Chapter 5

THE UNCERTAIN FUTURE[1]

History tells us that projections of past trends are not likely to provide reliable forecasts, whether these are projections of price, extraction costs, or user costs. On occasions, such forecasts may turn out to be quite accurate, but this is more a matter of luck than of any true power to discern the future. How then should we proceed? What, if anything, can we say about the future?

An alternative approach, one more likely to produce useful insights, analyzes the important underlying determinants of long-run mineral supply and demand. It is this approach that we pursue here. Though the chapter begins with a brief look at the prospects for shortages over the next several decades, the focus is largely on the long term, a period that begins 50 years from now and stretches into the distant future.

The chapter introduces the cumulative long run supply curve, a useful expository device for categorizing the important determinants of mineral availability. It also distinguishes between what we currently know and what is knowable, and suggests that the two may be different.

[1] This is chapter is based on a public lecture I have given over the years, often to audiences of geologists and earth scientists. It draws as well from Tilton and Skinner (1987) and Tilton (1991).

The Near Term

Over the next 50 years, the world is unlikely to face serious shortages of mineral commodities as a result of resource depletion. While global demand is expected to continue to grow, the reserves for almost all mineral commodities are sufficient to last for at least several decades even at growth rates above those currently prevailing (see Table 3.1). We also know that reserves are not fixed, but are more appropriately thought of as working inventories. By exploration and other means, companies can and do add to reserves over time, and additions to global reserves have in the recent past occurred on a regular basis. This coupled with the stable or falling production costs and prices for many mineral commodities over the past several decades has produced a widespread consensus among the experts that the threat of mineral depletion is not an immediate concern.[2]

Of course, mineral commodity shortages may still arise. Mineral depletion, as Chapter 1 points out, is but one of several factors that can threaten availability. Others include wars, accidents, strikes, political instability, cartels, as well as insufficient investment in new mines and processing facilities. In addition, the markets for mineral commodities are known for their cyclical instability, with shortages and high prices when the world economy is booming, and gluts and low prices when the world economy is depressed. In contrast to mineral depletion, the influence of these market disturbances tends to be temporary, often lasting no more than several years, and rarely more than a decade or two. Nevertheless, over the next 50 years, and probably far into the future, they can be counted on from time to time to cause temporary mineral commodity shortages.

The Long Term

Far less agreement exists among the experts regarding the long-run threat of mineral depletion. On one side of the on-going debate are the pessimists, often ecologists and other scientists and engineers, who are convinced the earth cannot forever support the world's demand for oil and other mineral resources.[3] On the other side are the optimists, often economists, who with equal conviction believe that the earth with the help of market incentives, appropriate public policies, material substitution, recycling, and new technology can satisfy the world's needs indefinitely.[4]

Different Paradigms and Faith in Technology

Just why the experts remain so polarized after decades of discussion and debate is not entirely clear. Part of the explanation lies in the different paradigms that each school tends to employ (Tilton 1996). The pessimists, as Chapter 1 points out, see mineral resources as nonrenewable over any time horizon of relevance to the human race. So supply is a fixed stock that can only diminish with use. Moreover, many believe an expanding population and rising per capita incomes is causing the demand for mineral commodities to grow exponentially, hastening the day when the world's mineral resources will be gone.

The optimists look at resource depletion in an entirely different way. They find the ultimate fixed-stock nature of nonrenewable resource supplies irrelevant, in part

[2] As the quote by Kesler in Chapter 2 indicates, this view, though widespread, is not universal.
[3] Well-known members of the pessimistic school include Kesler (1994), Meadows and others (1972, 1992), Park (1968), and Youngquist (1997).

because the quantities of mineral resources found in the earth's crust could last for millions, and in a number of cases even billions, of years at current rates of consumption (see Table 3.3). Moreover, many nonrenewable mineral commodities—all the metals, for example—are not destroyed when used. The quantity of these resources found in and on the earth's crust is as great today as they have ever been. Moreover, the substitution of abundant and perhaps renewable resources seems quite promising over the long term, particularly for petroleum and other nonrenewable sources of energy.

Finally, and this is a point on which a growing number of pessimists agree, increasing extraction costs and rising prices would cutoff demand long before all of a mineral commodity were completely extracted from the earth's crust. As a result, a growing consensus is emerging among the more informed members of both schools that the fixed stock paradigm should be retired in favor of an alternative that focuses on the opportunity costs of finding and extracting mineral resources.

The opportunity cost paradigm stresses the differences among ore bodies. The easiest-to-find and lowest-cost deposits tend to be exploited first. Over time the depletion of these deposits forces society to turn to lower-grade, more-remote, and more difficult-to-process deposits. This tends to push production costs and mineral commodity prices up, reflecting their growing scarcity. Indeed, if prices rise sufficiently, demand will fall to zero and production will cease even though uneconomic mineral resources remain in the ground. Economic depletion occurs before physical depletion becomes an issue.

Under the opportunity cost paradigm, however, growing scarcity is not inevitable. While depletion is pushing costs up over time, new technology, the discovery of new

[4] Julian L. Simon (1980, 1981) is probably the best known member of the optimistic school. Others include Adelman (1973, 1990) and Beckerman (1995).

low-cost ore bodies, and other developments are pushing them down. If the latter offset the cost-increasing effects of depletion, scarcity may decline and mineral commodity costs and prices may fall. As Chapter 4 documents, this favorable situation has actually prevailed over much of the past.

