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Part II

Natural Resources

Chapter Four

Long-Term Availability of Natural Resources

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Resources are conventionally classified as either renewable or nonrenewable. Renewable resources are generally taken to be of biological origin, that is, food and forest. The definition of nonrenewable resources is more difficult. Energy once used cannot be used again even though a small fraction of the used energy is chemically stored in the process of manufacturing or building. Phosphates and other components of fertilizers are similarly nonrenewable, though a portion of the constituent elements is stored in biologic matter. Metals are generally considered to belong to the nonrenewable class, although the potential for recycling blurs the definition. This paper deals with problems of what are conventionally called nonrenewable resources, that is, energy and materials derived from the earth's crust by extractive means.

In the current debate about the long-term availability of resources, there is a variety of views. The pessimist sees a future in which catastrophic exhaustion of resources is inevitable unless economic growth is brought to a stop by drastic measures. The optimist views the future as one in which nonrenewable resources are economically and physically infinite. There are, of course, gradations between these extreme points of view.

The simplest version of the pessimistic view is that growth is exponential in the consumption of metals and energy. Given a finite reserve of these materials, it is then a matter of simple arithmetic to show that exhaustion is inevitable. This thesis, explored in *The Limits to Growth*, has merit in dramatizing the qualitative implications of compound growth. Doubling of the resources does not double the time to exhaustion if there is exponential growth. For example, if the reserve in the ground is good for fifty years at current consumption rates, and if growth averages 7 percent per year (which is equivalent to a doubling time of ten years), then a doubling of the reserves extends the life of the reserve by only ten years. So, a doubling of reserves under the assumption of steady exponential growth increases the lifetime of the reserve by only 20 percent of its initially projected life.

Another less pessimistic view acknowledges that there are various economic feedback mechanisms that link consumption to scarcity. In this view the question is raised whether the efficiency of the marketplace can react quickly enough to impending shortages to avoid a disastrous situation. Actual or threatening scarcity of a particular resource will lead to price rises and consequent incentives to economize on scarce resources and substitute plentiful ones, but the question raised from this viewpoint is whether a society, consuming nonrenewable resources in all sectors, can react in time and in a way to prevent real economic dislocation?

A still milder form of pessimism assumes that the price mechanism will effectively ration scarce materials. However, the fraction of the society's total resources that must be allocated to the extraction and production sector grows. With this growth there will be fewer resources available for real income as relatively fewer goods and services are produced by the lowered resource base. This shift of economic resources toward the extractive and productive industry can result in major economic dislocations as the production of goods and services decreases, especially if the changes take place rapidly in relation to other time scales characterizing the economy.

Optimists are generally of one of two views, both of which rely on the efficiency of the market mechanism. Impending shortages generate rising prices. The rising prices act as a danger signal, discouraging the use of scarce minerals and stimulating technology and the use of alternative materials and energy sources. In this view there will always be enough materials and energy to satisfy demand, but at a price. The difficulty with this view is that the price may be great enough to impair the economic welfare, since capital and labor must be used to secure scarce raw materials and to develop the technology that efficiently employs these materials. In one form this view blends imperceptibly with the mildest form of pessimism discussed above.

The most optimistic view maintains that humanity through its inventiveness always will be able to counteract any possible effect of scarcity. New sources, substitution, recycling, and new technology, both in extraction and in the use of materials and energy, are conceived of as always being able to eliminate the evils of scarcity. The most optimistic optimist points out that the actual abundance of minerals, including energy resources, in the continental crust of the earth is many times—often millions of times—greater than known reserves. This observation is used to justify the position that the resources are essentially infinite.

Which view one adopts is very much a matter of judgment. However, some very basic considerations of the distribution of elements in the earth's crust and of the means of extracting metals rule out the most optimistic view with respect to the availability of many key metals. A critical examination of recoverable fuel resources suggests that the time scale for the exhaustion of fuel sources, hydrocarbon or nuclear, is indeed limited, though for how long is uncertain.

Of the resources for energy, the hydrocarbon fuels form a relatively straightforward case of the kind considered in *The Limits to Growth.* There are limited amounts of natural gas, oil, coal, peat, shale oil, and tar sands. Sedimentary rocks do contain in certain places trace amounts of hydrocarbons, but no one seriously would advocate that such traces could be enriched to form a fuel at any conceivable price. As hydrocarbon fuels become scarce, marginal resources will become reserves as the prices rise. New techniques for extraction and conversion of fuels to energy will become economical; but basically there is a finite limit to the resources. Once this limit is approached, then the price mechanism will favor the use of these resources for materials rather than for fuel.

The major question about hydrocarbon fuels is the extent of reserves and resources both proved and speculative. Most analysts would agree, however, that for oil and gas—assuming a continued world exponential growth for the next few decades—exhaustion will come within a few decades. A more precise estimate of the time to exhaustion will be explored in this paper. The situation with coal is somewhat more reassuring. Exhaustion comes, again with the assumption of exponential growth, in time measured in a century or so.

The situation for nuclear fuels, uranium and thorium, is less clear. Geochemically, uranium has certain properties that allow it to form separable minerals at low concentration. Further developments in the breeder reactor technology may make it possible to stretch existing reserves over a long time span. Fusion, if it becomes a reality, can also contribute to stretching uranium resources through a combined fusion-breeder reactor. Relatively little work has been carried out on determining the reserves of thorium, another potential nuclear fuel.

The present uncertainties in reserves and resources, particularly with regard to speculative resources, and the rapidly developing technical picture make it more difficult to assess the time scale for exhaustion of the nuclear fuels.

FUELS AND OTHER RAW MATERIALS

Fuels and other raw materials present very different problems of long-term availability. The workings of the law of conservation of mass ensures that metals once extracted from the earth can be used over and over again. Whether virgin or recycled metals are used depends on total demand and economics. If the demand for a particular metal exceeds that available from used materials, then economics dictate that new material will be extracted from the earth's crust. However, once extracted, the metal serves as a future source for reuse. The demand for new material is thus lessened by the availability of previously mined material.

Basically because of the second law of thermodynamics, energy cannot be recycled in the sense that metals can. Energy can be used more efficiently. Coal once burned to produce steam can generate only electricity, with the excess thermal energy dumped into the waterways or the atmosphere. Alternatively, the steam discharged from a turbine can be used in industrial processes so that the overall efficiency of the use of energy is increased. In the end, however, energy—once highly organized in the form of chemical energy in coal or oil or nuclear energy in the uranium ore—becomes dissipated as low-grade heat energy that is eventually radiated out into space.

Because of this fundamental difference between reusable materials and energy, primary attention is given in this paper to the availability of energy. In general, the problems of fuel availability, particularly fuels in a form that can be readily utilized by existing or developing technologies, seem more pressing than the problems of the availability of other raw materials. Data about reserves and resources of energy are in general more complete than those for most metals. Finally, for many if not all materials, substitutes can be found. There is no substitute for energy.

ENERGY SUPPLY AND DEMAND

An examination of the adequacy of fuels to support the economy of the United States and of the world requires some estimate of what future demands will be. Over the years many different estimates have been published. For example, the Ford Energy Study (5) outlines a number of scenarios for the United States. In the following, some limiting cases for future demand are briefly outlined.

Recently a number of surveys have been published of United States and world recoverable reserves and resources of hydrocarbon fuels and uranium (see, for example 1,6,7). These estimates and others have been used in developing the tables presented below, which provide one overview of the current resource picture. As in the case of estimate of demand, the estimates of recoverable reserves and resources remain most uncertain.

Data on reserves and resources together with estimates of demand can be combined to yield "index years" of availability. For the purposes of this paper, index years are an estimate of the time required to exhaust either the reserves or resources of a given fuel if that fuel is used to supply the total demand for energy for the world and the United States. The assessments of index years are made with differing assumptions about demand. Thus index years present a rough evaluation of the overall demand and supply picture for individual fuels.

Nonconventional sources of energy such as solar, geothermal, or fusion will not be considered. These sources may become important in the longer-term future but they are unlikely to make a major contribution to energy supplies during the critical transition period in which the world switches over from an economy based on liquid hydrocarbon fuels to one based on solid hydrocarbon or nuclear fuels.

Units to Measure Demand and Supply

The demand for energy differs greatly among developed and developing countries of the world. This demand is being met by a wide variety of fuels. Both the demand and fuel mixture are changing in response to changing industrial requirements, environmental constraints, patterns of transportation, and life-styles. In order to compare total energy demand with availability of various fuels, it is useful to discuss fuels in terms of a common unit rather than in terms of conventional bulk quantities such as barrels or tons in which fuels are measured. Since all energy can be converted into heat, the heating value of the fuels is a convenient common unit that allows for comparison across fuels.

The heating value of a fuel is the thermal energy that can be derived from a fixed quantity of the fuel. The derived thermal energy can then be converted by various means into more useful forms of energy to produce work. The conversion process will always involve some losses in energy. For example, hydrocarbon-burning electric-generating plants convert about one-third of the consumed thermal energy into electricity for an efficiency of about 0.33. Current methods of converting the stored thermal energy of fuels into useful work are inherently inefficient, so a substantial portion of the available thermal energy of fuels is directly dumped as waste heat into the environment.

Table 4-1 lists the conventional heating values of the major fuel sources in terms of the quantities used to measure fuels in the United States. The values listed are only approximations, since the precise value will depend on the details of the physical and chemical nature of the fuel. Government agencies have revised the conventional values from time to time. Recently the U.S. Bureau of Mines (2,3) has shifted the heating value of natural gas from 1,031 Btu per standard dry cubic foot of natural gas to 1,024 Btu for consumption during 1974/75. The value used by the United Nations in their compilations corresponds to 1,048 Btu/cubic foot.

The heating value of coal depends on its rank. In the United States more subbituminous coal and lignite have been used by the electric power industry in recent years so that the average heating value for coal has decreased. On the world scene, the proportion of subbituminous coal burned is greater than in the United States (4). The heating value for coal of 20 x 10^6 Btu/short ton is an approximation, probably high for many countries in the world and low for the United States.

The heating value for uranium in burner reactors corresponds to the amount of thermal energy to be derived by the burning of uranium in conventional light-water reactors in use in the United States today. The listed value approximates average current experience. The precise value for any reactor and fuel will depend on the details of reactor

Table 4-1. Heating Values Used in Converting from Conventional Quantities to Units of Energy

	Heating Value
Natural Gas	1031 Btu/cubic foot
Crude Oil	5.8×10^6 Btu/barrel
Syncrude from Shale Oil and Tar Sands	5.8×10^6 Btu/barrel
Natural Gas Liquids	4.1×10^6 Btu/barrel
Coal	20×10^6 Btu/short ton
Uranium Oxide U_3O_8	
In burner reactors without plutonium recycle	400×10^9 Btu/short ton
In breeder reactors	30×10^{12} Btu/short ton
One metric ton of coal equivalent (tce)	27.778×10^6 Btu

Table 4-2. World Energy Use

	Energy Consumption (quads/year)	*Population (millions)*	*Power per Capita (watts/capita)*
1950	76.8	2,500	1,025
1960	124.0	2,990	1,386
1974	220.9	3,890	1,906
Average Annual Percent Change			
1950-1974	4.50	1.85	2.62
Extrapolation to the Year 2000 at 1950-1974 Rate of Growth	693.8	6,265	3,734

design and on such factors as the degree of enrichment of U-235. The heating value for breeder reactors is far more speculative depending on the detailed nature of the fuel used in the breeder as well as on the reactor design.

Energy Use in the World and the United States

Since World War II world energy use has grown steadily, reaching a rate of about 221 quads (one quad equals 10^{15} Btu) per year in 1974 (see Table 4-2). The growth can be separated into two components: the growth in total population, and the growth in per capita use. In Table 4-2 the growth per capita is given in terms of watts, units of power (energy per unit time). Since World War II, the worldwide average yearly growth in energy use has been 4.5 percent. The larger part, 2.6 percent, comes from the increase in per capita consumption as industrialization and a general raising of the living standard has led to an intensive employment of energy. While the world average of per capita consumption in 1974 was about 1,900 watts per capita, there was a wide variation among nations. In the poorer nations of the world, energy use averaged less than 1,000 watts per capita, while the most energy-intensive country in the world, the United States, used energy at a rate corresponding to 11,400 watts per capita.

