents per kilowatt-hour, compared with prevailing costs of generating electricity, of a few mills per kilowatt-hour.

We also know that electricity can be generated by allowing the sun's radiation to fall upon semi-conductors. This phenomenon is now being put to good use in the Bell "solar battery," which can be used to generate electricity for a variety of small-scale uses. The large-scale use of this method would, however, involve prohibitively high capital costs. Other systems for the direct conversion of solar energy into electricity present the same difficulty.

One of the most efficient and least expensive means of producing mechanical and electrical energy from solar energy is to grow trees in the sun, to harvest the wood, and then to burn the wood in the firebox of a boiler. Or one can ferment sugar, which can be obtained in high yield per acre by growing cane or sugar beets, and thus obtain alcohol or a variety of combustible gases and liquids which can be used for generating power. But in view of the pressure on the world's agriculture to produce food and the probability that the food shortage will continue for a considerable time in the future, it is unlikely that much potential agricultural land will be diverted to the production of fuels.

Power from algae

An ingenious system has recently been described for the production of power from algae grown in a closed system containing a high concentration of carbon dioxide. The algae are cultured and then fermented in such a way that methane and hydrogen are produced. These gases are burned in a gas turbine or engine which is used to generate electricity. The carbon dioxide which results from the combustion is returned to the algae culture unit. In this way, under ideal conditions, one would have a closed system which would convert between 1 percent and 3 percent of the incident solar energy into electricity. It has been estimated that a system of this general type could be used to produce electricity at a cost of 2.5 to 5 cents per kilowatt hour, and liquid fuels at a cost of about $150 per ton.

Although it is doubtful that solar energy can compete with nuclear energy for the large-scale generation of power, there are areas where it will probably turn out to be very useful on a smaller scale. We have already mentioned the solar battery. Solar water heaters are coming into widespread use in tropical regions. An inexpensive solar cooker has been devised in the National Physical Laboratory in India; this could, if widely used, bring about the savings of substantial quantities of fuel. At the same laboratory a solar pump has been devised which could be used for pumping water on a small scale in isolated regions where fuels are not available.

It is likely that the most important use for solar energy in the future, however, will be for space heating. We now know that houses can be designed in such a way that requirements for space heating could be met almost entirely by solar energy in populated regions of the world as far north as Boston. The additional capital costs which would be required in house construction do not permit these techniques to be used widely at the present time. But as the prices of conventional fuels increase we will probably approach the time when most buildings will be designed to make maximum use of solar heat.

It is now reasonably certain that electricity can eventually be produced from nuclear energy at costs which are less than 1 cent (10 mills) per killowatt-hour. How much lower than 10 mills the cost can become, and how rapidly, are matters for conjecture. At the International Conference on the Peaceful Uses of Atomic Energy, which was held in Geneva in 1955, estimates as low as 4 mills per kilowatt-hour were given. Forecasts of the eventual nuclear-power-generating costs in the United States range from 4 to somewhat over 6 mills per kilowatt-hour. Sapir and Van Hyning, in their study on the outlook for nuclear power in Japan, have reviewed the evidence and made the reasonable assumption that we might have available 10-mill nuclear power by the mid-1960s, 7-mill power by the mid-1970s, with the cost gradually approaching 5 mills per kilowatt-hour. These estimates can be compared with generating costs of between 6 and 7 mills per killowatt-hour for new coal-fired units in the United States and about 18 mills for similar plants in Japan.

Nuclear electricity

It is likely, then, that nuclear electricity will compete with that generated from coal in the not too distant future. And it seems clear that this competition will take place unevenly throughout the world.

On a per capita basis the United States has the largest coal reserves in the world, with the result that we are not likely to encounter a fuel shortage for many decades. Our coal seams, however, are not uniformly distributed through the nation, and fuel costs increase as one moves away from the available supply. A number of areas which are far removed from coal fields—for example, southern California—are at present able to generate power at reasonable prices from petroleum or natural gas. There are other areas, however, where both coal and petroleum are expensive and where power costs are, as a result, considerably higher than the national average. It is in these areas that nuclear power might be expected to play its first major role in the United States.

