Wealth Creation in the Minerals Industry: Integrating Science, Business, and Education

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Chapter 3
Depletion and the Long-Run Availability of Mineral Commodities

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Abstract
The debate over the long-run availability of mineral commodities remains as polarized today as it was 30 years ago for three reasons. First, two different paradigms are used to assess the threat, which can lead to sharply contrasting conclusions. Second, the uncertainties regarding future changes in mineral supply and demand, which will govern the course of real mineral prices, are great. The geologic unknowns are particularly a problem in this regard. Finally, mineral commodity prices reflect only those social costs that producers pay. Just how much greater prices would be—and how their trends over time would be altered—if prices reflected all the costs of production and use is unknown. The available estimates vary greatly, and often reflect the values of individuals and groups rather than those of society as a whole. In light of the last two uncertainties, we simply do not know whether mineral commodities will become more or less available in the long run.

While this is disappointing, there is much we have learned about the nature of the threat from mineral depletion and its implications over the past several decades. For example, the world will not as a result of depletion abruptly run out of mineral commodities the way a car runs out of gas. If depletion creates problems, it will do so slowly over many years by persistently pushing real prices higher, and in the process making mineral commodities too expensive to use in one end use after another. We also know that this pessimistic scenario is not inevitable. If the cost-reducing effects of new technology more than offset the cost-increasing effects of depletion, mineral commodities will be more available a century hence, not less. Given the uncertainties, especially in forecasting technological change, we cannot predict with certainty the outcome between these two competing forces. However, a better understanding of the nature and incidence of mineral deposits that are, at present, subeconomically could provide useful insights.

Introduction
Concern over the adequacy of natural resources dates back at least two centuries to the writings of the classical economists. Indeed, Thomas Malthus remains well known today for his dismal prediction that population growth, coupled with limits on the availability of agricultural land, would ultimately cause the human condition to sink to the subsistence level.

The most recent wave of concern emerged in the early 1970s, thanks in part to the widely read book, Limits to Growth (Meadows et al., 1972). Using a computer simulation model, this book raised the possibility that mineral exhaustion will, by the middle of this century, cause the collapse of the high living standards that prevail today, especially in the developed world. For many, the jump in resource prices—the result of a simultaneous economic boom in the industrial countries, and in the case of oil, the collusive activities of the Organization of Petroleum Exporting Countries (OPEC)—that followed on the heels of Limits to Growth provided support for its dire predictions.

Others, however, took issue with both the book’s methodology and its conclusions, and a lively debate ensued that continues to the present. At one end of the spectrum are the pessimists, often geologists and other physical scientists faced with finding new supplies, who fear that resource depletion—in particular, the depletion of oil—poses a serious problem. Ayres (1993), Kesler (1994), and Defeyters (2001, 2005) are examples of contemporary scholars who fall within this camp. At the other end of the spectrum are the optimists, often economists (in spite of the discipline’s reputation as the dismal science), who see no threat, even in the distant future. Simon (1981), Lomborg (2001), and Beckerman (2003) belong to this camp.

Over time, the nature of the debate has shifted somewhat, as many pessimists have focused more on the external costs associated with the production and use of mineral commodities, especially the damage to the environment, and less on their actual availability. The social costs, they contend, will limit the future use of mineral commodities, even if availability is not an issue.

Still, the central question remains: Will mineral depletion ultimately threaten the welfare of humanity by unraveling the resource underpinnings of modern civilization? The pages that follow contend that, given the uncertainties examined, no one knows the answer to this question. Those who argue otherwise are asking the rest of us to accept their faith, or lack of faith, that technology will continue in the future to offset the adverse effects of mineral depletion.

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This study first focuses on the three main reasons why the debate remains so polarized despite the many opportunities enjoyed by the two competing camps—pessimists and optimists—to exchange views. It then concludes by examining what has been learned—where there is growing consensus among the informed participants in the debate—and the implications for society and public policy.

**Different Paradigms**

Most people use one of two mental models to assess the threat of mineral depletion. The first we call the fixed stock paradigm, the second the opportunity cost paradigm. These models have quite different implications for the nature of the depletion process.

The fixed stock paradigm starts with the self-evident observation that the earth is finite. This means that the supply of any mineral commodity must also be finite, and hence is a fixed stock. The demand for oil and other mineral commodities, however, is a flow variable. It continues year after year after year. So it is only a question of time before demand consumes the available supply. Moreover, if demand is growing exponentially, as has been the case at times for many mineral commodities, the end is likely to come sooner rather than later due to the tyranny of exponential growth.

This, for example, is the view of depletion found in *Limits to Growth*, and in the works of Hubbert (1962, 1969) and his successors (Campbell, 1997; Deffeyes, 2001, 2005). The human race is like a colony of mice that has had the good fortune to inherit a huge block of cheese. Today it is fat, happy, and multiplying. But the day must come when the cheese is gone, the cupboard is bare, and starvation looms.