The optimists realize that the past is not necessarily a good guide to the future, but stress that a rise in mineral commodity prices unleashes a host of countervailing forces. In particular, higher prices strengthen the economic incentives to develop new cost-saving technology, to discover new deposits, to recycle obsolete mineral commodities, and to find less-costly substitutes. Such self-correcting mechanisms, they believe, make the economy much more resilient to the threat of depletion than many suppose.

The optimists also point out that population growth impacts the supply as well as the demand for mineral commodities. While more people promotes the need for mineral commodities, which tends to accelerate depletion and to increase the upward pressure on costs and prices, more people also means more good minds to create the new technologies that will offset the cost-increasing effects of depletion. As a result, population growth is not all bad for resource availability, and may not be bad at all. Julian Simon in *The Ultimate Resource* (1981) argues that only human ingenuity, his ultimate resource, limits economic growth and the welfare of society.

The pessimists on the other hand are well aware that these forces, and in particular new technology, have in the past kept mineral costs and prices from rising. Their concern, however, is for the future. They see the demand for mineral commodities rising rapidly, and question the wisdom of assuming that market incentives and new technology can indefinitely keep mineral scarcity in check. New technology for them is a two-edge sword, to be viewed with some suspicion. While dispensing its largesse (such as lower-cost mineral commodities), it also creates serious problems (such as global warming).

As the debate between the optimists and the pessimists suggests, the availability of mineral commodities over the long run largely depends on a race between the cost-reducing effects of new technology and the cost-increasing effects of resource depletion. While new technology has successfully offset the adverse effects of depletion over the past century, the course of new technology in the future is impossible to predict. This means no one knows for certain the future trends in resource availability. Indeed, one might even be tempted to conclude that they are unknowable. This, however, may be too pessimistic. To illustrate why, we introduce the cumulative supply curve for mineral commodities.

The cumulative supply curve

This curve shows how the total or cumulative supply of oil, lead, or any other mineral commodity varies *over all time* with its price. It differs from the traditional supply curve found in introductory economic textbooks, which shows the quantity of a good offered to the market at various prices *over a specific time period*, such as a month or year. Supply figures provided by the cumulative supply curve are stock variables. Those provided by the traditional supply curve are flow variables, as they can continue from one period to the next indefinitely.

The cumulative supply curve makes sense only for commodities produced from nonrenewable resources. For wheat, automobiles, and many other goods, including renewable resources,[5] cumulative supply is infinite above a price that covers current production costs. For copper and other mineral commodities, however, cumulative supply at a particular price is fixed by the available quantities of the resources from which the commodity can be profitably extracted.

Like the traditional supply curve, the cumulative supply curve assumes that technology and all other determinants of supply, aside from price, remain fixed at their current prevailing levels (or some other specified levels). Exploration and new discoveries can take place, but both exploration technology and understanding of the geological sciences are presumed to remain unchanged.

Since rising prices permit the exploitation of poorer quality, higher cost deposits, the slope of the cumulative supply is positive. The higher the price, the greater cumulative supply. However, as Figure 5.1 illustrates, a variety of different shapes with very different implications for resource availability are consistent with an upward sloping curve. The gradually rising curve in Figure 5.1a favors future availability, as small increases in prices allow large increases in cumulative supply. According to this curve, over time growing demand will evoke at most only modest increases in the costs and prices of mineral commodities. In contrast, the other two curves shown reflect situations where at some point increases in cumulative supply require the exploitation of much more costly deposits, which in turn precipitates a sharp jump in price.

The many factors causing resource availability to change over time fall into three groups. The first group determines the shape of the cumulative supply curve. It encompasses various geological factors, such as the incidence and nature of mineral

[5] This assumes, of course, that the exploitation of renewable resources does not exceed their regeneration capacity.

occurrences. The second group determines how rapidly society advances up the cumulative supply curve. It includes population, per capita income, and other factors that shape the demand for primary mineral commodity production. The third group of factors includes changes in technology and input costs that cause the cumulative supply curve to shift over time.

The first two sets of factors determine the cost-increasing effects of depletion, while the third set of factors reflects the cost-reducing effects of new technology. Whether mineral commodities become more or less available in the future, as we have seen, depends on the relative influence of these three groups of factors on availability. What, if anything, do we know about their likely future evolution?

1. Geological Factors

Whether or not the shape of the cumulative supply curve favors the future availability of mineral commodities depends on the number, size distribution, and nature of mineral occurrences. Lasky (1950a, 1950b) and others assume that the tonnage of ore increases exponentially as the grade decline arithmetically.[6] So if mineral resources containing 1 percent or more copper were sufficient to last for 10 years at current rates of consumption, the resources containing 0.8, 0.5, and 0.3 percent or more copper might be sufficient for 50 years, 200 years, and 1000 years respectively.

This favorable relationship implies a unimodal distribution between the recoverable quantities of copper and grade, similar to that portrayed in Figure 5.2a. Skinner (1976), however, points out that the geochemical processes that cause the formation of mineral deposits long ago are still poorly understood, and do not necessarily guarantee a unimodal relationship between grade (or more generally deposit quality) and the available quantities of any desired mineral commodity. Aside from iron, aluminum, and a few other mineral commodities that make up a significant percentage of the earth's crust, Skinner raises the possibility that the relationship may have two peaks, as portrayed in Figure 5.2b, or multiple peaks.

