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Resources as a Constraint on Growth

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For a considerable part of its history, the American economy has functioned as a cowboy economy. It has been a cowboy economy in the sense that there have been no important resource constraints on growth. This is not to say that land, minerals, and a clean environment have been freely available. Rather, agricultural land could be obtained at roughly constant costs; most essential minerals have been present at fairly high grade in considerable abundance; and the environment could be used as a sink without becoming fouled. In the last several decades, however, cropland has stayed almost constant. Some high grade mineral deposits have been exhausted, and the carrying capacity of our environment has been strained.

The scarcity of resources has led many to argue that the operating rules of our economy must change. Whereas in the cowboy economy we could afford to use our resources profligately, the new view of economic growth is that the closing of all our frontiers means that we are now operating in a spaceship economy. In a spaceship economy, great attention must be paid to the sources of life and to the dumps where our refuse is piled. Things which have traditionally been treated as free goods—air, water, quiet, natural beauty—must now be treated with the same care as other scarce goods.

It would seem difficult to question the observation that the world economy is progressing toward a closed system. Many have carried this observation further, describing a future imperiled by famine, depleted of essential materials, running out of energy, or choking in its own exhaust fumes. Behind these pessimistic visions is a deeper skepticism about the very fruits of economic growth.

Economists have for the most part ridiculed the new view of growth, arguing that it is merely Chicken Little Run Wild. I think that the new view of growth must be taken seriously and analyzed carefully.

What have we learned about the new view?

The first set of studies relates to *theoretical* investigations. (By theoretical I mean propositions based on largely untested assumptions about model structure —perhaps hypothetical would be a more accurate term.) In this category belong the celebrated writings sponsored by the Club of Rome as well as many offshoots of this work (Jay Forrester, Dennis H. Meadows et al.). These works have demonstrated that, under certain conditions involving technology, population, and resource availability, a sustained growth path for consumption is not possible.

The conclusions of these works have not generally been accepted by economists because of the dubious nature of many of their assumptions. In particular, the assumptions regarding population growth and technology are quite unsatisfactory. Several authors have shown that the conclusions of these models are not robust to minor modifications in structure. Thus R. Boyd showed that introducing a new factor called "technology" would drastically alter the model's path. My work (1973a) showed that any of three changes in model structure—ongoing technological progress, adequate factor substitution or population decline—would lead to opposite and more optimistic results.

It should be stressed, however, that all

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of the debate about Club of Rome models has been theoretical. It has been demonstrated that different world models paint drastically different pictures of future economic life. It is at this moment an open question as to which is the preferred model. Only careful empirical analysis can indicate which of the alternative models is closer to reality.

What then of *empirical studies* of long-run constraints on growth? Although there have been no comprehensive studies, several particular problems have been investigated. I will report on recent findings for mineral resources and energy.

For centuries there has been virtually constant concern about the availability of mineral resources. Many recent studies have kindled this anxiety by showing that the ratio of proved reserves to current consumption (*R–C* ratio) for most minerals is very low. Fortunately, this is unduly pessimistic because the concept of reserves is entirely different from ultimate recoverable resources. Proved reserves are akin to the working capital or inventory of known resources. At the opposite extreme it is possible to calculate the total crustal abundance (*CA*) of different materials; of course this is unduly optimistic because it assumes that everything can be recovered. Somewhere between the two concepts lies the economically relevant measure—ultimate recoverable resources (*URR*). Although *URR* is a variable which depends on technology and price, we can as a first approximation use recent estimates prepared for the U.S. Geological Survey. These assume that *URR* is approximately 0.01 percent of total availability to a 1-kilometer depth (*Geological Survey*, p. 23). It should be emphasized that these estimates do not take into account the economic feasibility of mining lower grade ores as prices rise or techniques improve.

Table 1 shows estimates of the abundance of eleven important resources according to these three measures. (The first ten are the most important minerals by value of production.) It should be noted that *URR* is the most uncertain, especially because it involves estimates of what future prices and technologies will be.

The clear evidence is that the future will not be limited by sheer availability of important materials; rather, any drag on economic growth will arise from increases in costs. This raises the question of long-run movements in extraction costs of different materials.