If, as seems quite possible, we pass through a peak of domestic petroleum production by about 1970, nuclear power may well become important in those areas, such as the Far West, which lack coal but which at present have ready access to adequate supplies of petroleum or natural gas. After 1970 or 1975 the domestic importance of nuclear power may well increase rather rapidly. If, as seems possible, we pass through the peak of world petroleum production in about 1990, demand for coal will increase sharply and nuclear energy will probably be able to compete economically on a fairly broad front. But the production costs of coal in the United States are so low that it seems likely that it will remain our major fuel for a very long time.

The situation in the greater part of the world differs considerably from that in the United States, largely because of the substantial differences in fuel costs which prevail. In the United States we are able to generate steam electric power at coal costs which average about $6 per ton. In Western Europe, by contrast, the cost ranges from $13 to $20 per ton. Coal averages about $20 per ton in the United Kingdom. Western Europe is paying $20 per ton at the dock for large quantities of American coal. When we take into account the fact that more than 50 percent of the cost of generating electricity can be fuel cost, we can realize that nuclear electricity can probably compete with coal-generated electricity in other parts of the world long before it is competitive on a really broad base in the United States.

When we couple the fuel cost differential with two additional factors, the differences between the situation in the United States and that in other countries becomes even more dramatic. The first consideration is that of foreign exchange. Those regions of the world which must look forward to continued heavy imports of fossil fuels, and which face balance-of-payment difficulties, may well prefer to generate nuclear power, even when it is more expensive than power generated from conventional sources, if by so doing they minimize the drain upon their domestic financial resources.

The second major factor involves the striving on the part of most nations for economic self-sufficiency. Supplies of petroleum are uncertain. A very large fraction of the world's potential oil reserves are in the Middle East, where they are sensitive to the status of international relationships. Many nations will prefer an assured supply of nuclear power at relatively high but decreasing prices to less expensive but uncertain supplies of crude oil at prices which are destined to continue increasing.

The Soviet Union appears to be a rather special case with respect to nuclear-energy needs. Although she has vast coal resources, most of the coal lies in Siberia, while in the European part of the country there is a fuel shortage. Each year, apparently, nearly 15 million tons of coal are shipped from Karaganda and Kazakhstan to European Russia—a distance of some 1500 to 2000 miles. This is one of the reasons the Soviet Government has stressed the importance of the industrialization of Siberia. And it is one of the reasons it has announced the establishment of a program to build five new nuclear-electric plants in Moscow, Leningrad, and the Urals.

Nuclear energy and the United States

It seems clear that nuclear energy can play a major role in many regions of the world—particularly in Europe, South America, Southeast Asia, and Japan—just as soon as reactors are developed capable of producing power at costs of 10 mills per kilowatt-hour, or less. It is ironical that the United States, possessor of what is probably the world's most highly developed nuclear technology, has at the moment the least need for nuclear power, except for specialized military purposes. And the prospects are that, while our need will grow, it will grow considerably more slowly than will the needs of many other nations.

On the basis of the preceding discussion, let us now map out a possible but reasonable pattern of world energy consumption for the next century. Barring a world catastrophe, and assuming that industrialization will spread throughout the world, that population will continue to grow, and that we shall have adequate brainpower to solve our prodigious technical problems as they arise, total energy consumption will continue to rise rapidly following the law of compound interest. During the next ten to twenty years consumption of petroleum will probably increase more rapidly than will the consumption of coal, but at about 1975 the rate of increase is likely to slacken, so that the total rate of consumption will pass through a broad peak late in this century.

As the petroleum supplies diminish, increasing emphasis will be placed upon the production of liquid fuels from shales, tar sands, and coal hydrogenation. After about 1975 it seems likely that the gap between coal and petroleum as primary sources of energy will widen rather rapidly.