While the unimodal relationship favors a continuous cumulative supply curve with a decreasing slope over a wide range of quantities and prices, the bimodal curve is more troubling. It implies the cumulative supply curve contains a discontinuity in its slope, as shown in Figure 5.1b, or a steep jump in its slope, as shown in Figure 5.1c, at the point where the high grade deposits are exhausted and much lower grade deposits must be brought into production.

Empirical studies of the relationship between grade and tonnage do exist for a few mineral commodities.[7] However, as Singer and DeYoung (1980) note, the available data for the most part come from operating mines, and so provide little insight into how resource availability varies with grade at grade levels below those currently economic. Since most of the world's future supply of mineral commodities will come from deposits that are uneconomic at the present time, this is a problem. In addition, according to Harris and Skinner (1982), several biases in the available data may exaggerate the negative relationship between grade and tonnage. Indeed, they raise the possibility that the relationship may not be negative. As a result, there is still much we need to know before we can be certain that the availability of mineral resources increases at an increasing rate as grade declines.

---

[6] For an interesting analysis of Lasky's work, see DeYoung (1981).

[7] Singer and others (1975) have examined copper, Foose and others (1980) nickel, and Harris (1977) uranium and copper.

The nature of mineral deposits may also affect the shape of the cumulative supply curve. As depletion occurs, it may be necessary to bring entirely different types of deposits into production, which require a substantial increase in the energy and other inputs to process (Skinner 1976). For example, today the copper found in sulfide ores is concentrated by crushing and flotation before it is smelted and refined. Since smelting and refining are highly energy intensive, this substantially reduces the production costs. Copper is also found in silicate resources, which are not amenable to concentration. Should it eventually become necessary to extract copper from silicate minerals, Figure 5.3 indicates that the energy inputs needed could be as much as 10 to 100 times greater than for sulfide ores. This would cause a sharp rise in processing costs, and a discontinuity or jump in the slope of the cumulative supply curve.

While such mineralogical barriers may hold important implications for the long-run availability of mineral commodities, they have not received a great deal of attention. Little economic incentive exists to analyze such potential problems until the need to use new types of mineral resources actually arises.

2. Demand for Primary Mineral Commodities

The second group of factors we need to examine governs the speed with which society moves up the cumulative supply curve. In this group are the four basic determinants of primary mineral commodity demand—population, real per capita income, intensity of use, and secondary production.

The first three variables determine the total demand for a mineral commodity. Indeed, as equation 5.1 shows, an identity relates the product of these variables to total demand. This follows from the fact that by definition per capita income is total income (Y) divided by population (Pop) and intensity of use is the quantity of a mineral commodity demanded or consumed (Q) divided by income (Y). Therefore:

Total demand = (population) (per capita income) (intensity of use), or

$$Q = Pop \times (Y/Pop) \times (Q/Y) \quad (5.1)$$

Subtracting secondary production from total demand leaves the demand for primary production. The latter summed from the present to any particular year in the future gives the cumulative demand for the commodity over the intervening period, and hence how far up the cumulative supply curve society will advance.

Starting with **population**, let us examine each of these four variables. World population for centuries, even millennia, was both stable and small. As Figure 5.4 shows, it began to grow at an accelerating rate in the 18th century and exploded from 1.7 to 6.1 billion people during the 20th century. However, by the end of the 20th century, the rate of growth was slowing, and a stable world population at slightly above 9 billion people is anticipated by the middle of the 21st century (U.S. Bureau of the Census 2001c).

The decline in population growth has been most pronounced in the developed countries. Rising per capita income tends first to increase life expectancy, stimulating population growth. Eventually, however, as development proceeds the birth rate declines, causing population growth to slow and finally cease. In some developed countries, such as France, population is actually shrinking. In others, only immigration keeps the number of people from falling. In many developing countries, demographers expect population to follow the slowing trends found in the developed countries. As a result, the strong upward push on the demand for mineral commodities that population growth has exerted over the past century will certainly decline and perhaps even cease over the coming century.

While demographers can forecast population over the next 50 to 100 years with some accuracy, projections further into the future are notoriously difficult. Government policies, political stability, pestilence, economic conditions, customs, and human preferences all will influence birth and death rates in the future, but just how is impossible to project with any degree of accuracy more than a century or so into the future.

Per capita income is even more difficult to forecast into the distant future. Economists are still far from fully understanding why some countries have developed rapidly over the past century, while many millions of people remain at or near subsistence poverty in other countries. Social and political institutions, human capital, and open and competitive economies are all widely acknowledged as important. But why these and other favorable conditions arise in some countries and not others, and at certain times but not others, still baffles the experts.

Clearly, if explaining the past is difficult, forecasting when and where, and on what scale, economic development as reflected by the growth in per capita income will take place in the future, is even more of a problem. We simply have little or no idea what the average per capita income for the world will be a hundred years from now, let alone in the more distant future. Developing countries are striving to achieve living standards comparable to those in developed countries. Developed countries, in turn, hope to maintain the growth in per capita incomes they have experienced over the past century.