If the rates of growth of per capita energy use and of population for the years 1950-1974 were to persist until the year 2000, then the world would be consuming energy in the year 2000 at a rate of 694 quads per year, or about 3,700 watts per capita. With this rate of growth, the per capita consumption would still be a fraction, about a third, of the 1976 United States per capita consumption.

In developing estimates of the index years for world fuels, the rate of use in 1974, 220 quads/year, and the extrapolated value of 694 quads/year will be used. The 1974 value is certainly a "low" estimate of future energy use. Current trends indicate that there may be some slowing in rate of growth of world population, but there is no evidence of a decreasing rate of per capita use of energy. The industrialization of the developing countries, coupled with an increasing standard of living, will lead to a continued increase in the demand for energy for large parts of the world. The estimate of 694 quads/year for the world energy use will be taken as a representative extrapolation of what energy requirements will be in the year 2000.

The rate of growth of population and per capita energy use in the United States during the period 1950-1974 has been substantially less than for the world (see Table 4-3). The average yearly increase in per capita energy use in the United States was about 18 percent in the post-World War II years, corresponding to a total energy growth rate of 3.2 percent.

Energy use declined in 1974/75 as the effects of the Arab oil embargo came into full force, but energy use resumed its growth in 1976. Maintenance of the 1950-1974 rate of growth would yield an annual energy consumption in the United States of 164 quads in the year 2000, corresponding to a per capita consumption of 18,000 watts. While these figures are used later in constructing index year tables, these are very likely overestimates of the actual energy use in the year 2000. The rate of population growth has slowed in recent years so that

Table 4-3. Energy Use in the United States

	Energy Consumption (quads/year)	*Population (millions)*	*Power per Capita (watts/capita)*
1950	34.15	152.3	7,492
1960	44.82	180.7	8,283
1970	68.81	204.9	11,216
1974	72.58	212.2	11,424
1975	70.72	214.4	11,017
1976	73.0[a]	216.0[a]	11,288
Average Annual Percent Change			
1950-1974	3.19	1.39	1.77
Extrapolation to the Year 2000 at 1950-1974 Rate of Growth	164	304[b]	18,000

[a] Estimate.

[b] This figure should be compared with Series I, Bureau of the Census projection of 287 million. The difference is due to the sharp drop in annual percent change in recent years to less than 0.7 percent.

the current high estimate of the Census Bureau for the year 2000 is 287 million, rather than the 304 million that would be expected from a continuation of the 1950-1974 trends. The Census Bureau estimates a more moderate rate of growth if current values of birth expectation are used, leading to a population of 262 million in 2000.

The per capita consumption of energy is also likely to slow in future years as the conversion of the economy from one heavily dependent on energy-intensive industries to one more dependent on light industries and services is very likely to contribute to a slowing of the rate of growth of per capita use. Conservation policies would further lower the rate of growth of per capita consumption. A rate of energy consumption of 164 quads/year for the year 2000 is almost certainly a substantial overestimate; the expected demand for the year 2000 is expected to be between the 1976 rate, 73 quads/year, and the extrapolated year 2000 rate.

The demand for energy in the United States has historically been met by a changing mixture of fuels. Table 4-4 lists the percentage contribution of the various fuels to total energy use from 1950 to 1975. Overall, as energy consumption increased, the percentage contribution from coal has halved, even though the yearly amount of coal burned has remained about constant. The percentage contribution of natural gas increased from 1950 to the late 1960s. By 1970 use of natural gas increased at a rate greater than the discovery of new reserves. By 1975, nuclear power contributed only a small fraction of the total energy requirements, somewhat over 2 percent of the total demand.

The expected demand for energy in the United States in future years will depend on both the rate of growth of population and the per capita consumption. Table 4-5 illustrates the dependence of total energy consumption on these variables. The Census Bureau periodically updates its projections of future population for the United States. In 1975 the estimates for the year 2000 varied between 287 million, under the assumption that the rate of growth is maintained at about 1.1 percent per year, to a population of 245 million if the assumption is made that

Table 4-4. Energy Sources in the United States, by Fuel (percent)

Year	*Total Energy Use (quads)*	*Crude Oil*	*Natural Gas*	*Coal*	*Hydropower*	*Nuclear*
1950	34.1	34.5	18.0	37.8	4.7	
1960	44.8	44.6	28.2	23.2	4.0	
1970	68.8	43.0	32.8	20.0	4.1	
1974	72.6	45.8	29.8	18.2	4.5	1.6
1975	70.7	46.0	28.4	18.9	4.4	2.3

Table 4-5. United States Energy Demand at Current Power Consumption (11,300 watts/capita) and at an Annual One Percent per Capita Growth Rate

		Energy (quads/year)			*Energy (quads/year)*			*Energy (quads/year)*	
Year	*Population (Series I)*	*Current per capita use*	*1 percent annual growth*	*Population (Series II)*	*Current per capita use*	*1 percent annual growth*	*Population (Series III)*	*Current per capita use*	*1 percent annual growth*
1980	226	76.4	79.5	223	75.4	78.4	220	74.4	77.4
1990	258	87.2	100.2	245	82.8	95.2	236	79.8	91.7
2000	287	97.0	123.2	262	88.6	112.4	245	82.8	105.1
2020	362	122.3	189.6	294	99.4	153.9	252	85.2	132.0

Series I assumes annual percent increase of about 1.1.

Series II uses current data of birth expectation.

Series III assumes a gradual decline in annual percent change to zero in the years 2015-2020.

the rate of growth declines steadily and reaches zero sometime between 2015 and 2020. The intermediate projection of 262 million is based on current data about birth expectations of American women.

Depending on population projections, estimates of energy use in the year 2000 range from 83 quads to 97 quads per year if the current per capita rate of energy use is maintained. If the per capita energy use increases at an average rate of 1 percent per year, the range of energy use lies between 105 and 123 quads/year, depending on assumptions about population growth. An intermediate rate of population increase, coupled with an assumption of a 1 percent per year growth, yields an energy consumption of 112 quads per year, a value within the range of 73 and 164 quads/year discussed above.

Reserves and Resources

Estimates of fuels in the ground are usually categorized as either reserves or resources. The difficulty with this separation is one of definition. Definitions differ across fuels and among institutions responsible for the assignment of deposits to the categories of reserves or resources. As far as oil and natural gas are concerned, reserves refer to material in the ground that can be produced and sold with currently available technology at prevailing prices. Reserves of coal are defined by their physical characteristics such as depth of the deposit and thickness of the seam. The definition of uranium reserves involves the cost of recovery; in general detailed economic consideration does not enter into the definition of reserves of fuels other than uranium.

The concept of a reserve is further complicated by the existence of environmental regulations. Materials that could have been classed as reserves a few years ago now are questionable as limits on sulfur content or other regulations have been set. Reserves of coal may be appreciably affected as new mining methods are developed in response to new regulations governing surface mining.

The definitions of a resource are even less precise than those of reserves. In the view of some, everything in the earth's crust of a particular substance would be considered a resource, despite overwhelming technical difficulties and resulting high costs of ultimate recovery. For example, oil may be found in small deposits in isolated locations. It is difficult to conceive of conditions under which such a deposit could be economically developed.

In the United States Geological Survey (USGS) has had primary responsibility for estimating resources of hydrocarbon fuels. In its resource estimates, use is made of qualifying adjectives such as hypothetical and speculative. Resource estimates on a world basis differ greatly among the countries; the net effect is to make world estimates even more uncertain than those for the United States.

The Energy Research and Development Administration (ERDA) has inherited from the Atomic Energy Commission primary responsibility for estimates of the uranium resources of the United States. As in the case of the USGS for estimates of reserves and resources of fuels such as coal and oil, ERDA relies heavily on the industry for resource estimates. This reliance can lead to a distortion of the estimates as industry's view can be conditioned by market prospects. Further, resource estimates—like reserve estimates—may be affected, often in uncertain ways by changing environmental requirements.

The accuracy of resource estimates depends to a substantial extent on the availability of geological information. Coal deposits are found in layered strata that are more or less continuous. As a result, surface outcrops of coal seams can lead to a relatively accurate inference of the extent of the resources at depth and over an extended geographic area, particularly when test drilling is used to determine thickness and depth. Oil shale and tar sands deposits are similar to coal in that they occur in layered deposits. In contrast, oil and natural gas are found in relatively discrete deposits. Sophisticated geophysical methods generally used only by industry are required for resource estimation. In the United States most uranium deposits are found in discrete locations and thus also pose difficult problems in estimation.

Crude Oil

Reserves of crude oil in the United States are estimated on a regular basis by a number of organizations. The estimate listed in Table 4-6 represents the joint effort of the American Gas Association, American Petroleum Institute, and the Canadian Petroleum Association published in 1976 (1,11). Other estimates vary by a few billion barrels, with the difference due primarily to the interpretation of the definition of reserve rather than on a disagreement as to the amount of oil actually in the ground.

The principal published sources of worldwide oil reserves are the *Oil and Gas Journal* and *World Oil* (1,2,13). Both journals try to obtain reserve data for each producing country. The data in these publications refer to proven reserves, though a comparison with other sources suggests that the appropriate adjective may be probable (1). In any case, in areas undergoing rapid development, such as the North Sea, changes in the reserve category may take place rapidly.

Estimation of petroleum resources is much more difficult than that of proved reserves where information obtained from drilling provides a degree of precision. Geological and geophysical data are useful in locating potential sites, but such sites may not meet the conditions required for the formation of petroleum. The amount of oil accumulated in any one site will depend on many variables, including the character

Table 4-6. Crude Oil Reserves, Resources, and Production

	Recoverable Reserves		*Recoverable Resources*		*Production-1975*	
	Billion bbl	*Energy in quads*	*Billion bbl*	*Energy in quads*	*Billion bbl*	*Energy in quads*
United States	33	190	160-370	930-2100	3.0	17.4
World Excluding U.S.	510-610	3,000-3,500	1,100-1,700	6,500-10,000	16	95
World	530-640	3,200-3,700	1,500-1,900	8,700-11,000	19	110

of the reservoir rock and the nature of the adjoining geologic structure. As a result the amount of oil may vary greatly from site to site. The location of large accumulations are very unevenly distributed geographically, leading to further uncertainties in resource estimation; giant fields are the principal source of today's world oil.

A further uncertainty is the recoverability of oil. The recoverability in a particular site will depend on the physical parameters of both the reservoir rock and the oil. In the United States the current recovery factor in producing regions averages about 30 percent. This can be increased somewhat by the use of secondary and tertiary recovery techniques. Discussions in the literature suggest that over the next twenty years the recovery factor may increase to 40 percent. Higher figures would require the development of wholly new technologies.

A variety of models have been constructed over the years to obtain estimates of the world oil resources. Some models have been based primarily on geological information, while others have used historical data on such factors as the relationship of discovery to drilling rate. For the world, estimates of recoverable oil range from 1.5 to 2 trillion barrels. For example, the National Academy of Sciences (7) on the basis of a review of various estimates, concludes that undiscovered recoverable oil amounts to 1.1 trillion barrels. Moody and Geiger (14) estimate a value of 2 trillion barrels for the ultimate recovery, with 900 billion barrels as yet undiscovered.

Similar uncertainties surround estimates of recoverable resources in the United States. Past estimates of the U.S. Geological Survey and of the National Petroleum Council have tended toward the higher values. More recent estimates, including those of the Geological Survey, have favored values about half those previously published.

Table 4-6 also lists the production figures for petroleum in 1975. For the United States the ratio of imported petroleum to domestic production has increased markedly since 1950 (see Table 4-7). In the years prior to World War II, the United States had been a net exporter of petroleum. The discovery of large reservoirs in Venezuela and the Middle East in the 1930s changed this picture as these resources became available on the world market at low cost.