Under the fixed stock paradigm, one may see the remaining stocks declining, but the actual transition from resource availability to scarcity is abrupt and sudden and so, given society's myopia, is likely to come as a surprise. Mineral consumption accelerates the day of reckoning. The more we consume now, the sooner we run out. This means that both population growth and the profligate use of mineral commodities, particularly in the developed world, undermine the long-run availability of mineral commodities.

Proponents of the fixed stock model of depletion often attempt to estimate the remaining life expectancies for various mineral commodities. Such calculations require some assessment of both the available stock and its exploitation or consumption in the future. At one extreme, the available stock is measured by reserves, which by definition indicate the amount of a mineral commodity, such as oil or copper, found in fields or deposits that are both known and profitable to exploit given current technology and prices. Table 1 shows the life expectancies of the existing reserves for oil, copper, and a number of other mineral commodities, assuming that their primary production expands in the future at 0, 2, and 5 percent a year. These three rates bracket the actual average annual growth since 1975 for all of the commodities considered with the exception of tin and lead, which have in recent decades experienced negative growth. While the estimated life expectancies shown in Table 1 are not terrible comforting—varying from a high of 203 years to a low of 10 years—it is well known that reserves are not actually a fixed stock. New discoveries and the development of new technologies that permit the profitable exploitation of previously uneconomic resources are constantly adding to reserves, undermining the significance one can attach to reserve life expectancies for the long-run availability of mineral commodities.

At the other extreme, the available stock can be measured by the resource base, which by definition reflects all of a mineral commodity contained in the earth's crust. Of course, one could question whether reserves and the resource base were necessarily the two extremes of the available stock of a mineral commodity, since some reserves may ultimately prove uneconomic to exploit owing to future government regulations or other developments, and since the resource base excludes possible production in the future from below the earth's crust and from the moon, near-earth asteroids, and other extraterrestrial bodies. Despite such caveats, it seems reasonable to assume that the available stock of a mineral commodity is greater than its reserves and less than its resource base.

Table 2 shows the life expectancies of the resource base for various mineral commodities, again assuming that primary production grows in the future at an annual rate of 0, 2, and 5 percent. These results are more comforting. Indeed, at current production rates, the resource base would last for literally millions and in some cases for even billions of years for those mineral commodities for which we have reliable estimates of the resource base. Still, when primary production is allowed to grow at 2 and 5 percent, these huge figures drop to hundreds and thousands of years, again illustrating the tyranny of exponential growth. If reserve life expectancies are too low, those for the resource base are presumably too high, since society is unlikely to chew up the entire earth's crust in its quest for mineral commodities.

At a more fundamental level, however, the fixed stock paradigm, despite its logic and intuitive appeal, suffers from several serious shortcomings. First, many mineral commodities, especially the metals, are not destroyed when they are consumed. As a result, recycling and reuse are possible. Of course, recycling in some cases (such as the lead once used as an additive in gasoline) is prohibitively expensive, but this is a question of costs, not of actual physical availability.

Second, with few exceptions, society does not need natural resources as such, but rather the functions they fulfill. So for many mineral commodities, and in particular the energy minerals, substitution may alleviate the threat of mineral depletion. Coal, natural gas, petroleum, nuclear, hydropower, geothermal, wind, and solar energy can all be used to generate electric power. The mix of resources employed at any particular time reflects their costs. If depletion drives the costs of some energy sources up, society will rely more on the alternatives.

Third, as we have just seen, the amount of many mineral commodities found in the earth's crust is quite large. For example, as Table 2 notes, the copper and aluminum esti-
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Table 1. Life Expectancies of World Reserves for Selected Mineral Commodities

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<tr>
<td></td>
<td>2001–2003 reserves</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Coal</td>
<td>$9.8 \times 10^{11}$</td>
<td>$4.8 \times 10^{9}$</td>
<td>203</td>
</tr>
<tr>
<td>Crude oil</td>
<td>$1.1 \times 10^{12}$</td>
<td>$2.8 \times 10^{10}$</td>
<td>40</td>
</tr>
<tr>
<td>Natural gas</td>
<td>$6.3 \times 10^{15}$</td>
<td>$9.0 \times 10^{13}$</td>
<td>161</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$2.3 \times 10^{10}$</td>
<td>$1.4 \times 10^{8}$</td>
<td>34</td>
</tr>
<tr>
<td>Copper</td>
<td>$4.7 \times 10^{8}$</td>
<td>$1.4 \times 10^{6}$</td>
<td>22</td>
</tr>
<tr>
<td>Iron</td>
<td>$7.0 \times 10^{10}$</td>
<td>$1.1 \times 10^{8}$</td>
<td>46</td>
</tr>
<tr>
<td>Lead</td>
<td>$6.7 \times 10^{7}$</td>
<td>$3.0 \times 10^{5}$</td>
<td>14</td>
</tr>
<tr>
<td>Nickel</td>
<td>$6.2 \times 10^{7}$</td>
<td>$1.4 \times 10^{5}$</td>
<td>14</td>
</tr>
<tr>
<td>Silver</td>
<td>$2.7 \times 10^{6}$</td>
<td>$1.9 \times 10^{4}$</td>
<td>27</td>
</tr>
<tr>
<td>Tin</td>
<td>$6.1 \times 10^{6}$</td>
<td>$2.3 \times 10^{4}$</td>
<td>25</td>
</tr>
<tr>
<td>Zinc</td>
<td>$2.2 \times 10^{6}$</td>
<td>$8.7 \times 10^{4}$</td>
<td>25</td>
</tr>
</tbody>
</table>