While these aspirations may or may not be achieved, they do raise the possibility that real per capita income 50 years or more from now could be far above its current level.

Intensity of use reflects the consumption of a mineral commodity, usually measured in physical units, such as barrels of oil or tons of steel, divided by global GDP, measured in dollars or some other monetary unit appropriately discounted over time for inflation. It reflects the demand for mineral commodities per unit of income—the tons of copper consumed, for example, per billion dollars of GDP.

Some years ago, the International Iron and Steel Institute (1972) and Malenbaum (1973, 1978) advanced the hypothesis that the intensity of use for a mineral commodity depends on economic development as reflected by per capita income. Specifically, they argued that very poor countries with little or no development devote most of their efforts to subsistence agriculture and other activities that require minimal use of mineral commodities. Thus, their intensity of mineral use is low. As development takes place, however, their efforts shift to building homes, roads, schools, and hospitals. They begin to construct railroads and steel plants, and to consume first bicycles and then automobiles. Such activities push their intensity of mineral use up. At some point, however, most of these needs are satisfied, and further development leads to another shift in preferences, this time toward education, medical care, and other services that are less mineral intensive.

For these reasons, the intensity of use hypothesis anticipates an inverted U shape relationship, such as that shown by curve C_1 in Figure 5.5, between per capita income and the intensity of use for mineral commodities. This hypothesis has over the years been used as a simple technique for forecasting the future consumption of mineral commodities, but with only partial success. For this and other reasons, it has received considerable criticism. Still, the basic idea that the intensity of mineral use depends on economic development and the changes in consumer preferences it produces seems quite plausible.

Other factors influence intensity of use as well. Government policies (such as increased public funding for defense or education), the introduction of new goods and services (such as computers and mobile phones), shifts in demographics (such as a rise in the retired population), and other considerations (such as the decline in oil prices during the 1980s and 1990s that fostered a rise in the demand for sport utility vehicles and small trucks) can along with changes in economic development produce shifts in consumer preferences. Such changes alter the mix of goods and services produced by the economy or what is called the product composition of income (PCY).

In addition, intensity of use may shift over time as a result of changes in the mineral commodities used to produce particular goods or services, or what is called the material composition of products (MCP). These changes are largely driven by material substitution and resource-saving new technology. For example, the substitution of plastic beverage containers for aluminum cans increases the intensity of use of plastic and reduces the intensity of use of aluminum. Moreover, thanks to new technologies, we now make aluminum beverage cans with far thinner sheet and consequently less metal.

Because many factors affect intensity of use in addition to per capita income and economic development, the inverted U-shaped curve connecting intensity of use with per capita income is not stable, but rather shifts in response to changes in these other factors. Figure 5.5 portrays the intensity of use curve shifting downward over time from C_1 to C_2, to C_3, and so on. As a result, the intensities of mineral use that one actually observes as development occurs reflect various points on different intensity of use curves. These observed points trace out a hybrid curve, such as the heavy black curve shown in Figure 5.5.

The intensity of use curve can shift upward as well as downward. This occurred for aluminum, for example, when that material successfully displaced the tinplate beverage can in the 1970s and 1980s. For two reasons, however, the prevailing tendency at least for the widely used, traditional mineral commodities is for the curve to shift downward. First, resource-saving technology reduces but does not increase intensity of use. Bridges today can be built with far less steel than 50 years ago due to improved steels with far greater strength. New developments that increased the amount of steel required would not be advances and would not be introduced. Second, new technology is constantly developing new materials. Over the past several decades many new plastics, ceramics, and composites, for example, have penetrated the market. For the traditional materials, this means that material substitution, though it may on occasions increase intensity of use, tends on balance to have the opposite effect as new materials capture part of their historical markets.

The same tendencies are found for energy minerals as well. New technology allows automobiles to go further on a gallon of gas, and the use of passive and active solar energy reduces the amount of natural gas and oil needed to heat homes and to provide hot water.

For these reasons, the intensity of mineral use is likely to decline in the future as rising per capita income alters consumer preferences and new technologies affect the use of mineral commodities. This conclusion is reinforced by the available empirical studies (Tilton 1990, U.S. Energy Information Administration 2000), which show the intensity of use for the important metals and energy resources falling over the long run.[8] While this trend is likely to continue, forecasting the magnitude of the decline far into the future is not possible given the host of factors shaping intensity of use trends. Moreover, some determinants, such as the new technologies that will alter future mineral use are simply impossible to anticipate.

Recycling and secondary production cover the last of the four basic determinants of primary mineral commodity demand. While secondary production is not generally relevant for the energy minerals, it is important for many metals. In the United States, for example, the recycling of old scrap currently accounts for some 12, 20, and 61 percent of the domestic consumption of copper, aluminum, and lead respectively (U.S. Geological Survey 2001).

What then can we say about the future of recycling? First, secondary production is ultimately limited by the amount of scrap available for recycling. Since some scrap—lead in lead-based paint, for example—is prohibitively expensive to recycle, this means that secondary production by itself will almost certainly not meet the total future demand for mineral commodities. This would require a decline in demand sufficient to ensure that secondary production could provide all the needed output at costs below those of even the lowest-cost primary producer.