TABLE 1—RESOURCE AVAILABILITY FOR IMPORTANT MINERALS BY THREE MEASURES

	Known Reserves/ Annual Consumption (*R/C*)	Ultimate Recoverable Resource/Annual Consumption (*URR/C*)	Crustal Abundance/ Annual Consumption (*CA/C*)
Coal	2,736	5,119	na
Copper	45	340	242,000,000
Iron	117	2,657	1,815,000,000
Phosphorus	481	1,601	870,000,000
Molybdenum	65	630	422,000,000
Lead	10	162	85,000,000
Zinc	21	618	409,000,000
Sulphur	30	6,897	na
Uranium	50	8,455	1,855,000,000
Aluminum	23	68,066	38,500,000,000
Gold	9	102	57,000,000

Source: Geological Survey, pp. 22–23, 613–14, 140. *Statistical Abstract*, p. 651.

It is useful to view the problem of rising materials costs in terms of a simple model of production. If interest rates are relatively constant, then we can express the costs of production in terms of the costs of two primary factors, labor and resources. (Capital is simply dated labor and resources.) One way to view the long-run problem is whether technological progress has been sufficiently rapid to offset the diminishing returns in resource extraction which arises from mining lower grade ores (or deeper or thinner veins). A simple index of this process is the movement of the "labor cost of resources," that is, the ratio of resource price to labor price.

Table 2 shows the ratio of the prices of the eleven most important minerals to the price of labor. This indicates that there has been a continuous decline in resource prices for the entire century. Unless all minerals suddenly hit a kink in the cost curve at the same time, it seems unreasonable to foresee a drastic runup of the cost of minerals relative to wages in the near future.

In summary, we expect that higher consumption levels in the future will lead to mining of lower and lower grade ores. Whether or not this leads to continuing decline of the resource/labor price ratio depends on whether technological progress continues to outstrip the movement to lower grade ores.

Table 2—Relative Price of Important Minerals to Labor, 1970=100

	1900	1920	1940	1950	1960	1970
Coal	459	451	189	208	111	100
Copper	785	226	121	99	82	100
Iron	620	287	144	112	120	100
Phosphorus	—	—	—	130	120	100
Molybdenum	—	—	—	142	108	100
Lead	788	388	204	228	114	100
Zinc	794	400	272	256	126	100
Sulphur	—	—	—	215	145	100
Aluminum	3,150	859	287	166	134	100
Gold	—	—	595	258	143	100
Crude Petroleum	1,034	726	198	213	135	100

Source: Values are the price per ton of the mineral divided by the hourly wage rate in manufacturing. Data are from *Historical Statistics, Long Term Economic Growth, Statistical Abstract.*

A specific class of resources where there has been considerable concern and quantitative work is energy resources. Energy is in fact an excellent case study of the central propositions about the limits to growth. Unlike most mineral resources, energy is essential for many processes of production. In addition, energy resources are finite in supply; energy consumption is dissipative, and currently leads to serious environmental problems.

Three important questions about energy resources are important for assessing future long-run growth. These concern resource availability, price and environmental effects.

The first question is whether there are adequate energy resources to run the world's economy for an indefinite period of time. Unfortunately, a complete answer depends on the answers to the next two questions, but for a crude answer we can simply calculate the quantities of energy resources. Table 3 shows the ratio of reserves to 1970 consumption under certain assumptions about the feasible technology.

Pretty clearly, the sheer adequacy of energy resources depends on whether certain future technologies will become available. Even with only the current technology (Table 3, line 2) there are resources for more than 8,000 years at the current rate

Table 3. Resource-Consumption Ratio for Energy, 1970

1. Fossil fuels only	520
2. Fossil fuels plus current nuclear technology	8,400
3. Fossil fuels, current nuclear, and breeder technology	1,100,000
4. Fossil fuels, current nuclear, breeder, and fusion technology	53,000,000,000

Source: Hubbert, *Statistical Abstract* 1972, Nordhaus (1973b).

of consumption. With breeder reactors, and more dramatically with a fusion technology, there is virtually unlimited energy available.