Despite the Voluntary Oil Import Program initiated in 1957 to stem the flow of imports, imports of petroleum grew during the 1959-1967 period at an average annual rate of 4 percent. From 1968 through 1973 U.S. production fell increasingly short of demand, with the result that imports increased at a rate of 16 percent annually. Much of this increase came from Canada, Saudi Arabia, which has a large production capacity, and Nigeria, whose crude oil is especially adaptable to the U.S. market. The economic and political interest in the U.S.

Table 4-7. United States Dependence on Petroleum Imports (average annual growth rate of domestic demand: 4 percent for 1950-1974)

	Domestic Demand		*Imports*		*Ratio of Imports to Domestic Demand*
Year	*Thousands bbl/day*	*Quads/year*	*Thousands bbl/day*	*Quads/year*	
1950	6,507	13.8	850	1.8	13.1
1960	9,661	20.4	1,911	4.0	19.8
1970	14,697	31.1	3,419	7.2	23.3
1972	16,367	34.6	4,741	10.0	29.0
1973	17.308	36.6	6,256	13.2	36.1
1974	16,629	35.2	6,112	12.9	36.8
1975	16,288	34.5	5,993	12.7	36.8
1976[a]	17,185	36.4	7,217	15.3	42.0
1977[a]	18,039	38.2	8,324	17.6	46.1

[a] Forecast.

dependence on foreign imports came into sharp focus during the 1973/74 oil embargo. During 1974 and 1975 U.S. imports of petroleum products were at a slightly reduced level, initially because of the embargo. Reduced economic activity, higher prices, and conservation practices contributed to the reduced demand. However, imports rose significantly during 1976 as the economy picked up. The contribution of imported oil to demand is expected to increase further in 1977 in response to severe weather and continued improvements in the economic situation.

The recoverable reserves of the United States listed in Table 4-6, together with the historical pattern of events illustrated in Table 4-7, strongly suggest that regardless of energy policies that may be adopted over the short term, the United States will continue to depend heavily on imported oil. A decrease on the reliance of foreign oil can result only from a shift away from the historical dependence of the United States on crude oil as the major source of energy in meeting overall energy demands (see Table 4-4).

Natural Gas

The difficulties in estimating recoverable reserves and resources of natural gas parallel those of estimating these quantities of oil. Oil and natural gas are frequently found together and the geological and geophysical methods of resource estimation are similar. However, the differences among individually published estimates are greater for natural gas than for oil. For example, recent estimates of the worldwide remaining natural gas range from 7,000 to 16,000 trillion cubic feet.

Table 4-8 lists estimates of recoverable resources and reserves. The lower number represents evaluation by the National Academy of Sciences (7), while the higher values are derived from publications of the Institute of Gas Technology and the USGS (1). Special problems are associated with data on natural gas production since a distinction must be made between total production and marketed production. In 1975 U.S. gross production amounted to 21.1 trillion cubic feet, of which 20.1 trillion cubic feet were marketed (see Table 4-8), while the rest was used for re-injection in order to maintain pressure in oil reservoirs and a small part was flared. On a world basis, a far higher fraction of the natural gas produced is either vented or flared. Oil and natural gas together furnished 75 percent of the total energy for the United States in 1975 (see Table 4-4). While the fraction due to natural gas has begun to decline, these two fuels will continue to provide a major if not the largest source of energy through the end of the century.

Coal

Coal is a complex mixture of organic and inorganic compounds. Each coal bed differs from others in both physical and chemical properties. The variations in heat content, ash, and sulfur compounds complicate the use of coal to provide thermal energy for electricity and process steam or the use as a source of liquid or gaseous synthetic fuels.

In the United States the coal industry has passed through a variety of phases. Until well into the twentieth century, coal was a primary domestic source of energy for both stationary and mobile power. As early as 1885 the United States was producing over 100 million tons annually. The production continued to increase steadily, reaching 600 million tons in the early 1920s. In the years following, coal production declined as a result of cheap oil and the Depression. In the 1950s and

Table 4-8. Natural Gas Reserves, Resources, and Consumption

	Recoverable Reserves		*Recoverable Resources*		*Consumption in 1975*	
	Tcf[a]	*Energy in quads*	*Tcf*[a]	*Energy in quads*	*Tcf*[a]	*Energy in quads*
United States	230	240	530-1,300	540-1,300	20.1	20.6
World Excluding U.S.	1,500-2,300	1,500-2,300	7,600-9,100	7,800-9,300	28	29
World	1,700-2,600	1,700-2,600	8,900-9,600	9,100-9,800	48	49

[a] Tcf = Trillion cubic feet.

1960s production averaged between 500 and 550 million tons annually, increasing in the 1970s to 650 million tons by 1975 (see Table 4-9). In terms of percent contribution to the total energy use, coal declined from 50 percent in the mid-1940s to less than 20 percent in the 1970s (see Table 4-4).

The U.S. Bureau of Mines (2) has published data on the coal reserve base. The bureau estimates that the coal in place at depths less than 1,000 feet with bituminous seams at least 28 inches thick and subbituminous at least 5 feet thick amounts to 434 billion tons. Of this amount, 137 billion tons are in beds so near the surface as to be unsuitable for underground mining but suitable for surface mining.

The Bureau of Mines estimates recoverability of the coal in place to vary between 40 and 90 percent, with an average of about 50 percent. If the recoverability of the underground deposits is taken as 50 percent and that of surface deposits as 90 percent, then the total recoverable reserve for the United States amounts to 273 billion tons (see Table 4-9).

Table 4-10 gives estimates of the demonstrated reserve base and recoverable coal by geographic area and potential method of mining. About 54 percent of the total reserve base is found west of the

Table 4-9. Coal Reserves, Resources, and Production

	Recoverable Reserves		*Recoverable Resources*		*Production in 1975*	
	Billion short tons	*Energy in quads*	*Billion short tons*	*Energy in quads*	*Billion short tons*	*Energy in quads*
United States	273	6,000	1,000-1,800	22,000-40,000	0.65	12.6
World Excluding U.S.	452	9,000	2,400-6,800	64,000-120,000	2.85	57
World	725	15,000	4,200-7,800	86,000-160,000	3.5	70

Table 4-10. Demonstrated Coal Reserve Base in the United States

Location	*Reserve Base (millions short tons)*	*Recoverable Coal (millions short tons)*	*Recoverable Energy (quads)*
East of Mississippi			
Underground	169,000	84,500	1,853
Surface	34,000	30,600	673
West of Mississippi			
Underground	131,000	65,500	1,441
Surface	103,000	92,700	2,039
Total	437,000	273,300	6,006

Mississippi. About half of the western coals can be strip mined, while only 17 percent of the eastern coals can be recovered by surface mining. The western coals have lower sulfur content: nearly 85 percent of the coal with 1 percent sulfur or less is found west of the Mississippi.

Estimates of the world's coal reserves have been developed by the World Energy Conference (6). Estimates of recoverable reserves are thought to be reasonably accurate for industrialized countries that have had a long history of mining coal. Geologic exploration in these countries has been extensive, and it is unlikely that new large coal deposits will be found. The estimates for the Peoples Republic of China are most uncertain, but the consensus is that the potential for coal resources is high. Table 4-9 lists estimates of the world coal reserves assuming a 50 percent recoverability.

In the United States coal resources as estimated by their geologic occurrence are large, much larger than the resources of oil and natural gas. Coal-bearing rocks are known in at least 37 states. Since coal occurs in the form of continuous beds, geologists can estimate the areal extent. Test drill holes provide data about thickness and continuity. Table 4-9 indicates the range of values for U.S. recoverable resources. A part of the uncertainty is caused by assumptions about the thickness of seams that can be economically recovered. Averitt (15) for example, would exclude thin beds—14-28 inches for bituminous and 2-5 feet for lignite—and this assumption yields a lower value for recoverable resources.

The world resource picture is much more uncertain. In addition to the question concerning the Peoples Republic of China, little exploration has been carried out in Central and South America and in much of Africa, South Asia, and Oceania. Because of this the values listed in Table 4-9 represent a substantial underestimate of world coal resources.

Oil Shale and Tar Sands

Tar sands are rocks in which the hydrocarbon is present as a highly viscous material approaching the consistency of a solid. Oil shale differs from normal oil deposits and tar sands in that the "oil" is a waxy solid material known as a kerogen. Oil can be recovered from oil shale by the application of heat, which causes distillation of the lighter fractions.

Deposits of tar sands and oil shales are rated according to the oil content. It is conventional to regard a content of 25 gallons per ton as minimal for economic recovery. Uncertainties in seam thickness, reservoir size, and depth of overburden all complicate the estimation of recoverable resources. The USGS and the National Petroleum Council

(16) both estimated U.S. recoverable resources in the range of 1 to 2 trillion barrels (see Table 4-11).

U.S. tar sands deposits are small in comparison to those of Canada and the world. However, the United States has about three quarters of the world's recoverable oil shale, according to the World Energy Conference. As the values given in Table 4-11 indicate, large uncertainties exist in estimates of the world hydrocarbon resources tied up in oil shale and tar sands.

Hydrocarbon Fuels in the United States

Table 4-12 summarizes the energy content of the recoverable reserves and resources of hydrocarbon fuels in the United States. The dominance of coal as an energy source is apparent even when consideration is given to the large uncertainties in estimates of oil shale and tar sands.

In looking toward the future, it is essential to recognize that 75 percent of the total U.S. energy requirement is derived from oil and natural gas. These fuels are convenient for many energy uses, and with our current technology, indispensable for some. Natural gas provides a convenient and environmentally acceptable fuel for residential use, while derivatives of crude oil are almost the sole source of energy for transportation. Since the economy is so largely based on oil and natural gas, there is a large stock of existing equipment that is dependent on these fuels and cannot be replaced for many years.

Table 4-11. Recoverable Resources from Oil Shale and Tar Sands

	Recoverable Resources	
	Billions of barrels	*Energy in quads*
United States	1,000-2,000	5,800-11,000
World	2,400-17,000	14,000-99,000

Table 4-12. Summary of U.S. Hydrocarbon Fuel Recoverable Resources and Reserves (units-quads)

	Recoverable Reserve	*Recoverable Resource*
Crude Oil	190	930-2,100
Natural Gas	240	540-1,300
Coal	6,000	22,000-40,000
Oil Shale and Tar Sands		5,800-11,000
Total	6,430	29,270-54,400

Oil and gas can be produced from coal. Coal gasification is a relatively old technology developed before cheap natural gas became plentiful. Coal gasification plants are in production today in countries where natural gas is unavailable. Industrial coal liquefaction plants were developed in Germany during World War II.

For the United States the principal barriers to the development of a synthetic fuels industry have been cost and environmental and resource considerations. The existing price structures for both natural gas and oil make synthetics uncompetitive. Current estimates of the cost of synthetic oil run at about $20 per barrel with natural gas at $4 per thousand cubic feet. Synthetics will become price competitive only as the scarcity of natural gas and oil drives the price up. Environmental regulations, either existing or proposed, coupled with uncertainties in the supply of water in the western states, provide additional constraints on private investment in the synthetic fuel industry.

The danger of a dependence, over the longer term, on synthetic fuels lies in the appreciable time—at least a decade—required for the development of such an industry. The need for synthetics as natural supplies of gas and oil dwindle must be anticipated on a timely basis if major disruptions in the energy economy are to be avoided.

Uranium

In considering sources for nuclear power, only uranium will be discussed. Uranium is the only nuclear fuel in commercial use today, and current plans indicate that it is likely to be the sole source in the next few decades. Thorium can be used as a nuclear fuel source and may be in the future, but little is known about thorium reserves and resources.

Uranium is found in a variety of compounds widely distributed in the earth's crust, but at low concentrations. Large deposits have been identified in the United States, Canada, South Africa, and Australia. In addition, deposits are known to exist in the Soviet Union, the Peoples Republic of China, and the Democratic Republic of Germany. Because of the importance of uranium to nuclear weapons programs, up-to-date data about reserves and resources in Communist countries are incomplete. Tables 4-15 and 4-16 list world resources, and refer only to non-Communist countries.