[8] Interestingly, the intensity of use for copper and for a few other metals, both for the United States and for the world as a whole, rose during the 1990s, bucking previous trends (Crowson 1996). Part of the explanation for this surprising development lies in the recent growth in demand for communication and electronic equipment. How long this upward trend will continue, however, is not clear.

Second, and related to this first point, the faster the demand for a mineral commodity grows, the smaller the proportion of total consumption secondary production is likely to provide (Radetzki and VanDuyne 1985). This follows from the fact that the amount of old scrap available for recycling at any point in time depends on the amount of metal consumed in the past, often many years in the past.

Third, secondary metal production is a close substitute for primary production, and so its future is closely tied to trends in primary metal markets. While some scholars (Ayres 1997) contend that the role of secondary production must grow in the future, this conclusion rests on the assumption that primary resources will suffer a decline in availability. If depletion or other factors drive metal prices up, this will increase the demand and output of secondary copper. Alternatively, if new technology more than offsets the adverse effects of depletion causing primary production costs to fall, secondary metal output will decline relative to primary production unless it can reduce its costs at an even greater rate (Tilton 1999).[9]

In short, the bleaker the prospects for primary production, the greater the likely role for recycling, and vice versa. This finding, while comforting in that it suggests that the beneficial impact of recycling increases with society's need, is not particularly helpful for the purpose at hand. It indicates that the amount of recycling in the future will depend on the availability of primary mineral commodities, which is exactly what we are trying to determine by assessing long-run trends in recycling and primary mineral commodity demand.

[9] Of course, public policies that require or subsidize recycling could ensure a bright future for secondary production even though primary production is cheaper. Chapter 7 examines the role of public policy in fostering recycling.

This brief tour of the four basic determinants of the demand for primary mineral commodities suggests that over the next century population growth will slow and probably stabilize, real per capita income barring a major catastrophe will continue its upward climb, intensity of use will likely persist in its long-run decline, and recycling will account for a portion—perhaps a growing portion, perhaps a declining portion—of the world's consumption of major metals.

While this is of some interest, we unfortunately have no clear picture of the net effect over the coming century of these conflicting influences, and thus how rapidly the world will move up the cumulative supply curve. Moreover, the view becomes even more opaque as we venture further into the future.

3. Technology and Input Costs

Finally, we turn to the forces—changes in technology and input costs—that cause the cumulative supply curve to shift. Having seen that new technology on the demand side, which affects the use of mineral commodities, influences the speed with which society ascends the cumulative supply curve, we now focus on changes in technology that influence production costs and in turn the supply of mineral commodities.

Such new technology shifts the cumulative supply curve downward. If this were not the case, it would increase rather than reduce production costs, and so would not be adopted. Changes in input cost, on the other hand, can move the curve in either direction.

Labor, mineral reserves, capital, energy, and materials are the crucial inputs for most mineral commodities. Over the past century, the real cost of labor, at least in the United States and other developed countries, has risen greatly, largely accounting for the dramatic improvements these countries have enjoyed in their standard of living. This has exerted upward pressure on the cumulative supply curve. The available estimates for the value of mineral resources in the ground (user costs), reviewed in Chapter 4, though not entirely consistent indicate that the price of obtaining new reserves either by exploration or purchase has remained stable or perhaps fallen. Prices for the other three inputs have varied, at times rising and at other times declining.

While these changes are important, new technology has in the past dwarfed their impact on the cumulative supply curve. Barnett and Morse (1963), Simon (1981), and many of the other writers whose works are reviewed in earlier chapters stress the important role that new technology has played in reducing costs and increasing availability. In addition, the literature is filled with examples of important new technologies affecting mining and energy production in general as well as individual mineral commodities in particular.[10] Horizontal drilling for oil and gas, solvent-extraction electrowinning for copper, high pressure acid leach for nickel, longwall mining for coal, electric furnaces and minimills for steel, larger trucks and shovels, bigger and faster drills, satellite imagining for exploration, and computer controlled operations are but a few of the better known, new techniques that are making it easier and cheaper to produce mineral commodities.

It is, however, far easier to assess the impact of new technology in the past than to forecast its future effects. Indeed, projecting new technology is notoriously difficult even over the near term. Looking out 50 years and further into the future is simply impossible. We know the development and introduction of new technologies will continue, but we simply have no way to measure reliably their likely impact on production costs in the distant future.

Prospects for Resource Availability

Future trends in resource availability, we have seen, will depend largely on the outcome of the cost-increasing effects of depletion and the cost-reducing effects of new technology. On the positive side, the availability of mineral commodities is not likely to become a problem over the near term, the next half century.

Over the long run, should mineral depletion cause shortages, they are likely to emerge gradually, perhaps over decades, as the real prices and costs of mineral commodities rise slowly but persistently. In this respect, shortages due to depletion are quite different from the abrupt but temporary shortages produced by wars, cartels, strikes, natural disasters, insufficient investment, and economic cycles. We also know that shortages from depletion, should they occur, will restrict the use of mineral commodities by raising their real prices. As a result, the world is not likely literally to run out of mineral commodities.

Moreover, even in the long run depletion is not inevitable, at least on any time scale of relevance to humanity. The future could conceivably be like the past, and enjoy growing rather than declining availability of mineral commodities. Past trends, however, cannot be counted on to continue indefinitely.