Sources: Updated from table 3.1 in Tilton (2003b); U.S. Geological Survey (annual); U.S. Energy Information Administration (annual)

1 For the metals other than aluminum, reserves are measured in terms of metal content; for aluminum, reserves are measured in terms of bauxite ore
2 Reserves and primary production are measured in metric tons except for crude oil (measured in barrels) and natural gas (measured in cubic feet)
3 Life expectancy figures were calculated before reserve and average production data were rounded; as a result, the life expectancies shown in columns 4, 5, and 6 may deviate from the life expectancies derived from the reserve data shown in column 2 and the average annual primary production data shown in column 3

Table 2. Life Expectancies of the Resource Base for Selected Mineral Commodities

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<tr>
<td></td>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Coal</td>
<td>n/a</td>
<td>$4.8 \times 10^{9}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Crude oil</td>
<td>n/a</td>
<td>$2.8 \times 10^{10}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Natural gas</td>
<td>n/a</td>
<td>$9.0 \times 10^{13}$</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$2.0 \times 10^{18}$</td>
<td>$1.4 \times 10^{6}$</td>
<td>$1.1 \times 10^{8}$</td>
<td>$756$</td>
</tr>
<tr>
<td>Copper</td>
<td>$1.5 \times 10^{15}$</td>
<td>$1.4 \times 10^{7}$</td>
<td>$1.1 \times 10^{8}$</td>
<td>$860$</td>
</tr>
<tr>
<td>Iron</td>
<td>$1.4 \times 10^{18}$</td>
<td>$1.1 \times 10^{9}$</td>
<td>$9.7 \times 10^{7}$</td>
<td>$750$</td>
</tr>
<tr>
<td>Lead</td>
<td>$2.9 \times 10^{14}$</td>
<td>$3.0 \times 10^{6}$</td>
<td>$1.6 \times 10^{8}$</td>
<td>$521$</td>
</tr>
<tr>
<td>Nickel</td>
<td>$2.1 \times 10^{12}$</td>
<td>$1.4 \times 10^{6}$</td>
<td>$9.5 \times 10^{7}$</td>
<td>$728$</td>
</tr>
<tr>
<td>Silver</td>
<td>$1.8 \times 10^{12}$</td>
<td>$1.9 \times 10^{6}$</td>
<td>$1.8 \times 10^{8}$</td>
<td>$762$</td>
</tr>
<tr>
<td>Tin</td>
<td>$4.1 \times 10^{13}$</td>
<td>$2.5 \times 10^{6}$</td>
<td>$2.5 \times 10^{8}$</td>
<td>$778$</td>
</tr>
<tr>
<td>Zinc</td>
<td>$2.2 \times 10^{13}$</td>
<td>$8.7 \times 10^{6}$</td>
<td>$2.5 \times 10^{8}$</td>
<td>$778$</td>
</tr>
</tbody>
</table>

Sources: Updated from table 3.2 in Tilton (2003b); data on the resource base are based on information in Erickson (1978, p. 22–25) and Lee and Yao (1970, p. 778–786); figures for the 2001–2003 average annual production and the annual percentage growth in production for 1975–2003 are from Table 1 and the sources cited there

1 The resource base for a mineral commodity is calculated by multiplying its average elemental abundance per metric ton times the total weight ($24 \times 10^{14}$) in metric tons of the earth's crust; it reflects the quantity of that material present in the earth's crust
2 Estimates of the resource base for coal, crude oil, and natural gas do not exist; as a result, data for the resource base and life expectancies for these commodities are not available (n/a); the U.S. Geological Survey and other organizations do provide assessments of ultimate recoverable resources for oil, natural gas, and coal; while these are at times referred to as estimates of the resource base, they do not attempt to measure all the coal, oil, and natural gas found in the earth's crust; as a result, they are more appropriately considered as resource estimates than assessments of the resource base

mated to exist in the earth’s crust would last 110 million and 14 billion years, respectively, at current rates of production. These are big numbers. Homo sapiens as a species has existed for only several hundred thousand years.