While all estimates of reserves and resources are uncertain, uranium presents special problems. Originally, in the non-Communist world, the U.S. government was the single buyer for noncommercial purposes: weapon-making. Prior to the development of a commercial market, the U.S. government set a "fair" price, and entrepreneurs developed deposits to meet the buyer's terms. Uranium was originally bought for about $8 per pound of U_3O_8, and it was not until the late sixties that higher-cost U_3O_8 reserves were considered. Current U.S. surveys estimate reserves that could be available at various costs up to $30 per pound.

The use of cost in defining reserves can be misleading, since for historic reasons the cost is not the actual cost of production or the selling price. The cost used in the surveys refers to the operating and capital cost not yet incurred at the time the estimate is made. The use of cost is further complicated by changes over time as inflation and the cost of labor and materials change. The use of cost associated with reserves can give the impression that these reserves are much better defined than for fuels for which cost data are not used. In fact, the geologic character of uranium deposits leads to large uncertainty in reserve estimation. Actual prices of U_3O_8 declined in the early 1970s but rose sharply in 1974, as did the price of other energy sources, and contract prices for future delivery have risen dramatically. The higher prices led to increased exploration and mining activity in 1975/76.

Table 4-13 lists the 1976 ERDA estimates of reserves and potential for the United States. The cost group into which a uranium deposit falls depends in a general way on the grade and geologic setting. For example, the bulk of the reserves in the up to $15 group ranges between 0.1 and 0.15 percent in grade, lies at a depth less than 700 feet below the surface, and is found almost exclusively in sandstone; the $30 ore averages 0.08 percent in grade. It should be noted that the estimate for $30 uranium includes tonnages available at lower costs.

ERDA has classified potential deposits in three categories of declining levels of confidence: probable, possible, and speculative. The defini-

Table 4-13. U.S. Uranium Resources (thousands of short tons of U_3O_8)

		Potential			
$/lb U_3O_8 Cutoff Cost[a]	*Reserves*	*Probable*	*Possible*	*Speculative*	*Total*
10	270	440	420	145	1,275
15	430	655	675	290	2,050
30	640	1,060	1,270	590	3,560
50	–	–	–	–	8,400[b]
100	–	–	–	–	17,400[b]

[a] Each class includes material in lower class or classes.

[b] A. Weinberg, *Report of the Cornell Workshop on the Major Issues of a National Energy Research and Development Program* (Cornell University, College of Engineering, 1973).

Source: Energy Research and Development Administration, *Statistical Data of the Uranium Industry* (Grand Junction, Colorado, 1976).

tions are based on the geologic setting, in particular whether the rock of interest lies within areas that have previously proved productive.

Most of the exploration for uranium in the United States has been conducted in the western states, the Colorado plateau, the Wyoming basin, and the Texas coastal plains. Other areas in the country have not received as much attention, and as a result the values listed in Table 4-15 may be low.

Early U.S. uranium discoveries were made in sandstone. As a result, less attention has been given to other host rock environments. However, uranium has been found in a number of rock formations other than sandstone (see Table 4-14). These discoveries parallel experiences in other countries. Canada's uranium is found in veins and conglomerates, Australia's in veins and calcrete, Sweden's in shale, and Brazil's in granite. New ERDA programs are designed to explore geologic environments other than those found in the western states.

Estimates of world reserves and resources have been prepared by a number of agencies, the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, the International Atomic Energy Agency, and the World Energy Conference. Table 4-15 lists representative estimates.

Current U.S. production accounts for about 45 percent of the world's 1975 production of 26,000 tons of U_3O_8. Canada contributes about 25 percent, South Africa 15 percent, and France and Nigeria the bulk of the remaining balance.

The energy obtainable from uranium depends greatly on the manner of usage. Table 4-16, listing the thermal energy content of uranium deposits, is based on a conventional value of 400 billion Btu per short ton of U_3O_8, assuming a burner reactor without plutonium recycle and 30 trillion Btu per short ton of U_3O_8 if a breeder reactor is employed.

Table 4-14. Distribution by Host-Rock of \$30/lb U_3O_8 in the United States (thousand tons U_3O_8)

Host Rock	*Probable*	*Percent*	*Possible*	*Percent*	*Speculative*	*Percent*
Sandstone	847	80%	820	64%	358	61%
Conglomerate	56	5	76	6	53	9
Veins	100	9	202	16	162	27
Limestone	16	2	5	21	13	2
Lignite	15	1	2	21	4	41
Volcanic Rocks	26	3	165	13	0	0
Total	1,060	100%	1,270	100%	590	100%

Source: Energy Research and Development Administration, *Statistical Data of the Uranium Industry* (Grand Junction, Colorado, 1976).

Table 4-15. World Uranium Resources and Production (thousands of short tons)

	Recoverable Reserves at up to $30/lb	*Total Recoverable at up to $30/lb*	*Production*	
			1974	*1975*
World Excluding U.S. and Communist Countries	1,100-1,800	3,000-8,100	12.6	14.8
World Excluding Communist Countries	1,740-2,440	6,600-11,000	24.1	26.5

Future Fuel Availability

The considerable variation in published estimates of recoverable reserves and resources has made it necessary to give range of values in most of the tables discussed above rather than a single most probable value. The numbers given should not be regarded as fixed, since future production, exploration, and development can cause changes. Indeed, changes—for the most part upward—are to be expected for estimates of the world resources and reserves, since major geographical areas, South America for example, have not been well explored and may prove to have more fuel resources than now known.

The values assigned to the estimates depend on a variety of institutional, technological, and economic considerations outside the physical definition of the deposits. For example, changes in U.S. regulatory practices toward natural gas may bring about rapid increases in the discovery rate.

U.S. recoverable reserves of hydrocarbon fuels are sufficient to provide for the total energy demand of the country for a period of between 40 and 90 years, depending on the assumptions made about the average rate of annual energy consumption (see Table 4-17). These estimates are based on the consumption of no net imports. The striking feature of Table 4-17 is that recoverable reserves of oil and natural gas can supply only three to six years of the total energy demand for the United States, even though these fuels—domestic and imported—are currently providing 75 percent of the total domestic energy demand.

Worldwide recoverable reserves of hydrocarbon fuels are sufficient to supply world needs for comparable times, 30 to 90 years (see Table 4-18). As in the case of the United States, coal is the dominant source, although oil reserves would have a greater potential than those of the United States.

If recoverable resources in the United States are considered, then the time scale of availability is lengthened from decades to hundreds of years, though uncertainties in these estimates are far greater than in the case of reserves, both because of the unknown nature of demand

Table 4-16. Energy Content of Uranium Reserves and Resources (in quads)

	Recoverable Reserves at up to $30 per Pound		*Recoverable Resources at up to $30 per Pound*	
	Burner Reactors without Pu Recycle	*Breeder Reactors*	*Burner Reactors without Pu Recycle*	*Breeder Reactors*
United States	260	19,000	1,400	110,000
World Excluding Communist Countries	700-1,000	52,000-73,000	2,700-4,400	200,000-330,000

Table 4-17. Index Years for Total Energy Production for the United States

	Use at 1976 Rate (73 quads per year)		*Use at Extrapolated Year 2000 Rate (164 quads per year)*	
Fuel	*Reserves*	*Resources*	*Reserves*	*Resources*
Crude Oil	2.6	12.7-28.8	1.2	5.7-13
Natural Gas	3.3	7.4-17.8	1.5	3.3-7.9
Coal	82	300-550	36	130-240
Oil Shale and Tar Sands	–	80-150	–	35-67
Total Hydrocarbon Fuels	88	400-740	39	170-330
Uranium (burner reactor)	3.6	19	1.6	8.5
Uranium (breeder reactor)	260	1,500	120	670

Table 4-18. Index Years for Total Energy Production for the World

	Use at 1975 Rate (221 quads per year)		*Use at Extrapolated Year 2000 Rate (694 quads per year)*	
Fuel	*Reserves*	*Resources*	*Reserves*	*Resources*
Crude Oil	14-16	39-50	4.6-5.3	12-16
Natural Gas	7.7-12	41-44	2.4-3.7	13-14
Coal	68	390-720	22	120-230
Oil Shale and Tar Sands	–	63-450	–	20-140
Total Hydrocarbon Fuels	90-96	530-1300	29-31	160-400
Uranium (Burner Reactor, Excl. Communist Countries)	3.2-4.5	12-20	1.0-1.4	3.9-6.3
Uranium (Breeder Reactor, Excl. Communist Countries)	230-330	900-1500	75-100	290-470

over the longer period of time and the larger uncertainty in the estimate of resources. As in the case of reserves, coal is the dominant fuel source, though oil shale and tar sands can significantly aid in meeting future needs. On the world scene, hydrocarbon resources are sufficient to supply demand for a time measured in centuries.

The principal problem with depending on hydrocarbon resources for future energy is that the present economy is based on liquid hydrocarbon fuels, while the reserves and resources for the future are either solid hydrocarbon in coal and oil shale or highly viscous hydrocarbon in tar sands. There appear to be no insurmountable technical problems in shifting to the solid fuels of the future, but the institutional and economic barriers are real and have not been subjected to detailed analysis.

The values in Table 4-17 illustrate the vulnerable position the United States is in with respect to liquid hydrocarbon fuel supplies. Domestic reserves and resources are only sufficient for a very few decades if liquid hydrocarbons are to be correct, then domestic supplies are sufficient for only ten to fifteen years.

The addition of uranium to the potential fuel supplies for the United States does not alter the projections of energy availability in any major way if uranium is used in burner reactors without plutonium recycling. The same conclusion holds for the world energy supply.

The introduction of breeder reactors on a large scale would significantly lengthen the time over which reserves and resources of uranium could supply U.S. and world energy demand. The future dependence of the energy economy on breeder reactors raises a host of institutional and economic questions as well as the environmental and safety issues. Present and projected reactors are designed to generate electricity. Currently, in the United States only about a quarter of the total energy consumed is used in generating electricity. The shift to an electric energy economy based on breeder reactors, would require major adjustments in the transportation, residential, and industrial sectors of the economy. The character and time scale of such adjustments have not been subjected to detailed analyses.

Summary of Fuel Availability

If the total energy demand in the United States grows at an annual rate of 3.2 percent, representative of the years 1950 to 1974, domestic coal reserves can supply this demand for about fifty years, while domestic oil and natural gas reserves can only make a minor contribution. Nuclear power in the form of conventional light water reactors is capable of adding only a few years' supply to the total energy demand. If domestic coal resources can be converted to reserves, then the energy supply measured in thermal units is sufficient for at least one to two centuries. Similarly, the use of uranium in breeder reactors can make this fuel sufficient for times measured in hundreds of years.

The use of either coal or uranium poses difficult environmental problems in mining and in the control of effluents. In the case of coal, its use would be enhanced by the further development of technologies for more efficient and cleaner burning, such as fluidized bed combustion; technologies for transforming coal to gas and oil; and technologies for the more efficient transportation of energy. The further development of the breeder reactor hinges on the solution of a host of problems dealing with the handling of, and prevention of diversion of, plutonium; and the development of acceptable methods of dealing with the waste products of the operation of the nuclear fuel cycle.

The shift toward either a coal- or breeder-based energy economy will require the shift of substantial economic resources from other sectors of the economy to support the development of the extraction of new energy sources and the production of energy. At present in the United States, energy extraction and production represents about 5 percent of GNP. The development of new resources could conceivably double the energy part of GNP. Such a doubling could have disruptive effects on the economy if the change takes place over a short period of time—on the order of a decade. Adjustments over considerably longer periods could likely take place without major alterations in the functioning of the economy.

AVAILABILITY OF NONENERGY RAW MATERIAL

While the effects of the 1973/74 oil embargo have highlighted the impending shortages in certain energy sources, relatively less attention has been focused on the longer-term availability of metals and other raw materials. Because of their importance to society, it is necessary to discuss their geologic occurrence and means of extraction in order to place gross limits on their future availability.