---

[10] For a sample of such studies, see Bohi (1999) for petroleum, Darmstadter (1999) for coal, Manners (1971) for iron ore, Barnett and Crandall (1986) for steel, Tilton and Landsberg (1999) for copper, and the National Research Council (1990, 2001) for the mining industry in general.

Our efforts to assess long-run prospects on the basis of the fundamental factors influencing the supply and demand for mineral commodities came up wanting. While providing some interesting insights, they encountered too many unknowns to make useful projections much beyond the next several decades.

So the central question remains unanswered. We simply do not know whether future trends in resource availability will foster or thwart the desires of people around the globe to improve their standard of living. Those who claim to have an answer to this question, and as we have seen quite a few can be counted on both sides of the issue, explicitly or implicitly rest their claims on debatable assumptions, and in particular on assumptions about the future course of technology.

If the distant future is unknown, largely as a result of the impossibility of forecasting new technology, does this mean that the future is also unknowable? This query brings us back the cumulative supply curve, and raises two questions. Is it possible to assess the shape of this curve for individual mineral commodities? And if so, is it worthwhile?

The answer to the first question is presumably yes. The necessary information, as pointed out earlier, entails geologic data on the number, nature, and size of mineral deposits that exist in the earth's crust. Already considerable information exists for economic deposits (that is, deposits that are currently profitable to exploit), which provides some knowledge about the shape of the lower end of the cumulative supply curve. Understandably much less information is available for sub-economic deposits, since exploration companies and other private entities have few economic incentives to acquire knowledge about such deposits. Presumably, however, this information could be obtained if society were sufficiently concerned about future resource scarcity to foot the bill and so provide the needed incentives. This would provide a clearer picture of the cumulative supply over a much wider range of ore grades and prices.

The answer to the second question is definitely yes. Mineral commodities whose cumulative supply curves rise gradually with no discontinuities or sharp upturns (and so are similar to the curve shown in Figure 5.1a) are unlikely to suffer from significant scarcity even if their demand expands rapidly and technological change is ineffective in reducing their costs. In contrast, mineral commodities whose cumulative supply curves contain discontinuities or sharply rising segments are much more prone to scarcity.

In short, while the future availability of mineral commodities beyond the next 50 years is unknown, it may not be unknowable. While the difficulties of forecasting technological change and its impacts into the distant future make it impossible to determine how quickly society will move up the cumulative supply curve or how much the curve will shift downward, much can be learned about the shape of the curve. If society is concerned about mineral scarcity, investing in the geologic information that determines the shape of the cumulative supply curve would provide many useful insights on the threat that depletion poses over the long term.

References

Adelman, M. A. (1973). The World Petroleum Market. Baltimore, Johns Hopkins for Resources for the Future.

Adelman, M. A. (1990). "Mineral depletion, with special reference to petroleum." Review of Economics and Statistics 72(1): 1-10.

Ayres, R. U. (1997). Metals recycling: economic and environmental implications. Third ASM International Conference, Barcelone, Spain, ASM International.

Barnett, D. F. and R. W. Crandall (1986). Up From the Ashes: The Rise of the Steel Minimill in the United States. Washington, DC, Brookings Institution.

Beckerman, W. (1995). Small Is Stupid. London, Duckworth.

Bohi, D. R. (1999). Technological improvement in petroleum exploration and development. Productivity in Natural Resource Industries. R. D. Simpson. Washington, DC, Resources for the Future: 73-108.

Crowson, P. C. F. (1996). Metals demand and economic activity: some recent conundra. 1996 Proceedings of the Mineral Economics and Management Society Fifth Annual Professional Meeting. Henry N. McCarl. Montreal, Quebec: 28-42.

DeYoung Jr., J. H. (1981). "The Lasky cumulative tonnage-grade relationship--a reexamination." Economic Geology 76: 1067-1080.

Foose, M. P. and others (1980). The Distribution and Relationships of Grade and Tonnage Among Some Nickel Deposits. Washington, DC, U.S. Geological Survey.

Harris, D. P. (1977). Mineral Endowment, Resources, and Potential Supply: Theory, Methods for Appraisal, and Case Studies. Tucson, AZ, Minresco.

Harris, D. P. and B. J. Skinner (1982). The assessment of long-term supplies of minerals. Explorations in Natural Resource Economics. V. K. Smith and J. V. Krutilla. Baltimore, Johns Hopkins for Resources for the Future: 247-326.

International Iron and Steel Institute (1972). Projection 85: World Steel Demand. Brussels, International Iron and Steel Institute.

Kesler, S. E. (1994). Mineral Resources, Economics and the Environment. New York, Macmillan.

Lasky, S. G. (1950a). “Mineral-resource appraisal by the U.S. Geological Survey.” Colorado School of Mines Quarterly 45(1A): 1-27.

Lasky, S. G. (1950b). “How tonnage and grade relations help predict ore reserves.” Engineering Mining Journal 151(4): 81-85.

Malenbaum, W. (1973). Material Requirements in the United States and Abroad in the Year 2000, Research project prepared for the National Commission on Materials Policy. Philadelphia, University of Pennsylvania.

Malenbaum, W. (1978). World Demand for Raw Materials in 1985 and 2000. New York, McGraw-Hill.

Manners, G. (1971). The Changing World Market for Iron Ore, 1950-1980. Baltimore, Johns Hopkins for Resources for the Future.