After about 1980 nuclear energy should represent a significant proportion of world power production, primarily as a replacement for fossil fuels in electrical power production. Its use should spread rather rapidly. By the end of the century nuclear energy may account for about one-third of our total energy consumption. During this period demand for coal will continue to increase, largely because of the continually increasing demand for liquid fuels and for a variety of complex chemicals. By the middle of the next century it seems likely that most of our energy needs will be satisfied by nuclear energy, with coal reserved almost entirely for the production of liquid fuels and chemicals.

Uranium and thorium supplies

We must now ask how long we can expect the earth's supplies of uranium and thorium to power an industrial world. These elements, like coal and petroleum, are fossil fuels; they were made when the elements were formed, and they are not being made at the present time. The quantities of uranium and thorium which are available to us are, then, finite. Nevertheless, the energy available to man in the form of uranium and thorium is enormously greater than the energy contained in our reserves of coal and petroleum. This is because uranium and thorium are found in low but significant quantities in the common rocks of the earth's crust.

An average piece of granite contains only about 4 parts per million of uranium and about 12 parts per million of thorium. These are indeed small quantities, yet the uranium and thorium in 1 ton of average granite contains energy equivalent to about 50 tons of coal. Of course, not all this energy is available, as the process of extracting the elements from the rock necessitates a substantial energy expenditure. Energy is consumed in quarrying, crushing, and grinding the rock, in transporting the rock to the chemical plant, in making the chemicals which are used in processing, and in the manufacture of the processing equipment. Clearly, if the energy required to extract the uranium and thorium were as great as the energy content of the extracted material, there would be no profit.

It has been found, however, that about one-third of the uranium and thorium is localized within the rock in such a way that it can be extracted with very little expenditure of energy. Thus, from 1 ton of ordinary granite, energy which is equivalent to about 15 tons of coal can be economically extracted. This means that from the long-range point of view man need not be confined to high-grade uranium and thorium ores for his energy. He will be able, if need be, to extract his energy needs from the very rocks of the earth's crust. And, as we saw earlier, the same rocks can supply the variety of metals which are necessary for the perpetuation of a highly industrialized civilization.

Power from thermonuclear reactions

There is, in the long run, the possibility of producing power from thermonuclear reactions—from fusion of hydrogen as distinct from fission of uranium. No one as yet sees very clearly just how this is to be done, but it is nevertheless a very real possibility. If the technical problems are solved, the waters of the seas will be available to man as an almost infinite source of energy. This new energy may well be more expensive than that obtained from uranium fission. Nevertheless it may well be available for tapping when it is needed, at some distant time.

It is interesting to speculate about the pattern of energy consumption in a highly industrialized world, a world in the distant future when all fossil fuels have been consumed. Let us assume that human beings learn to regulate their numbers and that the population of the world is eventually stabilized at about 7 billion persons. Let us assume further that energy requirements amount to the equivalent of 10 tons of coal per person. This would be larger than the present per capita consumption of energy in the United States. But it should be emphasized that the per capita flow of goods would be considerably less than at present, for the reason that all goods would be more expensive, in terms of energy needed to produce them, than they are today. The total energy requirements for this society would amount to the equivalent of 70 billion tons of coal annually. We can assume that by then solar energy is being used, wherever possible, for space heating. We can assume further that all potential hydroelectric sources have been developed and that the world's forests are developed and harvested on a self-sustaining basis. Under these circumstances about 65 percent of the total energy needs would be satisfied by nuclear energy.

In conclusion, it seems clear that man has available potential supplies of energy which are sufficient to satisfy his needs for a very long time. However, these sources have yet to be transformed from potential supplies into actual ones. Before they can be used they must be developed. Whether or not man will be able to develop them in time is a very real question, the answer to which will be determined, in the long run, by many factors of a political, economic, and social nature.