With some exceptions—such as gold and platinum—metals do not occur as elements in the earth's crust. They are present as compounds of two or more elements; the compounds are called minerals. In recovering metals from the mineral, the least expensive option is to extract and process only the minerals that contain the desired metal. In practice this means choosing those minerals that require the least expenditure of energy to bring about chemical disintegration and release of the metal. Sulfides, oxides, hydroxides, and carbonates all require less energy for their disintegration than the highly refractive silicates that make up the bulk of the rocks in the earth's crust.

The production of metals from ores and rocks requires two separate and quite different steps. The first involves mining the desired mineral from the ground and separating it from valueless and unwanted minerals with which it occurs. In the concentration process the material is crushed to a fine grain and then the minerals are separated on the basis of differences in physical properties of the desired mineral and the waste products. While the crushing and concentration of desired minerals are not very energy-intensive processes, the next step in separating the metal, the smelting and refining process, is. During smelting the concentrated mineral is broken down chemically and the desired metal is separated from the unwanted elements. Because of the energy requirements of smelting, less refractory minerals are selected as the principal sources of the desired metal.

The upper tens of kilometers of the earth form the earth's crust and contain minerals that are accessible with current or projected technologies. The crust under the continents has the average chemical composition given in Table 4-19, although individual rock types vary greatly in composition. Several of the most abundant elements are those that are in common use today: aluminum, iron, magnesium, titanium, manganese, and phosphorous. Minerals containing these elements, present in abundance, can, in principle, be mechanically separated and then refined and smelted. For these elements the entire crust can be considered a potential resource. The parent minerals occur in high enough abundance in the earth's crust that usual techniques of concentration can be employed. Given the total mass of the earth's crust, there is virtually an infinite source of these abundant elements to be recovered by conventional methods, although at a relatively high energy cost because of difficulties in refining and smelting refractory silicate minerals.

Table 4-19. Concentration of Major Chemical Elements in the Continental Crust

Element	*Concentration (weight percent)*
Oxygen	45.20
Silicon	27.20
Aluminum	8.00
Iron	5.80
Calcium	5.06
Magnesium	2.77
Sodium	2.32
Potassium	1.68
Titanium	.86
Hydrogen	.14
Manganese	.10
Phophorous	.10
Total	99.23

The geochemically scarce metals—those present in concentrations much lower than the abundant elements listed in Table 4-19—present an entirely different situation. Rarely do the scarce elements form separate minerals that can be separated and concentrated by usual mechanical methods. Instead, these scarce elements form a dilute solution with the more abundant elements in common rock-forming minerals. For example, lead is found in concentrations of about 10 parts per million in common rocks, contrasting with much higher concentrations, 10-15 percent, in rare ore deposits. Lead does not occur as a separate mineral in common rock, but appears in a chemical solid solution with potassium in the mineral feldspar. Concentration of the mineral feldspar by conventional means will lead to a concentrate with a proportion of lead of no more than about 100 parts per million. In order to release the lead from the silicate cage in which it is chemically bound, the entire mineral must be broken down and the small concentrations of lead separated chemically or by some other means from the other much more abundant constituents such as potassium. This is a complicated and very energy-intensive process. The extremely low concentration of lead and the high energy requirements for separation make lead in common rocks a highly uneconomical resource. This implies that when ores having a high concentration of lead in minerals in which lead is a major component are exhausted, lead will no longer be available except at an exceedingly high cost in energy.

Lead and other geochemically scarce metals are mined today from ores containing minerals with a high concentration of these metals. Ore bodies are the result of unusual geological processes that have naturally brought the metal to a concentration of a few percent in the rock rather than a few parts per million found in abundant crustal materials. Of the total amount of scarce metals in the crust, only a small fraction is found in rich ores; by far the larger fraction is found in very small concentrations in ordinary rock. A consequence of this bimodal distribution of metals in ores and rocks is that there exists a concentration of the metal in the rock below which the metal does not appear in a mineral of its own. Instead it appears in a solid solution with other elements in common rock-forming silicates. There is thus a mineralogical barrier or limit to concentration below which the metal appears only in common rock-forming minerals, and at very low concentrations in these minerals. The limit, with a few exceptions such as gold and uranium, appears to lie at concentrations between 0.1 to 0.01 percent. At concentrations of less than 0.1 to 0.01 percent, the scarce metal occurs only as a minor solid solution substitute for the more common elements and not as a separate mineral that can be concentrated mechanically in the usual way. Gold and uranium form separate minerals at concentrations of less than 0.01 percent, but they are the exceptions to the rule.

The total amount or mass of metal in concentrated ores, rocks in which scarce metals occur in minerals of their own, can be estimated if the assumption is made that the total amount of the element in rich ore deposits is proportional to the concentration of the metal in the crust. This assumption is suggested by the fact that the discovered reserves of various metals are roughly proportional to the crustal concentration. With this assumption all that is needed to calculate total available ore is an estimate of the total amount of one metal. The National Academy of Sciences' Committee on Mineral Resources and the Environment (COMRATE)(7) has carried out the calculation leading to an estimate of the abundance of one such metal, copper. The committee estimates that the barrier at which copper no longer forms a separate mineral occurs at a concentration of 0.1 percent. It also estimates that no more than 0.01 percent of the total amount of copper in the continental crust will be found in ore bodies with a copper concentration of 0.1 percent or greater. The committee's reasoning was based on the volume percentage of mineralized rock in the most intensely mineralized region so far discovered and on the frequency of copper deposits in the crust. The committee's figure of 0.01 percent must be taken as a maximum possible yield. The maximum amounts of scarce metals concentrated in ore deposits, calculated relative to copper, are given in Table 4-20. These values are intended to indicate the

Table 4-20. Estimate of Maximum Quantities of Metals in Ore Deposits in Continental Crust

Metal	*Abundance in Continental Crust (percent)*	*Maximum Tonnage in Ore Deposits (millions of metric tons)*
Copper	0.0058	1,000
Gold	.0000002	0.034
Lead	.0010	170
Mercury	.0000002	0.34
Molybdenum	.00012	20
Nickel	.0072	1,200
Niobium	.0020	340
Platinum	.0000005	0.084
Silver	.000008	1.3
Tantalum	.00058	100
Tin	.00015	25
Tungsten	.00010	17
Uranium	.00016	27

maximum amount of metal that can be recovered from ores; the remainder of the metals are in exceedingly low concentration in common rocks.

Using the above kind of reasoning, COMRATE estimated that present reserves plus past production of copper already amount to 3 percent of the world's ultimate yield from ore deposits. The equivalent figure for the United States is estimated to be 16 percent. With such large depletions the time scale for exhaustion, assuming exponentially increasing consumption, cannot be more than a few decades.

For the geochemically scarce metals found in high concentrations only in rare ore deposits, the concept of a finite resource is appropriate. Like hydrocarbon fuels, there is a finite reservoir of materials available in a mode that can be exploited. The scarce metals are thus different from the abundant metals for which the entire crust can be considered a resource. Copper is definitely a limited resource, while iron and aluminum are essentially unlimited. At present rates of usage, combined with an exponential rate of increase, it will take only a few decades to exhaust the readily available ore resources of copper. On the other hand, aluminum—present in a variety of common rock-forming minerals—can be expected to be available in substantial quantities for the indefinite future. Once bauxite or other rich reserves of aluminum are depleted, alternate deposits of aluminum in such minerals as anorthite or nepheline would become abundant sources of the metal. In summary, geochemically abundant metals such as iron, aluminum, titanium, and manganese will be plentiful in the indefinite future, while the supply of scarce metals such as copper, lead, and zinc will be exhausted in a matter of decades.

These observations on abundant versus scarce materials suggest the priorities for future research. Studies should be undertaken to identify how the geochemically abundant metals can substitute for the geochemically scarce metals. For example, steps have already been taken with aluminum replacing copper in a variety of uses. A further research priority should be in the area of the metallurgical treatment of the abundant elements. The means of smelting and refining silicate minerals will differ from the classical metallurgy of simpler compounds. Finally, there should be continued emphasis on reuse, particularly of the scarce metals.

ECONOMIC GROWTH AND RESOURCE AVAILABILITY

The issues of the availability of nonrenewable resources and of economic growth are closely linked. Growth has depended on, and indeed demanded, abundant natural resources, particularly energy. The relationship between economic growth and natural resources is well illustrated by the pattern of events in the United States between 1900 and 1970:

1. Population climbed from 76 million to over 200 million, or by an increase of less than a factor of three.
2. Gross National Product expanded from around $100 billion to about $1 trillion (1967 dollars), or by a factor of ten.
3. Natural resource consumption (excluding food) increased from $7 billion to $35 billion, or by a factor of five.
4. Energy utilization alone increased from $2 billion to more than $20 billion a year, or by a factor of ten.

Gross National Product and energy utilization have had parallel rates of growth, leading to the often-quoted observation that an abundant supply of cheap energy is essential to economic growth. Total demand on all natural resources went up at half the rate of GNP, or energy increase, but at almost twice the rate of population increase. The proportion of GNP devoted to energy resources is relatively small, in absolute terms. The extraction, preparation, and consumption of energy amounts to about 5 percent of GNP. What makes energy nevertheless a subject of great concern is that, unlike any other resource except labor, energy enters into every sector of the economy. It is input that is small but critical. At the same time it follows that the key factor in the energy equation is not the cost of energy but its availability. On the average, a doubling of energy cost over five years would only preempt an extra 1 percent of economic product each year. This increase could be accommodated without reducing real income. However, a reduction of energy availability by 50 percent over 5 years would virtually paralyze large sectors of the economy and substantially change the life-style of a modern industrial society.

In simplified terms, growth in a modern economy includes the following items. Individuals wish to acquire goods. Producers increase output to meet demand. This means more jobs and probably greater earnings for the worker. The newly employed, together with employees who are earning more, have additional money to spend or save. In either case, more production is necessary. As the economy grows, more nonrenewable resources are used. As fossil fuels and metals become scarce, a greater fraction of income and savings goes into securing natural resources. This, then, implies fewer dollars for other goods and services and a slowing of the overall increase in real income. Until the 1973/74 oil embargo, the U.S. government and industry operated largely on the assumption of an unlimited supply of energy and of all natural resources. The dependence of economic growth on an abundant energy supply was assumed and the availability of that supply not seriously questioned.

Since economic growth both in the United States and abroad was a major goal, government planning and implementation were concerned largely with stimulating demand. To implement a policy of increased demand, the U.S. government used government spending, taxing, borrowing, and movements in the bank rate. To stimulate a lagging economy, government prods demand by stepping up its own spending, thereby placing more money in the hands of individuals or corporations, or both. For example, in the early 1970s government stimulation caused demand to outrun supply. During that period there was a worldwide boom; in the United States the Federal Reserve Board, the Administration, and the Congress each took turns trying to forestall a downturn. As a result, demand continued to increase at a rate greater than could be met by scarce natural resources—for example, natural gas. In virtually all countries, national policy toward the use of natural resources has resulted from a heritage of an era of abundance and low prices. These policies have called for economic growth based on the lavish use of irreplaceable or difficult-to-replace nonrenewable resources.

In view of the limited nature of many of the natural resources, assumptions of the past need serious reconsideration. The goals of a fuel and materials policy for the United States should include a reduction in the rate of growth of demand as well as an increase in supply, taking into account recoverable quantities and time intervals needed for major readjustments in the materials and technology employed. This will require a comprehensive natural resources policy that includes the following:

1. Reduction of demand by conservation, substitution, and new technology.
2. Increase supply by exploration, investment, and new technology.
3. Prepare for emergency shortfalls, including stockpiling of materials vulnerable to foreign actions.
4. Determine the management method, private or government, or a combination of both.

In all of this it is very important to consider the issue of lead times. The problems of time and money dominate any discussion of materials and fuel scarcity. It takes at least five years to locate and bring offshore oil into production. It takes ten years or more to put a nuclear plant into operation, and at least as long to open up a new coal mine.

The more exotic sources of energy or materials are decades away.