Fourth, and perhaps most important, long before the last barrel of oil or ton of copper is extracted from the earth’s crust, costs would rise, at first curtailing but eventually completely eliminating demand. In short, what we have to fear is not physical depletion, where we literally run out of mineral resources, but economic depletion, where the costs of producing and using mineral commodities rise to the point where they are no longer affordable.

For these reasons, there is growing interest in the second perspective or model of depletion, the opportunity cost
paradigm. It assesses the availability of mineral commodities by considering what society has to give up in order to obtain another barrel of oil or another ton of copper. Several measures can be used for estimating these opportunity costs, including extraction costs and the value of identified mineral reserves in the ground, but the most widely available and reliable is real price (that is, the price adjusted for inflation) for mineral commodities. When its real price is rising over the long run, a commodity is becoming less available or scarcer.

How we consider depletion matters. With the opportunity cost paradigm, depletion over time reflects the exploitation of poorer quality deposits, which tends to drive up the real prices of mineral commodities. However, this upward pressure can be partially or totally offset by new technologies and other innovations that reduce the cost of finding and producing mineral commodities. With the fixed stock paradigm, depletion is inevitable. While new technology may permit the exploitation of poorer quality deposits, it is just a matter of time before the given stocks of varying quality run out.

Despite the shortcomings of the fixed stock paradigm, its simple intuitive logic continues to attract adherents. This, then, is the first reason why the debate between the pessimists and optimists continues. The second reason arises because expectations vary greatly regarding the future course of mineral demand and the ability of mineral producers to meet this demand.

Mineral Supply and Demand

A convenient way to consider how the various supply and demand factors might govern the future course of mineral prices is the cumulative supply curve. This curve, illustrated in Figure 1 and described more fully elsewhere (Tilton and Skinner, 1987; Tilton, 2003b), shows how the total amount of oil, copper, or any other mineral commodity that producers will offer to the market over all time varies with its real price. As the price of copper, for example, rises from 50 cents to 5 dollars a pound, poorer quality deposits can be profitably exploited, and the total amount of copper that can be economically mined from the earth’s crust increases. Thus, the curve rises monotonically with price, as all three of the curves shown in Figure 1 illustrate.

The cumulative supply curve, it should be noted, differs from the traditional supply curve found in every introductory economics textbook. The textbook curve shows how the supply of a good varies with price over a given period, such as a month or year. Supply, in this case, is a flow variable that can continue indefinitely from one period to the next. Cumulative supply, on the other hand, is a stock variable, in the sense that it shows how much of a mineral commodity is economically available over all time at various prices. The concept of cumulative supply makes sense only for nonrenewable resources. For renewable resources such as wheat or fish, for example, there is no reason why supply cannot continue indefinitely into the future as long as production during any particular period does not exceed the level that allows the resource to replenish itself.

The cumulative supply curve, like the traditional supply curve, assumes that with the exception of price all the determinants of supply (such as the costs of labor and other inputs) remain fixed at current or given levels. Exploration, new discoveries, and the development of new mines can take place, but technology, including exploration technology, is assumed to remain unchanged.

The many factors that influence long-run trends in mineral commodity prices can be separated into three groups. The first includes the incidence and nature of mineral deposits along with other geologic considerations, and determines the shape of the cumulative supply curve. The second group contains those variables that determine the demand over time for mineral commodities, such as the level and growth of population, trends in per capita income, and changes in consumer preferences. These variables affect the speed at which society moves up the cumulative supply curve. The third group contains those variables that cause the cumulative supply curve to shift over time. Changes in wage rates and other input costs belong to this group, but over the long run technological change, which pushes the curve down, has been by far the most important of these factors, and probably will continue to be so in the future.

The first two groups determine the cost-increasing effects of depletion, the last the cost-reducing effects of new technology. The availability of mineral commodities, as a result, will increase over the long run if the tendency for mineral prices to rise as society moves up the curve is more than offset by downward shifts in the curve. Why do the optimists believe this will be the case? Why are the pessimists skeptical?

Though well aware that past trends need not continue indefinitely, the optimists note that technological change has been for some time successful in offsetting the cost-increasing effects of mineral depletion (Barnett and Morse, 1963; Krautkraemer, 1998; Howie, 2002). Moreover, this success has occurred over a century (the twentieth century) when mineral resource use exploded as a result of population growth and rising per capita incomes in the developed countries.

The optimists point out that population growth is slowing. Demographers now believe that the world’s population, currently between 6 and 7 billion, could peak at slightly above 10 billion around 2200 (United Nations, July 28, 2005, http://www.un.org/esa/population/publications/sixbillion/sixbilkpart1.pdf). They also highlight the tendency for the intensity of energy and material use (that is, the quantity used per real million dollars of gross domestic product or GDP) to decline over time (Tilton, 1990), which should offset at least in part some of the anticipated effects on mineral demand of growth in per capita income.