Meadows, D. H. and others (1972). The Limits to Growth. New York, Universe Books.

Meadows, D. H. and others (1992). Beyond the Limits. Post Mills, VT, Chelsea Green Publishing.

National Research Council (2001). Evolutionary and Revolutionary Technologies for Mining. Washington, DC, National Academy Press.

National Research Council (1990). Competitiveness of the U.S. Minerals and Metals Industry. Washington, DC, National Academy Press.

Park Jr., C. F. (1968). Affluence in Jeopardy: Minerals and the Political Economy. San Francisco, Freeman, Cooper and Company.

Radetzki, M. and C. Van Duyne (1985). “The demand for scrap and primary metal ores after a decline in secular growth.” Canadian Journal of Economics 18(2): 435-449.

Simon, J. L. (1980). “Resources, population, environment: an oversupply of false bad news.” Science 208: 1431-1437.

Simon, J. L. (1981). The Ultimate Resource. Princeton, NJ, Princeton University Press.

Singer, D. A. and others (1975). Geology and Resources of Copper Deposits. Washington, DC, Government Printing Office for the U.S. Geological Survey.

Singer, D. A. and J. H. DeYoung Jr. (1980). “What can grade-tonnage relations really tell us?” Resources Minerales, Memoire du BRGM no. 106.

Skinner, B. J. (1976). “A second iron age ahead?” American Scientist 64: 158-169.

Tilton, J. E., Ed. (1990). World Metal Demand: Trends and Prospects. Washington, DC, Resources for the Future.

Tilton, J. E. (1991). “The changing view of resource availability.” Economic Geology (Monograph 8): 133-138.

Tilton, J. E. (1996). “Exhaustible resources and sustainable development: two different paradigms.” Resources Policy 22(1 and 2): 91-97.

Tilton, J. E. (1999). “The future of recycling.” Resources Policy 25: 197-204.

Tilton, J. E. and H. H. Landsberg (1999). Innovation, productivity growth, and the survival of the U.S. copper industry. Productivity in Natural Resource Industries. R. D. Simpson. Washington, DC, Resources for the Future: 109-139.

Tilton, J. E. and B. J. Skinner (1987). The meaning of resources. Resources and World Development. D. J. McLaren and B. J. Skinner, John Wiley & Sons: 13-27.

U.S. Bureau of the Census (2001a). Historical Estimates of World Population. http://www.census.gov/ipc/www/worldhis.html.

U.S. Bureau of the Census (2001b). The World Population from 1950 to 2050, Global Statistics 2001. http://www.xist.org/global/hist3.htm.

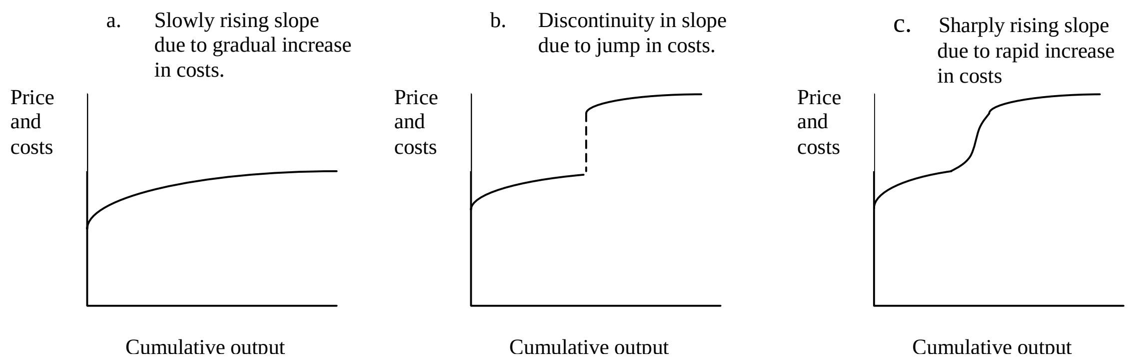
U.S. Bureau of the Census (2001c). World Population Information. http://www.census.gov/ipc/www/world.html.

U.S. Energy Information Administration (2000). Annual Energy Outlook 2001 With Projections to 2020. Washington, DC, Government Printing Office.

U.S. Geological Survey (2001). Mineral Commodity Summaries 2001. Washington, DC, Government Printing Office.

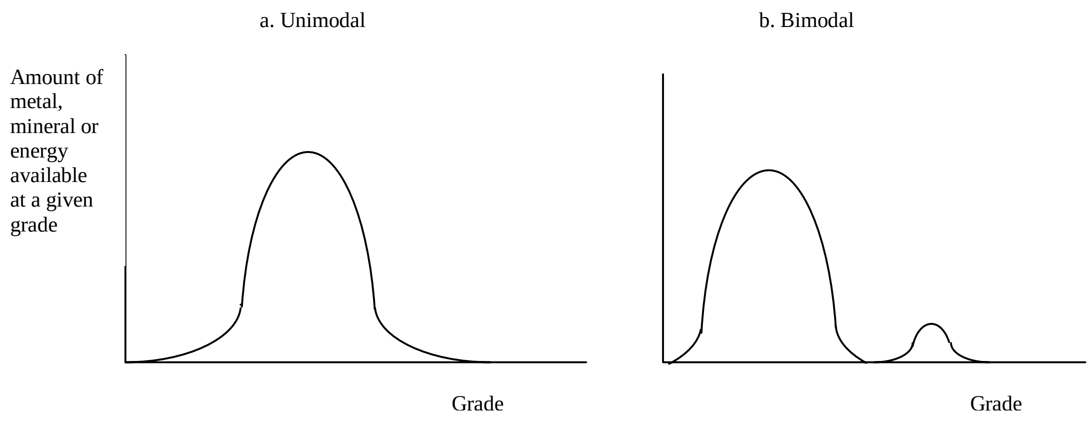
Youngquist, W. (1997). GeoDestinies. Portland, OR, National Book.