Demand virgin materials can be reduced by conservation. The demand for geochemically scarce metals will be lowered by the substitution of geochemically abundant metals. This substitution will require the development of improvements in technology that will permit the smelting and refining of refractory silicate minerals.

In the short term, major efforts should be mounted to extend the supply of oil and natural gas reserves and resources. These are limited and will be depleted in a few decades. Because of this, new investment will be required to bring into production coal and the coal-based synthetic fuels. Since nuclear fuels are certain to make some contribution to the overall fuel economy, uranium reserves and resources need to be better defined and expanded if possible. Since uranium, coal, and oil are all finite resources, the development of new technologies to use less limited resources, such as fusion and solar power, needs attention.

As long as their energy programs are primarily based on oil and gas, the Western nations will continue to be dependent on foreign sources, particularly the OPEC countries. To guard against future embargoes, the Western nations need a standby capacity to carry them through any emergency. In the longer term a synthetic fuel capability is badly needed by the United States to counteract any threat of an embargo.

Government is heavily involved in the fuel and raw materials industries through such mechanisms as tax policies, leasing, and the various permit programs. Government also plays a major role through budgetary and monetary means in determining whether and to what extent the economy is a demand economy. A further role of government is that of financing key research and development activities that will encourage new technology, conservation, and the capability for substitution. The future degree of government involvement remains a matter for debate. There is general agreement that government should take the lead in providing for an emergency stockpile of key materials. Less clear is the extent of government financing of new developmental activities, particularly of synthetic fuels. Even less certain is whether government should participate in the marketplace by placing a floor under the price of synthetic fuels.

In sum, fossil and nuclear fuels are finite resources with a lifetime of a few decades for oil and a century for coal. Solar and fusion sources have the potential for supplying energy for long periods of time, but the technology remains to be developed. Scarce metals, in the geochemical sense, are also finite resources. While the geochemically abundant elements are in principle nearly infinite, the time scale for depletion depends heavily on the nature of the economy. If government policies foster a demand economy, where increased demand drives growth, then the time scale for depletion is diminished. If, on the other hand, the economy emphasizes a reduction of demand by conservation, substitution, and new technology, the time scale for depletion is increased. Because of the nature of the economic dislocations that are bound to arise in any shift from one energy or material source to another, the lengthening of the time scale is desirable in that this allows time for adjustment.

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Chapter Five

Discussion of "Long-Term Availability of Natural Resources," by Gordon MacDonald

John R. Meyer

Professor MacDonald's paper on the "Long-Term Availability of Natural Resources" represents a very useful point of departure for analyzing that always difficult question of the extent to which future economic development is likely to be seriously constrained by shortages of energy and raw materials. It is an impressive tour de force. He summarizes and organizes a remarkable range of statistics relevant to assessing the relationship between supply and demand for natural resources, energy in particular. Above all, his paper is replete with suggestions for further analysis and research.

My remarks, in fact, will be primarily focused on these very possibilities. As an economist, of course, I find discussions of demand and supply inherently interesting, if not intriguing. However, as I read Professor MacDonald's paper, I also find his approach to these concepts at least somewhat different from those to which I have become professionally accustomed or attuned. Specifically, price as a rationing mechanism plays a somewhat minor role in Professor MacDonald's narrative.

A particular charm of the market mechanism for economists is that it induces specialization, and thereby efficiency, in the use of factors of production. Even noneconomists are probably familiar with Adam Smith's famous Pin Factory as an illustration of these principles. In general, economists look to the market mechanism to allocate resources and consumption so as to maximize economic well-being. For an economist there are many, many benefits derivable from a well-operating market mechanism, but almost surely the most important is that it helps insure—or at least substantially increases the probability—that various resources will be used efficiently and consumption will pursue logical and rational patterns that maximize society's satisfactions.

I was therefore struck by Professor MacDonald's central metric for relating supply and demand, his "Index Years of Availability." Index years as he defines them are "an estimate of the time required to exhaust either the reserves or resources of a given fuel if that fuel is used to supply the *total* demand for energy for the world and the United States" (emphasis added). The striking thing to an economist in this definition is the use of the world total. Specifically, there is only a very limited meaning in such a construct for an economist since, as Professor MacDonald points out, many raw materials and sources of energy are rather specialized in their adaptability to different functions. A more useful construct, therefore, might be years of availability of a resource or its reserves, taking into account necessary, probable, or optimal specialization of resources by use. This line of inquiry led me to speculate to what extent Professor MacDonald's major conclusions might be altered by shifting from his generalized metric to one that was more specialized. Specifically, what would be the adequacy of various energy reserves if only used in their most productive applications?

To perform such an exercise, an identification must first be made of the major functional uses of energy. I must admit that I am not enough of a specialist in these matters to be able to specify this distribution with any precision. However, by manipulating some of the numbers in Professor MacDonald's paper and by calling on some of my own knowledge of at least one major application, transportation, I did manage to construct some figures that I think are at least suggestive. Specifically, it would seem that about 25 percent of U.S. energy is consumed by transportation, 35 percent for electrical generation, 30 percent for space heating (exclusive of electrical), and 10 percent for a variety of miscellaneous uses, the most important of which are direct inputs to industry. I would stress that these numbers are tendered as only rough approximations to facilitate discussion. I do believe, though, that they are within some rough order of accuracy. Perhaps, too, greater precision would be impossible without more detailed information than is now available on energy use in the United States.

This crude functional breakdown does, in turn, permit one to make some inferences about how energy resources might be deployed more sensibly in a world, say, in which the market mechanism had not been too inhibited and prices had been permitted to allocate fuels to their most logical or economically efficient use. Technological limitations also play a role, of course. Thus, transportation under current technological conditions is heavily dependent on the use of oil derivatives as an energy source. For the generation of electricity, by contrast, the technology is not so limiting; for this application one would expect that in a more rational world natural gas would not be used and the major reliance would be on coal and uranium, as augmented by hydroelectric power.

Development of recent concerns about air pollution would only fortify this conclusion, since cleaning up air pollution is apparently characterized by considerable economies of scale. Accordingly, in a rational allocation, one would expect clean fuels, such as natural gas, to be used primarily or almost exclusively in small-scale applications such as space heating; cleaning up air pollution at a relatively few electrical generation plants should be, by comparison, relatively inexpensive. In sum, in a world in which markets were permitted to achieve a rational allocation of resources one would expect that: (1) transportation energy requirements would be mainly, although not exclusively, satisfied by oil derivatives; (2) space heating would be primarily done by natural gas and electricity; and (3) electrical generation would be primarily performed by the burning of coal or the development of nuclear energy, augmented wherever possible by hydroelectric power.

With such specialization, the consumption of various major energy sources (at current or 1976 economic activity levels) might be as reported in column 1 of Table 5-1. I would emphasize that I am *not* asserting that these consumption levels represent a sensible target for

Table 5-1. U.S. Energy Reserves at Current Use Levels with Specialization by Sources and Uses

	Annual Consumption (quads/yr)	*Recoverable Reserves*	*Recoverable Resources*
		(years)	
Crude Oil (exclusive of tar sands and oil shale)	18	10	50-115
Crude Oil (inclusive of tar sands and oil shale)	–	-	370-725
Natural Gas	15	16	36-87
Coal	23	260	950-1,740
Uranium	13	24-1,500	100-8,000
Hydroelectric	4	N.A.	N.A.
	73		

U.S. energy policy. For example, it is not at all clear to me that total self-reliance or independence in energy resources is a sensible policy for the United States; if petroleum can be imported from abroad for a reasonable price—with reasonableness being defined as being cheaper than alternative and equivalent sources—then it is not apparent to me that we should eschew all imports. With the continuation of imports, of course, 18 quads per year of crude oil consumption may well be an impractically low goal. Similarly, it is obvious that one could not move quickly from the present U.S. production of approximately 12 to 13 quads of coal per year to 23 or so. I have also finessed the coal versus nuclear debate for electrical generation; in constructing Table 5-1, I simply assumed that these two fuels would share equally in filling any void created by withdrawing liquid hydrocarbons from electrical generation.

Though counterfactual in construct, the numbers in column 1 of Table 5-1 do indicate some directions in which American energy consumption might sensibly move. The figures in columns 2 and 3 also indicate that with specialization in use, and reliance on U.S. domestic reserves and resources only, we have *slightly* more time to adjust our economic patterns than would be suggested by the numbers in Professor MacDonald's Table 4-17, a table that would seem most directly comparable to my Table 5-1.

The numbers in my table do *not*, however, indicate anything more than a minor qualification to Professor MacDonald's major conclusion; namely, that if the U.S. is determined to be more self-sufficient in energy, we must make a major shift from oil and gas to coal and nuclear energy. We may have three or four decades to do this rather than one or two, but the inevitability of making some such shift seems well established.

These extra decades, though, can be important. As Professor MacDonald notes, a gradual evolution is the only sensible way for such a transition. For an economist, moreover, it is also obvious that the simplest and most effective way to bring about this gradual transition is to unleash the pricing mechanism in energy markets. Without much question, much of what we now consider to be a natural gas shortage is one that is artificially created by government action—specifically, regulation of natural gas prices to levels that dissuade seeking of new supplies or through exploitation of existing sources and proper conservation of that output we now have. Much the same applies, with only slightly less vigor, to government intervention in crude oil and uranium prices. In a certain sense, present energy crises are not so much functions of a *lack* of government policy as perhaps a consequence of too much policy—although in deference to government it has *not* created all the cartel arrangements in the energy industries by any means. I should also quickly add that a more coherent government policy toward developmental research, stockpiling, and other such possibilities still has much to recommend it.

I was tempted at times, reading through Professor MacDonald's paper, to wonder whether the whole exercise of attempting to estimate resource availability really has much meaning in a world of cartels and government controls. My skepticism surfaced whenever Professor MacDonald indicated the extent to which availability was, as an economist would have guessed right from the start, dependent on relative factor prices. In essence, the characteristics that determine availability are also a function of availability. In a market economy, the feedback between supply shortages and demand excesses would be pronounced and reasonably prompt; these feedbacks, moreover, should provide a bit more advance warning of where demand excesses or shortages are likely to develop next, and thereby provide investment incentives to forestall the worst of such developments in the future.

This does not mean, of course, that there wouldn't be transition difficulties in moving from where we are now to a less regulated environment. Nevertheless, these difficulties may be easily exaggerated. Oil, after all, is used to heat many homes and its price has shot up about as much as gas might if deregulated; society has been buffeted by this oil price change, but does seem to have survived. In general, the maldistribution of wealth in today's regulated structure may be as great as under deregulation. Furthermore, in an economy such as ours with well-developed fiscal mechanisms, equity issues are almost surely better treated by tax policy or direct government transfers than by market distortions.

I would conclude by observing that I have long been struck by the sharply different intellectual approaches that economists, on the one hand, and physical scientists, on the other, bring to these considerations of identifying resource availability and needs. Engineers, I might add, seem to fall somewhere in between the two. At any rate, most (though certainly not all) physical scientists, particularly biologists and ecologists, when pursuing these problems seem to have an affinity for unstable or degenerative models. (I would immediately remind everyone that Professor MacDonald is a geophysicist.) Economists, by contrast, are clearly much more comfortable with relatively stable and equilibrium-oriented systems; that is, economists seemingly prefer models that, when disturbed by an outside shock, return to some acceptable equilibrium value. Many biological or ecological models, by contrast, degenerate or move inexorably toward what can be construed as intolerable or highly unfavorable asymptotic values. As a consequence, it is easy enough to divide the different disciplines into Professor MacDonald's optimists and pessimists. For those of us coming from the "dismal science," it is rather heady stuff to be known as optimists!

Clearly a certain pessimism or alarm is to be found in many physical science analyses of these problems that is not widely shared by economists. Indeed, the natural instinct of an economist when encountering unstable or degenerative systems is to seek devices to make them automatically stable or to presume that human behavior almost invariably has a large corrective component built into it. The pricing mechanism, as I have pointed out (perhaps ad nauseum), is surely one of the more potent of these corrective possibilities. I suspect that we economists overemphasize its potential, but on the other hand, I also suspect that many others vastly underestimate its possibilities.