Optimists stress, furthermore, the robustness of the marketplace. They point out that any tendency for depletion to drive mineral commodity prices up unleashes powerful forces that mitigate scarcity—more exploration for undiscovered and lower grade deposits, more development of new sources of supply, more substitution toward abundant resources, more recycling, and more conservation. Of even
greater importance, especially over the long term, higher prices increase the expected returns to new technologies that reduce production costs, at times by exploiting completely new sources of supply, and as well the expected returns to new technologies that reduce consumption.

The pessimists have far less confidence in the marketplace and the development of new technology; they believe it irresponsible to assume that new technology will forever offset the cost-increasing effects of mineral depletion. In the shorter run, they worry about a 50 percent plus increase in world population over the next century, and surging mineral demand in China and elsewhere in the developing world.

Whether the future conforms more closely to the expectations of the optimists or the pessimists will likely depend on the shape of the cumulative supply curve. The curve shown in Figure 1a suggests that as cumulative production proceeds over time, the price needed to elicit additional supply increases but at a decreasing rate. If this is the true shape of the curve, then new technology should find it increasingly easy to offset the cost-increasing effects of depletion, lending support to the optimists. However, some geologists suggest that the true cumulative supply curve may be far less benevolent than the one shown in Figure 1a.

In particular, Skinner (Skinner, 1976; Gordon et al., 1987) notes that nine elements (oxygen, silicon, aluminum, iron, calcium, magnesium, sodium, potassium, and titanium) together account for 99 percent of the weight of the earth's crust. While the cumulative supply curves for the metals in this group may follow the benign pattern shown in Figure 1a, he believes that the cumulative supply curves for copper, lead, tin, zinc, and many other metals may possess sharply rising slopes or even discontinuities over certain segments. Figure 1b and c illustrates cumulative supply curves with one jump or discontinuity. The curves for some mineral commodities might, of course, have multiple jumps or steps.

Skinner suggests that such jumps or steps occur because the geochemical processes creating mineral deposits millions of years ago are unlikely to have produced a unimodal relationship between the grade and quantity of available metal, such as that shown in Figure 2a. Rather, he contends, this relationship is likely to possess two or more peaks, as shown in Figure 2b. Thus, once the higher grade deposits are exploited, society must use much lower grade, and so much more costly, deposits for additional supplies.

In addition, the processing methods required to liberate the copper and other metals in very low grade deposits will be quite different from those in use today. In particular, mechanical and chemical processes for concentrating the ore mineral before treatment will not be feasible. In this case, the energy required could be one or two orders of magnitude greater, causing a sharp jump in costs. Using copper to illustrate this possibility, Skinner shows in Figure 3 how energy requirements could increase if the world had to extract copper from low-grade silicate rock rather than high-grade sulfide ores.

The Skinner thesis is not universally accepted, even among geologists. Moreover, as Skinner himself points out, it is based on theoretical analysis. Very little empirical work has been carried out on processing very low grade deposits, largely because they are currently of no commercial interest. As a result, sharp jumps and discontinuities in the cumulative supply curve are possible, but not certain. In addition, if jumps and discontinuities do exist, we have little or no idea when they are likely to be encountered, just how large in fact they are, or how serious a threat they pose.

As one optimistic reviewer noted, the world has in the past experienced such transitions without detrimental effects on costs. The clearest example is the shift from small high-grade copper ores to massive low-grade deposits early in the twentieth century. Something similar may be happening today in the switch from nickel sulfide to laterite deposits, the latter long regarded as very high cost. There are also the interesting cases of locational shifts: iron ore in far away places, which historically was presumed to be highly uneconomic, but with the revolution in the technology of shipping of bulk commodities, now dominates global supply; and natural gas in remote locations, where LNG and gas-to-liquids technology has converted previously uneconomic resources into valuable reserves.

Given the uncertainties, we simply do not know whether mineral commodities will be more or less expensive, more or less available, 100 or 500 years from now. This, then, is the second reason why the debate continues. The next sec-
tion examines the third reason, the widely disparate estimates of the social costs associated with the production and use of mineral commodities.

**Environmental and Social Costs**

Many pessimists are now more concerned about the effects on the long-run availability of mineral commodities of the associated environmental and other social costs than they are about the supply and demand issues examined in the previous section. Even if new technology succeeds in offsetting the cost-increasing effects of depletion, they believe that society may severely restrict the use of mineral commodities owing to the damage they inflict on indigenous cultures, local communities, biodiversity, pristine wildernesses, and other aspects of the human and biological environment.