The second question concerns the price at which energy resources will be available over the long run. The new view of growth sees a future in which energy resources become extremely expensive as mining turns to lower and lower grade energy resources. Thus it may well be that resources are available, but they are so expensive and so many resources are devoted to extraction that a dwindling amount of output is left for actual consumption.

I have recently considered the likelihood of this in another context (Nordhaus, 1973b). Starting with energy resources, with plausible demand paths, and with current estimates of the costs of extracting and processing energy resources, it is possible to calculate the results of a stimulated competitive market unfolding over time. In making this calculation, I assumed that the world's energy resources are efficiently allocated over time and space with an interest rate of 10 percent, and that the supply of energy resource was that given by technological assumption 3 in Table 3 (that is, breeder reactors would be technically and environmentally feasible by the year 2010).

The calculated path for energy prices was quite remarkable. The starting point in 1970 showed calculated energy prices very close to the actual. The efficient solution traced out a transition to the ultimate technology, with the final nuclear-based technology ultimately taking over about 150 years out. The most interesting part was the price path. Over the next 50 years, the calculated price index of final energy products rose 2.2 percent annually relative to the general price level. The growth rate of energy prices relative to the general price level over the next 100 years was 1.3 percent annually—after which time energy prices were constant relative to the general price level.

Whether movements of relative prices of this magnitude become a drag on consumption depends on the future pattern of technological change. If productivity increases at its historical rate—output per manhour growing at about 2.5 percent over the last few decades (see E. Denison)—then a rise in energy prices of the order of magnitude cited above would mean that energy prices would continue to fall relative to labor's price and to average incomes. In this case, there would be no drag on consumption standards stemming from the gradual exhaustion of low cost fuels. Under the assumptions of the model it thus appears that the long-run outlook for energy prices is favorable, although less favorable than over the last few decades. (The assumption of competitive behavior is clearly unrealistic. A cartel of oil producers would drive up the short-run price. But as Robert Solow has noted, monopolists are the conservationists' best friends: higher prices lead to lower consumption, a stretching out of finite resources, and possibly even lower prices in the future.)

The final and probably the most difficult question concerns the environmental effects of energy use. Up to now, there has been considerable attention given to the "local" environmental problems—especially sulphur emissions from stationary sources and the emission of oxides of nitrogen, carbon monoxide and hydrocarbons from automobiles. Adapting a technology to these new constraints has proved difficult and costly, but there seems to be wide agreement that—with sufficient time and money—emissions can be brought in conformity with any reasonable set of standards (see National Academy of Science Report).

A second set of environmental problems

concerns "global" standards, of which the most prominent is the earth's heat balance. The report on *Man's Impact on the Global Environment* reviews very thoroughly knowledge about the possible adverse global effects of energy consumption. The most important of these for energy were a possible "greenhouse effect" stemming from a large increase in carbon dioxide (CO_2) production from fossil fuels and the problem of global heat balance. Although there is great uncertainty, meteorological studies indicate that a change of two degrees Centigrade in average temperature is the order of magnitude which could trigger "albedo instabilities" leading to melting ice caps or "equator-to-pole ice cover" (Massachusetts Institute of Technology, p. 98). Studies report that such a temperature rise could result from a doubling of atmospheric CO_2 or from net waste heat of around 3 percent of total solar radiation (*MIT*, p. 88). These thresholds are well beyond current levels of human activity. Moreover, our limited supply of fossil fuels limits the production of CO_2 to acceptable levels.

I have performed a rough calculation of the atmospheric concentration of CO_2 along the efficient path described above. Assuming that 10 percent of the atmospheric CO_2 is absorbed annually (G. Skirrow), the concentration would be expected to rise from 340 ppm in 1970 to 487 ppm in 2030—a 43 percent increase. Although this is below the fateful doubling of CO_2 concentration, it may well be too close for comfort.

Waste heat could conceivably be a problem—but not for a while. Energy consumption is currently about 0.003 percent of incident solar energy—a five hundred-fold increase (160 years at a 4 percent annual growth rate) would be environmentally unacceptable.

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