Chapter Six

Discussion of "Long-Term Availability of Natural Resources" by Gordon MacDonald

Bruce Yandle, Jr.

Gordon MacDonald's paper has three components: a discussion of nonrenewable resources and how their scarcity may be viewed; an identification of scarcity with respect to presently defined energy resources and other minerals; and a discussion of economic growth and the attendant policy for dealing with scarcity. My comments follow the same outline.

PESSIMISTS AND OPTIMISTS

The first part of the MacDonald paper develops an interesting psychological interpretation of resource scarcity. Depending on one's belief in or interpretation of data, one is either classified as a pessimistic pessimist, an optimistic pessimist, a pessimistic optimist, or an optimistic optimist.

At one extreme are individuals who do not accept the idea that particular physical resources matter, at least in the long run. For example, the optimistic optimist would not have become distraught in the 1800s when the world appeared to running out of whale oil, a principal source of energy at the time.[1] It would not have been technical knowledge about whales or other energy sources that would have made the double optimist less concerned. That viewpoint, as suggested by MacDonald, may have been this: Whale oil is not the question, energy or utility is. And given the incentive structure of a market system, if there is to be a specific solution, it will be developed.[2] If there is no specific energy solution, the price system will allocate whatever resources available in a way superior to any other system. That is, the optimistic optimist's concern is how to draw on human *resourcefulness* when faced with scarce natural resources.

At the other extreme, using the same example, were the pessimistic pessimists. These people perhaps believed that they knew all that would ever be known. In other words, they were convinced that the world's store of knowledge had reached its zenith just at the time when whale oil hit its nadir. Thus, in their book, rising prices would not produce whales. Facing the exhaustion of whale oil, the double pessimist must have: (1) moved to the tropics or the land of the midnight sun; (2) tried to cartelize the whale industry and ration the oil; or (3) called for repentance, for the end of the world was at hand.

On the other hand, those between the extreme optimists and pessimists probably cursed the rising price of whale oil, which made them seem poor, and in the meantime tried to modify their lifestyles in order to economize on energy. Other greedy souls saw an opportunity to get rich and got busy looking for substitute fuels. The high price of whale oil prodded them along and made the search potentially profitable. Those fortunate ones who found new energy sources—flaxseed oil and ultimately kerosene—got rich by increasing the supply of energy, which led to even lower prices. They no doubt joined the ranks of the double optimists. Those entrepreneurs who went broke in their search for new energy sources were called pessimistic optimists. They had the right idea but the wrong solution. That is, the price system worked, but not as they intended.

Thus, in the first part of his paper, MacDonald reminds us that how one views any problem of scarcity—particularly that of nonrenewable resources—depends on one's acceptance of the price system as a means of communication.[3] I would put greater emphasis on the ability of efficient markets to minimize the problems of scarcity, to maximize human welfare no matter how scarce a given resource in the short run, and, if a future substitute for a nonrenewable resource is to be found, to identify it and bring it forward at the optimal time. Of course, my emphasis generally reflects the economist's view.

THE DIMENSIONS OF SCARCITY

The dimensions of scarcity are important, no matter what view one takes of the problem. And the second and third parts of MacDonald's paper give some important insights into some of these dimensions. As an addition to the data he has presented, I would suggest that further emphasis be given to the *economic* nature of reserves and man's historic success in dealing with lower quality ores.

The recent report of the National Commission on Materials and

Shortages contains the kind of evidence I have in mind.[4] For example, the question of "known reserves" is discussed in some detail. We are reminded that such reserves are a function of price:

> Resources are more properly measured in economic terms. Additional productive land can be "created" by swamp drainage, irrigation, forest clearing, etc., and yields per acre can be increased. New mineral resources can be "discovered" by investments in exploration and by technological change which allows the mining of ores previously not amendable. In other words, advancing technology can add to supplies of "fixed" resources.[5]

While the statement is based on economic theory it is buttressed with empirical evidence. Consider the percentage increases in known reserves calculated for the period 1950 to 1970, shown in Table 6-1. Bear in mind that these are increases in known reserves after twenty years of production. As reported in Table 6-1, tungsten is the only metal listed where reserves declined. Such evidence suggests that the market or price system has communicated scarcity and has in the past been reliable in providing an incentive to listen for the market signal.

MacDonald's paper suggests that the approaching age of scarcity may raise serious questions about the ability of the market to maximize humanity's social well being. In other words, this new age of scarcity comes at a time when the old rules may not work. Of course history is a pageant of scarcity. Not only do we encounter new scarce

Table 6-1. Increases in Known Reserves: 1950 to 1970

Ore	*Percentage Increases in Known Reserves*
Iron	1,221
Manganese	27
Chromite	675
Tungsten	–30
Copper	179
Lead	115
Zinc	61
Tin	10
Bauxite	279
Potash	2,360
Phosphates	4,430
Oil	507

Source: National Commission on Materials and Shortages, *Government and the Nation's Resources* (Washington: Government Printing Office, 1976), p. 16.

resources but we are often confounded by our scarce knowledge. Both scarcities appear to have been dealt with historically. But let us focus on a very brief period—current history in a sense—to see how economic forces have driven technology to reduce the cost of minerals.

Table 6-2 shows a measure of real cost for five important minerals: copper, iron, zinc, aluminum, and crude petroleum. The index numbers in the table were developed by William Nordhaus for the years 1900 to 1970 and are the ratios of the nominal U.S. price of the commodity to the average wage of American workers.[6] I have extended the series to include 1974, 1975, and 1976 data.

As may be noted these rough indexes shows dramatically lower costs for all five commodities when compared to 1900. The 1976 indexes, when compared with 1970, are lower for copper and aluminum. The index for zinc is 50 percent higher today than it was in 1970. Iron ore is 3 percent more costly. And crude petroleum is more than twice as costly. However, even with its higher cost, crude oil is just slightly more costly in real terms than it was in 1950.

Results similar to these have been reported by Richard Erb in his recent survey of international raw materials.[7] In Erb's analysis of world prices of petroleum, copper, tin, lead, zinc, and aluminum, he notes that "Inflation-adjusted prices began to rise for lead and zinc in late 1971, for tin and copper in late 1972, and for aluminum in mid-1973."[8] This noted increase reached its peak in 1974 and was pressured by two actions by the U.S. government. First, Erb notes that "U.S. zinc refinery capacity was reduced by 17 percent during 1971, to a large extent because of pollution controls."[9] Second, the United States imposed embargoes on soybeans in 1973, which caused Japan particularly to begin stockpiling commodities, including metals, as a protection against future shortages.[10]

After the 1974 peak, metal prices began to fall on international

Table 6-2. Price of Minerals Relative to Average Cost of Labor (1970 = 100)

	1900	*1920*	*1940*	*1950*	*1960*	*1970*	*1974*	*1975*	*1976*
Copper	785	226	121	99	82	100	101	76	74
Iron	620	287	144	112	120	100	98	93	103
Zinc	794	400	272	256	126	100	111	100	152
Aluminum	3,150	859	287	166	134	100	92	97	81
Crude Petroleum	1,034	726	198	213	135	100	160	224	234

Source: 1920-1970: W.D. Nordhaus, "Resources as a Constraint on Growth," *American Economic Review* (May 1974), p. 24, as reported in National Commission on Supplies and Shortages, *Government and the Nation's Resources* (Washington: U.S. Government Printing Office, December 1976), p. 19; 1974-1976 calculated from U.S. Department of Commerce data. Crude Oil price based on refiner acquisition cost for composite crude.

markets, eventually reaching or going below the 1967 price. Again, however, zinc was the exception. The point is this: significant technological change has occurred across the years and, as a result, output has increased from lower grade ores and deeper wells and at a lower cost.

Over the last 26 years, mining's share of total investment in new plant and equipment in the United States has fallen, not increased.[11] That is, our national experience still indicates that many stubborn scarcities have been dealt with at a diminishing cost to society. Since market forces were able to function rather freely during much of the period, the result described might increase the ranks of the optimists. However, governments around the world now have a heavy hand in the control of basic metals and petroleum.

In the last part of his paper, MacDonald describes the economic process and suggests that "as fossil fuels and metals become scarce, a greater fraction of income and savings goes into securing natural resources." Since we are not given a time period for the development, one might conclude that the time of scarcity has not yet arrived. However, some people might debate that conclusion. By examining data on personal consumption in the United States for the period 1960 to 1976 one can see if there have been any apparent changes in the share of consumption expenditures going to commodities related to nonrenewable resources. Table 6-3 reports the consumption data.

It may be surprising to see that the proportion of expenditures out of consumption for all durable goods was almost constant across the 16-year period. Furthermore, the proportion of all consumption expenditures spent for gasoline and oil was the same for 1976 as for 1970, and relatively constant. The same result is seen for fuel oil and coal. Simply put, there appears to have been no disruption of consumer expenditure patterns among the broad and narrow categories reported. In other words, consumers have found substitutes for the higher priced commodities. Perhaps even the optimists would be surprised. But the story is not complete.

POLICY IMPLICATIONS AND CONSTRAINTS

On the basis of his presentation of data and knowledge of the social environment, MacDonald recommends certain goals regarding national policy for dealing with energy and mineral resources. They include a reduction in the rate of growth of demand; an increase in supply; stockpiling of vulnerable materials; and a determined management policy.

The double optimist would quickly suggest that the policymakers

Table 6-3. Proportion of Personal Consumption Expenditures by Major Category (current dollars 1960, 1965, 1970-1975) (percent)[a]

Expenditures	*1960*	*1965*	*1970*	*1971*	*1972*	*1973*	*1974*	*1975*	*(est.) 1976*
Durable Goods	13.3	14.6	13.7	14.5	15.2	15.3	13.7	13.5	14.6
Motor Vehicle & Parts	6.1	6.9	5.6	6.5	6.9	6.8	5.4	5.4	6.6
Furniture & Household Equipment	5.4	5.7	5.9	5.9	6.1	6.3	6.2	5.9	5.9
Other Durables	1.8	1.9	2.1	2.1	2.3	2.2	2.2	2.2	2.1
Nondurable Goods	46.5	43.6	42.8	41.6	40.8	41.2	42.4	42.0	40.8
Total Food	21.7	19.9	19.2	18.3	17.8	18.1	18.8	19.0	18.5
Nondurables Less Food	24.8	23.9	23.6	23.3	23.0	23.1	23.6	23.0	22.3
Clothing & Shoes	8.2	7.8	7.5	7.6	7.5	7.6	7.4	7.2	6.9
Gasoline & Oil	3.7	3.4	3.6	3.5	3.5	3.4	4.1	4.0	3.8
Fuel Oil & Coal	1.2	1.0	.9	.8	.9	1.0	1.1	1.0	1.0
Other Nondurables	8.5	8.6	8.8	8.6	8.5	8.5	8.5	8.3)	10.6
Alcoholic Beverages	3.3	3.1	2.9	2.8	2.7	2.6	2.6	2.5)	
Services	40.2	41.6	43.5	43.9	44.0	43.6	43.9	44.4	44.6
Housing	14.8	15.2	15.2	15.4	15.3	15.2	15.4	15.4	15.4
Household Operation	6.2	6.1	6.2	6.2	6.3	6.2	6.3	6.6	6.5
Transportation	3.3	3.2	3.4	3.6	3.5	3.4	3.5	3.5	3.5
Personal Care	1.8	1.7	1.4	1.3	1.2	1.1	1.1	1.0)	19.2
Recreation	2.0	2.0	2.1	2.0	2.0	2.0	2.0	1.9)	
Personal Business	4.4	4.6	5.1	5.1	5.1	5.0	5.0	5.2)	
Medical Care	4.7	5.6	6.7	6.9	7.1	7.2	7.4	7.7)	
Private Education	1.2	1.3	1.6	1.6	1.6	1.6	1.5	1.5)	
Religious & Welfare	1.5	1.4	1.4	1.4	1.4	1.3	1.3	1.2)	
Foreign Travel	.4	.4	.5	.5	.5	.5	.4	.4)	

[a] Totals may not add due to rounding.