The potential for public restrictions arises because the full social costs of producing and using mineral commodities are only partially internalized—that is, paid for by producers of mineral commodities, and so ultimately by the consumers of these goods. When a copper smelter emits sulfur dioxide emissions into the air, some of the costs are borne by people living downwind. Unless producers are charged for these costs, they are not passed on to consumers in the price they pay for copper.

External costs create a number of problems. They mean, firstly, that society is subsidizing goods by paying for the external costs, and so their market price is lower and output greater than what is optimal from the perspective of society as a whole. Secondly, when some inputs into the production process, such as clean water or clean air, are free to producers, they tend to overuse these resources.
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substituting them wherever they can for the capital, labor, and other resources for which they must pay. Third and probably of greatest importance over the longer run, when inputs are underpriced or free, there is little or no incentive to develop new technologies that save or conserve these resources.

Indeed, the rising environmental costs that the pessimists claim are associated with mineral commodities may largely or entirely reflect this lack of incentive to develop new environmentally friendly technologies. Where producers and consumers pay, we have seen that new technology has managed over the past century to offset the cost-increasing effects of depletion. Internalize the environmental and other external costs, the optimists contend, and new technology will reduce these costs just as technology has in the past reduced the capital, labor, and other costs for which producers and consumers have traditionally paid.

While there is much to recommend this proposal, its successful implementation requires the three conditions explained below.

First, to charge producers we have to be able to measure the external costs with reasonable accuracy. For many environmental goods, this turns out to be difficult. This is particularly so for those social goods we prize for their non-use value. For example, many people may place a positive value on maintaining the pristine wilderness of the Amazon region or the slopes of northern Alaska, even though they never plan to visit the areas. Similarly, a sense of fairness and equity may mean that many value preserving the culture and lands of the aboriginal peoples of Australia, even though they are not part of that culture and may not directly benefit from its preservation. The values people attach to such social goods vary greatly, and we have no operating markets where these goods are bought and sold—and in the process, priced—to turn to for guidance.

Over the past several decades efforts to value such social goods have relied on either imperfect political processes (similar in ways to the processes that society uses to determine how much to spend on more traditional social goods such as elementary education or defense) or on contingent valuation techniques. The latter rely on sampling procedures that ask people what they would be willing to pay to preserve pristine wilderness or other social goods. However, respondents do not actually have to pay, and for this and other reasons, these techniques remain quite controversial. Carson et al. (2001) provide a review of this debate, suggesting that most of the shortcomings of contingent valuation can be overcome. Still, despite considerable progress in this area over the past several decades, much more is needed before we have a widely accepted means of measuring the value of many social goods.

Second, once the external costs are measured, governments must have the means and the will to force the firms responsible to pay them. This second necessary condition is much less of an issue. Governments in most countries possess the means. Indeed, the current debate in this area is largely over which set of means to use: command and control regulations that stipulate how firms should behave, including the technologies they must use, or taxation and other economic incentives that encourage firms to meet certain goals, but leave them more freedom to achieve the goals in the most cost-efficient manner.

In most instances, governments also possess the will to internalize the social costs, but problems arise when the external costs are global in nature, as for example in the case of global warming. In such instances, many governments lack the will to impose appropriate charges on domestic producers, preferring to have firms in the rest of the world cover most or all of the external costs. Artisanal mining is another example where the lack of will can be a problem. In many ways, artisanal mining is mining at its worst. Small scale and largely unmechanized, it tends to be highly inefficient. It is also dangerous and, per unit of output, extremely damaging to the environment. Many developing countries around the world, however, are reluctant to force artisanal miners to pay the full social costs of their operations. Doing so would force many to close, and remove one of the few economic opportunities—albeit at significant personal risk—available to poor people living at the margin of subsistence.

Third, once the external costs are measured and internalized, technology must be developed to meet the challenge of reducing the costs over time. Whether this will actually be the case or not is uncertain, although the anecdotal evidence is encouraging. Over the past several decades governments around the world have increased the stringency of their environmental regulations. In many instances, this has led to the introduction of new technologies and the sharp reduction in the environmental costs associated with mineral commodities.

For example, 40 years ago copper smelters released most or all of their sulfur dioxide emissions into the air. Today, most smelters capture 80 percent or more of this pollutant, and modern smelters in Japan and elsewhere are recovering 98 percent or more (Tilton, 2003b, p. 89). In addition, over this period, a growing share of the world’s copper has been produced by a new technology, solvent extraction electrowinning, which completely bypasses the smelting stage and generates no sulfur dioxide emissions.

Countless other examples could be cited, demonstrating the power of new technologies to reduce the environmental costs of mineral commodities once the internalization of these costs creates the incentives to develop such technologies. Of course, anecdotal evidence does not prove that new technology can forever reduce the environmental costs associated with mineral commodities, but it does suggest that new technology may be just as effective in reducing these costs as the labor, capital, and other, traditionally internalized, costs of mineral production.