Figure 5.1. Illustrative Cumulative Supply Curves



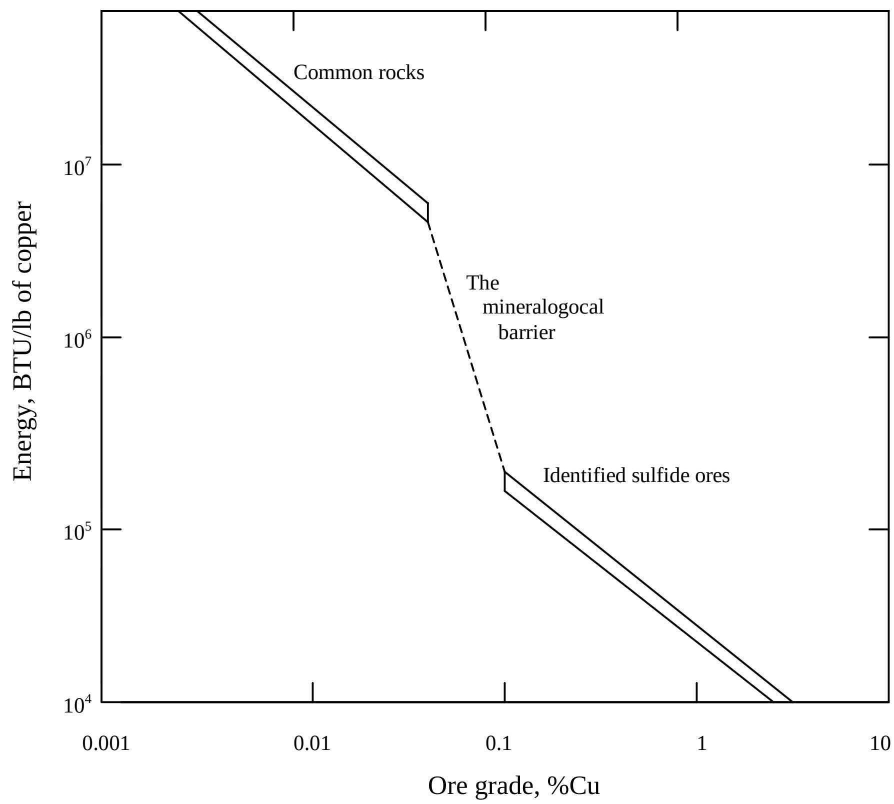
Source: Tilton and Skinner (1987).

Figure 5.2. Two Possible Relationships Between Ore Grade and the Metal, Mineral, or Energy Content of the Resource Base



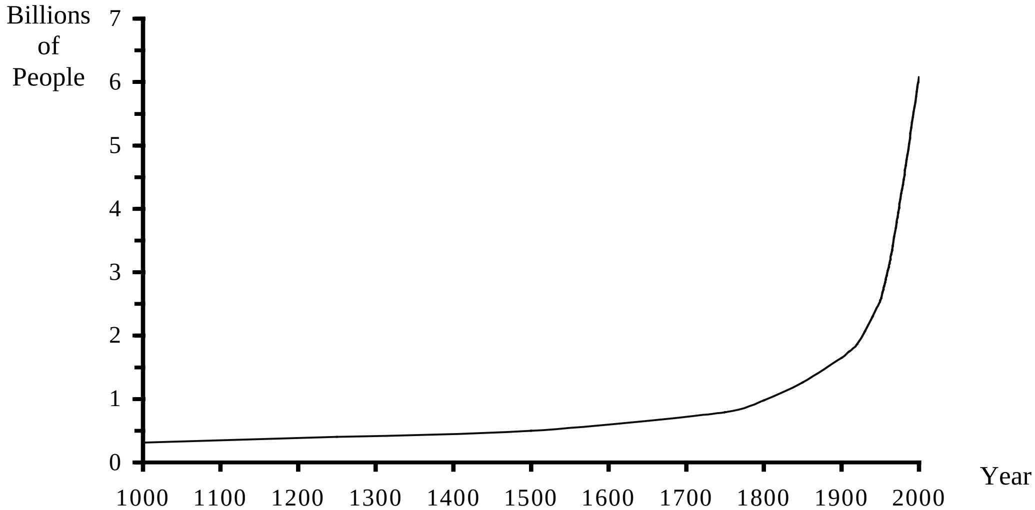
Source: Skinner (1976).

Figure 5.3. Energy Required per Pound of Copper From Sulfide Ore and Common Silicate Rock



Source: Skinner (1976).

Figure 5.4. World Population, 1000-2000



Sources: U.S. Bureau of the Census (2001a and 2001b).

Figure 5.5. Intensity of Use Curves