Source: Computed from U.S. Department of Commerce, Bureau of Economic Analysis data, reported in J. Dawson Ahalt, "Trends in Food Consumption, Prices and Expenditures," paper presented at the American Enterprise Institute Conference on Food and Agricultural Policy, Washington, D.C., March 10-11, 1977, Table 9, p. 29.

accept the recommendation, pointing out that MacDonald has described the normal operation of efficient markets. That is, when a resource becomes more scarce, its relative price goes up. The rising relative price reduces the quantity demanded and increases the quantity supplied. Furthermore, the rising price signals the start of exploration and the development of new technologies and substitutes. As to stockpiles, if investors predict that embargoes or other interruptions in supply are to occur, they will likely speculate and stockpile, causing scarce resources to be allocated efficiently between present and future consumption. The optimistic optimist sees no need for government concern. The private market can handle the problem. In my opinion, the double optimist is correct. However, many laws will have to be repealed to clear the way—and that is why the optimistic optimist is getting slightly pessimistic.

While the market system *could* handle the problem, policymakers have chosen to take a different approach. Instead of allowing the price of scarce petroleum products to rise, prices have been controlled and shortages are now added to scarcity. Natural gas, gasoline, old oil, new oil, entitlements—all are a part of our policy. The quantity demanded wants to increase instead of decrease. Of course, the control of price drives down the incentive to increase supply. We have the opposite result to that recommended by MacDonald.

Since there is so much concern over profits, speculators are now fearful to invest in a stockpile that might become more valuable. Windfall profits are to be avoided. Thus the speculator cannot cover his "windfall losses." What was a normal operation of the market has now been removed. In its place is the Energy Policy and Conservation Act of 1975 (P.L. 94-163), which requires a government stockpile of 150 million barrels of oil by December 1978 and 500 million barrels by 1982.[12] The estimated taxpayers' cost of storage, transportation, and purchase of this oil is $8 billion. We are in the stockpiling business. The price system has been moved away.

One can find other indications of the movement away from the price system. For example, government policies have moved the economy to a system of barter, where economic studies of government programs require that impact be measured in the number of barrels of crude oil which may be used. In some cases, measurements are made in oil, not dollars.[13] Government-mandated fuel-economy measures are also based on saving oil, not dollars or energy in all forms.[14] It is possible that auto producers may use more energy-intensive materials and more oil in order to show increased miles per gallon. Even the pessimistic pessimist could become more pessimistic.

In terms of other minerals, air pollution regulations have effectively cut off the expansion of copper production until 1983. A recent study for EPA indicates that the enforcement of the Clean Air Act will cause a copper shortfall of as much as 28.6 percent over baseline production in 1985; employment in the industry could be reduced by as much as 20,300 jobs by 1985.[15] In short, the supply of copper has been reduced significantly as efforts are made to reduce the amount of emission from the industry. The real cost of marginal improvements in air quality could be rather high in this case.

The problems related to scarce minerals discussed by MacDonald are made graphic when the effect of environmental regulation on mining is considered.[16] The U.S. mining industry expects to invest $2.5 billion in new facilities between 1975 and 1983. Of the $2.5 billion, $862 million or about 35 percent of total investment will go for water-treatment equipment. In barter terms, the equipment will require 1.4 million barrels of oil annually to operate. Approximately 50 percent of the additional investment will go to reduce effluents by another 5 percent. The tradeoff here is very clear.

When we consider MacDonald's recommended policy for expanding the supply of energy resources we might be aware of the environmental constraints faced by the U.S petroleum industry. A study prepared by Battelle Columbus Laboratories for the American Petroleum Institute reports that the p etroleum industry can expect to invest $28.9 billion in environmental control equipment by 1985.[17] Annual operating costs for the equipment could reach as high as $17 billion, which translates into a price increase of $2.05 per barrel of crude oil or 20 percent of total cost.[18] The values here represent Battelle's most restrictive analysis. Eighty percent of the cost derives from reaching for another 3 to 5 percent reduction in emissions or effluent discharge. In terms of energy impact, by 1985 it will take 322.7 million barrels of oil annually in equivalent energy to operate the pollution control equipment in the petroleum industry.[19] That is equal to 14 days supply of oil for the entire nation.

A recent Commerce Department report explained the petroleum industry's problem in yet another way.[20] The investment requirements mentioned above would construct plants capable of producing 1 million barrels a day of shale oil, or 4 million barrels a day in additional refining capacity.

The regulatory constraints imposed on the mining and petroleum industry in the pursuit of environmental quality indicate that humanity may have added significantly to the problem of resource availability. In some cases, nature's bounty has been hidden in a maze of regulatory red tape. To remedy the problem of environmental degradation, standards have been promulgated which, because of their inherent inefficiency, foster unnecessary consumption of valuable energy and other resources.

The experience with the National Environmental Act of 1969 (NEPA), and its requirement of environmental impact statements for actions by federal departments and agencies, provides a final straw for the optimists who hope that market forces may break through the problem of scarcity.[21] Due partly to NEPA and other safety constraints, the Nuclear Regulatory Commission now takes approximately seven and one-half years to review and approve an application for a new nuclear facility.[22] This estimate does not include litigation delays that arise in many cases. In other words, if a group of investors was ready today to go forward with complete engineering plans and all the attendant documentation required for a proposed nuclear generating plant, they would consider themselves fortunate to have the plant on line by 1985. They could anticipate that much delay in their planning. Litigation and other regulatory problems might bring unanticipated delays, which generate unplanned costs. Along these lines it has been estimated that by 1980 the *daily* cost of delaying a nuclear generating facility will be $6.7 million.[23]

CONCLUSION

This brief discussion of some of the more onerous regulatory constraints faced by the energy and mining sectors may help to explain the dichotomy between pessimists and optimists presented early in MacDonald's paper. Those who argue that the free market cannot be relied on to assure a long-run supply of energy and other resources may have unwittingly based their judgment on markets that have not been allowed to function. They are pessimistic, but may have pointed to the wrong culprit in placing the blame for "market failure." Those who see market forces as beneficial but question the ability of the market to respond quickly to new scarcities may know about the complex of government mandates that muffle, delay, and sometime even make illegal the legitimate operation of markets. They are pessimistic optimists for logical reasons. Finally, those who survey the situation described by MacDonald, understand the regulatory dilemma, and still think that market forces will prevail, are truly optimistic optimists. And let us hope that they are correct.

In the long run, costs will be paid no matter how we seek to assure supply. And nonmarket institutions that attempt to outperform free market forces will likely fail and be pushed ultimately to one side. James Schlesinger, now chief energy advisor to the President, described ultimate institutional change in this way: "Perhaps only dramatic, interest-arousing events are sufficient to persuade the public that the productive period of an institution's life is near its end."[24]

Perhaps we are now witnessing such a conflict, one which will bring a more rational time when free markets will be aided, not eroded, in performing their function of minimizing social cost, that is, maximizing happiness in a world of scarce resources. As has been suggested before, scarcity can be the prelude to plenty. It is the potential of humanity that we question. The free spirit of all people when released can perform a Titan's task in dealing with scarcity.[25] Perhaps there is something to learn from the optimistic optimists.

NOTES

1. For an interesting discussion of this early energy crisis see Paul H. Giddens, "The Shortages that Yielded Oil," *Petroleum Today* 16 (1975):1-5; and Walter B. Wriston, "Whale Oil, Baby Chicks and Energy," *National Review*, June 7, 1974, pp. 643-46.

2. After the whale oil crisis, the nation faced its first natural gas shortage in the mid 1900s. Just as in the current situation, doomsday prophets saw no solution and attempted to regulate. However, national regulation had not developed. Thus prices went up, allocations of natural gas changed, and in five years new technology provided new supplies. For a complete discussion of this and other related points, see Edmund W. Kitch, "Regulation of the Field Market for Natural Gas by the Federal Power Commission," *Journal of Law and Economics* 11 (October 1968): 243-80.

3. For a discussion of this function of the price system in the same context, see H. H. Macaulay and Bruce Yandle, *Environmental Use and the Market* (Lexington, Mass.: Lexington Books, D. C. Heath, 1977).

4. National Commission on Supplies and Shortages, *Government and the Nation's Resources* (Washington: U.S. Government Printing Office 1976).

5. Ibid., p. 15

6. The original table and this discussion is drawn from the report of the National Commission on Supplies and Shortages, op. cit., pp. 18-19.

7. "International Raw Materials Developments: Oil and Metals," in William Fellner, ed., *Contemporary Economic Problems* (Washington: American Enterprise Institute, 1976), pp. 323-69.

8. Ibid., p. 349.

9. Ibid.

10. Ibid., p. 352.

11. See *Economic Report of the President, 1977* (Washington: U.S. Government Printing Office, January 1977), p. 237.

12. See Federal Energy Administration, *Strategic Petroleum Reserve Plan* (Washington: U.S. Government Printing Office, December 15, 1976).

13. For example, OMB Circular 107, which implemented Executive Orders 11821 and 11949, required the executive regulatory agencies to perform economic impact analyses of all "major" regulator agencies. The agencies were allowed to define "major" subject to OMB approval. Most agencies include in their major criteria any action which increases the demand or reduces the supply of crude oil by 0.1 percent of annual crude oil usage (approximately 25,000 barrels daily). I will give some of this data later in the paper.

14. See Council on Wage and Price Stability, "Passenger Automobile Average Fuel Economy Standards," a filing before the National Highway Traffic Safety Administration, Docket No. FE 76-2 (January 3, 1977).

15. See Arthur D. Little, Inc., *Economic Impact of Environmental Regula-*

tions on the U.S. Copper Industry (draft report) (October 1976). Appreciation for permission to quote is expressed to the U.S. Environmental Protection Agency.

16. This discussion is drawn from American Mining Congress, *Study of Cost of Compliance with Federal Water Pollution Control Act* (Washington, D.C., 1976).

17. Battelle Columbus Laboratories, *The Economic Impact of Environmental Regulations on the Petroleum Industry—Phase II Study*, A Report to The American Petroleum Institute (Washington: American Petroleum Institute, June 1976), p. I-3.

18. Ibid.

19. Ibid., p. I-19.

20. U.S. Department of Commerce, *Toward Regulatory Reasonableness*, (Washington: U.S. Government Printing Office, January 13, 1977), p. 105.

21. For a discussion of NEPA and environmental impact statements, see: Council on Environmental Quality, *Environmental Impact Statements: An Analysis of Six Years' Experience by Seventy Federal Agencies* (March 1976).

22. Based on private conversations with Mr. Jim Fitzgerald, General Counsel's Office, Nuclear Regulatory Commission, March 3, 1977.

23. This estimate was given by Mr. J.L. Leporati, Vice President of EBASCO Services in a speech, "The Expanding Role of the States in Power Regulation," Hilton Head, S.C., October 1976. Appreciation is expressed to Mike Maloney, Department of Economics, Clemson University, for providing this item.

24. James R. Schlesinger, "Systems Analysis and the Political Process," *Journal of Law and Economics* 11 (October 1968): 293. Current efforts to bring about regulatory reform may indicate that we have reached the "Schlesinger Point" with some institutions. In this sense, it appears that the most stringent regulations offer the greatest prospect for revision. For example, among environmental regulations, the Clean Air Act of 1970 sets the most stringent regulatory framework. That law resulted in the identification of "nondegradation" and "nonattainment" areas. The first were "very clean" while the latter did not meet national ambient air quality standards. Industrial expansion was cut off in both situations. Recent pressures for industrial growth have reached the point where revision is being made in both the interpretation of the Clean Air Act and perhaps in the Act itself. See Council on Wage and Price Stability, "Air Quality Standards: Interpretative Ruling," a filing before the U.S. Environmental Protection Agency (March 3, 1977).

25. For an excellent expansion on this theme and the source of the idea, see Wilfred Malenbaum, "Scarcity: Prerequisite to Abundance," *Annals of the American Academy of Political and Social Science* 420 (July 1975): 72-85.

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