Many pessimists, however, place a very high value on indigenous cultures, biodiversity, pristine wilderness, and other social goods that mineral production and use can threaten. And they believe that society as a whole also holds such high values, or at least should. Therefore, in their view, the external costs remain very high, indeed often many multiples of the currently internalized costs, notwithstanding...
the recent efforts by governments to internalize more of these costs. If true, even though the internalization of all costs would encourage new technologies that reduce the previously external costs, the costs that producers and consumers would have to pay would likely rise, and possibly rise substantially. This could, as the pessimists predict, curb the use of mineral commodities in the future. However, this pessimistic scenario assumes that the true external costs are very high. While such an assessment may accurately reflect the values of particular individuals, the extent to which it can be generalized and thus used to represent the values of society collectively is uncertain.

Unraveling the third reason why the debate between the optimists and the pessimists continues—the issue of environmental and social costs—thus awaits the development of more widely accepted methods for estimating the full social costs associated with mining and mineral commodities. Of the three needed conditions to resolve this issue, this remains the most challenging.

**Scarcity or Abundance?**

The debate over the long-run availability of mineral commodities continues for three reasons—the use of different paradigms, the uncertainties regarding future developments in mineral supply and demand (and especially the unknown shape of the cumulative supply curve), and the lack of widely accepted methods for assessing the full social costs of producing and using mineral products.

Given the inherent shortcomings of the fixed stock paradigm, we can with some confidence resolve the first of these three issues. Indeed, within the debate informed participants increasingly favor the opportunity cost paradigm (Krautkraemer, 1998; Tilton, 2003b). The uncertainties associated with future developments in mineral supply and demand and those associated with full cost pricing, however, pose much more troubling hurdles.

If the slope of the cumulative supply curve rises gradually and at a decreasing rate, then new technology should have little trouble offsetting the cost-increasing effects of depletion over time. Conversely, if segments of the curve turn dramatically upward or incur discontinuities, future trends in resource availability could prove troubling. More geologic information on subeconomic mineral deposits would provide useful insights into the shape of the cumulative supply curve. At the present time, empirical evidence on the nature and incidence of subeconomic deposits, particularly very subeconomic deposits, is quite limited, making it difficult to confirm, refute, or modify the Skinner thesis. Without such information, forecasting long-run trends in real mineral commodity prices with any accuracy is simply not possible. Perhaps the time has come for a Society of Subeconomic Geologists.

Added to this problem are the uncertainties surrounding full cost pricing. While there is widespread agreement that the prices of mineral commodities should reflect their full social costs, including all external costs, there is considerable disagreement over the actual magnitude of the latter and how to appraise them. This is troubling for two reasons. First, public policy cannot internalize external costs if they cannot be measured. And, as long as producers do not pay for the environmental and other social costs associated with mineral commodities, they will have little incentive to develop new technologies to reduce these costs. This robs society of its most effective weapon for keeping the cost-increasing effects of depletion at bay. Second, without a reliable method for measuring external costs, a wide range of opinions—from quite modest to many multiples of the current internalized costs—must be considered seriously. If the external costs are in fact quite large, mineral commodity prices could be much higher once firms and consumers are forced to pay them. This could limit the future use of mineral commodities.

Unfortunately, the more widely used methods for assessing external costs provide highly variable estimates. Contingent valuation studies are known for their sensitivity to the procedures adopted and the assumptions made. The political process also provides mixed signals. Some countries, such as Chile, have a favorable regulatory environment for companies to develop new mines (Otto et al., 2000). Presumably these states believe that the environmental and other social costs associated with mining are modest compared to the benefits for the country. In California, Wisconsin, and British Columbia, however, it is more difficult to get the necessary permits for new mines. Their collective assessment of the associated external costs presumably is far higher. Fifty years ago society paid little attention to the external costs associated with mineral commodities. While this is clearly no longer the case, we simply do not know whether the assessment and policies of California, Wisconsin, and British Columbia are peculiar and passing anomalies, or whether they are the wave of the future.

What are the implications of these uncertainties, both for the long-run availability of mineral commodities and for the on-going debate over this issue? It is clear that neither the optimists nor the pessimists currently can marshall the needed evidence to prove the other side wrong. Therefore, perhaps the only reliable prediction one can make is that the debate will continue. Claims that mineral depletion unquestionably will, or will not, pose a serious threat to future generations should be treated with skepticism.

While this is disappointing, we have nevertheless learned much over the past 50 years about the nature of mineral depletion. With the possible exception of oil, few today, for example, argue that depletion will be a problem over the next 50 years, in light of known reserves and resources, the rapid pace at which new technological developments are transforming the mineral industries, and the likely consequences over the near term for the cost of producing mineral commodities.

The growing consensus favoring the opportunity cost paradigm is also quite significant, and has several important implications. First, mineral commodities may become too expensive to use even though large quantities of lower quality mineral resources still remain in the ground unexploited. The concern from the perspective of society is eco-
economic depletion, not physical depletion. What matters is the trend in mineral commodity prices, not their physical availability.

Second, if depletion does occur, it will occur gradually over time as the real prices of mineral commodities rise persistently, slowly reducing and then eliminating the demand in one end use after another. Depletion will not be a surprise. We will not wake up one day and find the cupboard bare.

Third, and particularly important for the long-run human condition, depletion—economic or physical—is not inevitable, as the fixed stock paradigm implies. While the need to exploit lower grade, more remote, and more difficult to process deposits tends to drive the costs and prices of mineral commodities up over time, new technology can offset this upward pressure. In short, the long-run availability of mineral commodities is now determined by a race between the cost-increasing effects of depletion and the cost-decreasing effects of new technology.

It is thus possible for mineral commodities to become more available or less scarce over time, despite the fact that they are constantly being consumed. Moreover, this possibility is not merely theoretical speculation. As noted earlier, the available empirical evidence indicates that this race over the past century has largely been won by new technology, as the long-run trends in real prices for most mineral commodities have either declined or remained relatively unchanged.

Fourth, population growth may no longer undermine the long-run availability of mineral commodities. Every new baby is born with a brain as well as a mouth. While population growth tends to accelerate the consumption of mineral resources, pushing costs and prices up over time (by accelerating the rate at which society moves up the cumulative supply curve), it also increases the human resources generating the new technologies that lower costs and prices (by shifting the cumulative supply curve down).

This raises the possibility that population growth may actually increase the long-run availability of mineral commodities, a possibility that Simon (1981) argues is actually the case. It also suggests that poverty and discrimination, which prevent as many as 2 to 3 billion people from developing their potential and so the ability to contribute back to society, pose a significant obstacle to keeping mineral depletion at bay. In effect, it means that a third to a half of the world’s potential human capital is left unused and undeveloped.

Fifth, the developed countries with 20 percent of the world’s population have, at least until the recent surge in Chinese consumption, accounted for some 80 percent of its resource use. While this may seem unfair to the rest of the world, where billions of poor people are struggling just to survive, under the opportunity cost paradigm the high levels of mineral consumption in the developed world may not increase resource scarcity in the rest of the world. It is true that this consumption accelerates mineral depletion, but the wealth that it creates supports the technological efforts that reduce the cost and prices of mineral commodities over time. It is not an accident that most of the new technologies increasing the availability of many mineral commodities over the past century have come from the United States and other developed countries. Though somewhat counter intuitive, this raises the possibility that the poor may actually benefit from the use of mineral resources in the developed world, in the sense that today they have access to cheaper mineral commodities than the developed countries did at comparable stages of development.

Findings from the on-going debate over mineral depletion have interesting implications in other areas as well—sustainable development, green accounting, recycling, the use of renewable resources, and conservation—that run counter to many of our preconceived notions (Tilton, 2003b). Although we still do not know whether or not mineral depletion will ultimately pose a serious threat to humanity, the on-going debate over this issue has been useful and presumably will continue to be so.

In the end, perhaps the most important lesson highlighted by the debate is that the world is in transition and evolving, and cannot be preserved in its present state. A century ago, we relied heavily upon wood and coal to heat our homes and drive the economy. Today, we use much more oil, natural gas, and nuclear power. A century from now, the mix will certainly be different again. Those who claim that our reliance on conventional oil and rich mineral deposits—copper deposits blessed with grades of 0.8 percent and higher—must decline are probably right. But this, by itself, has little significance or relevance for the future welfare and sustainability of the human race.

The important question is whether society will be able to satisfy the needs currently being served by these high-quality mineral deposits from other resources at real prices close to or even below current prices. Nonrenewable mineral resources make it abundantly clear that a world without change, even if it were desirable, is simply not possible.

In a sense, then, we are living on borrowed time. The current exploitation of high-quality mineral resources provides us with the opportunity—the wealth—to develop the new technologies that will allow us to satisfy future needs from other resources, and to do so in ways that do not spoil the environment or destroy other important social assets.

While nature, along with the geologic legacy that it has left behind over the ages, defines the challenge—the rules of the game, if you wish—it has been quite generous. Moreover, the human race is not a passive spectator watching helplessly as external forces over which it has no control determine the outcome of the race between the cost-increasing effects of depletion and the cost-reducing effects of new technology. Our behavior affects the pace of both mineral depletion and technological change. In no small measure we can shape the future. Specifically, by encouraging new cost-reducing technologies, by reducing poverty and discrimination, by improving our knowledge of subeconomic deposits, by developing better measures of full social costs, and by promoting innovations that reduce the environmental costs of mineral production and use, we can foster the conditions that keep resource scarcity and depletion at bay and promote the increasing availability of mineral commodities.
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