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Depletion and the Long-run Availability of Mineral Commodities

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DEPLETION AND THE LONG-RUN AVAILABILITY OF MINERAL COMMODITIES

by

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PREFACE

Since the early 1970s the long-run availability of nonrenewable mineral resources has intrigued me. In part, this interest simply reflects the importance of mineral resources to human welfare. Without adequate supplies of oil, natural gas, coal, steel, aluminum, zinc, and phosphate rock, modern civilization as we know it is difficult to imagine. Resource availability is widely considered one of the major challenges facing humanity along with nuclear war, population growth, and environmental preservation. Of course, all of these vital issues shaping the long-run future of the human race and the rest of the world as well are not independent.

In addition, I find the topic fascinating because the debate between those who are concerned about the depletion of mineral resources, often referred to as the pessimists, and those who are unconcerned, the optimists, seems as lively and contentious today as it was three decades ago. I marvel at how this can be—how can intelligent and informed people remain so divided on such an important issue after decades of discussions and research?

Over the years I have tried in my own small way to contribute to this discussion, beginning with a short book, *The Future of Nonfuel Minerals*, which the Brookings Institution published in 1975. Other publications I have since added to the burgeoning literature in this field are noted in the references. This study draws heavily from my earlier efforts, and in this sense is not entirely an original contribution. That in any case is not its purpose.

Rather it is an attempt to provide a concise and short primer on the long-run availability of mineral resources for the non-specialist. The goal is to offer an overview of the important issues along with the necessary conceptual tools for the reader to come to his or her own conclusions regarding the seriousness of the depletion threat and the appropriate policy response. I, of course, have my own opinions, which must inevitably and insidiously influence the presentation, though I have tried to be objective in discussing the controversial issues.

I would to thank Thitisak Boonpramote for his research assistance, and Carol Dahl, Peter Howie, and John Taylor for their helpful comments on parts of this study. I am also grateful to the Viola Vestal Coulter Foundation, the Kempe Foundation, Resources for the Future, and the Mining Minerals and Sustainable Development Project of the International Institute for Environment and Development for their support and encouragement. Of course, the usual caveat applies: The views expressed here are my own. They may or may not coincide with those of these organizations, or those of the individuals recognized above.

John E. Tilton
Golden, Colorado
March 1, 2001

Chapter 1

INTRODUCTION

Mining and the consumption of nonrenewable mineral resources date back to the Bronze Age, indeed even the Stone Age. So for millennia, they have made the lives of people nicer, easier, and more secure.

What is new is the pace of exploitation. The human race has consumed more aluminum, copper, iron and steel, phosphate rock, diamonds, sulfur, coal, oil, natural gas, and even sand and gravel over the past century than over all earlier centuries put together. Moreover, the pace continues to accelerate, so that today the world annually produces and consumes nearly all mineral commodities at record rates.

Several underlying forces are driving this explosion in use. First, advances in technology allow the extraction of copper, coal, and many other mineral commodities at increasingly lower costs. Advances in technology also permit new and better mineral commodities serving a range of new needs. Second, rapidly rising living standards in many parts of the globe are increasing the demand across the board for goods and services, including many that use mineral commodities intensively in their production. Third, the surge in world population means more and more people with needs to satisfy. Of these forces, only population growth shows any sign of abating.

The sharp rise in mineral consumption and production has, understandably, raised concerns about the long-run availability of mineral commodities. Since mineral resources are by nature nonrenewable, their supply is a fixed stock. The earth contains only so

much oil, copper, and other mineral commodities. Demand, on the other hand, continues year after year. As a result, many believe that it is just a matter of time before the availability of mineral supplies is threatened. Should the rate of mineral exploitation continue to grow as it has over the past several decades, mineral depletion, it is argued, is likely to create serious problems sooner rather than later. Moreover, as society is forced to exploit lower grade and more remote deposits, the environmental and other social costs associated with producing and using mineral commodities are likely to rise, perhaps limiting their use even before depletion.

Concern over the long-run availability of mineral resources, however, is not universal. On the other side of the debate are those who believe that the market coupled with appropriate public policies is sufficiently robust to deal with any threats. Pending shortages push mineral prices up, which in turn unleashes a host of countervailing forces. Exploration rises, increasing the likelihood of new discoveries. Research and development produces new technologies that allow the recovery of mineral commodities from previously unusable resources. Less scarce, and possibly renewable, resources are substituted for minerals facing growing shortages.

The stakes are not trivial. Nonrenewable resources matter. Long-run availability has consequences for the world's ability to sustain its current population, let alone accommodate increases, for lifestyles and living standards, and indeed for modern civilization as we know it.

As Chapter 2 shows, the debate over resource availability is not new. It can be traced back at least 200 years to the Classical economists, though the past 30 years have been particularly active. Much of the recent literature, however, is technical, written by

economists and other specialists in a manner that the interested layperson often finds difficult to follow.

Purpose and Scope

This study proposes to provide a framework for analyzing the on-going debate over mineral resource availability, and to review the important literature in a manner that the non-specialist can appreciate. It attempts to answer a number of questions: What have we learned? Where is there now widespread agreement among the experts? Where do they continue to disagree, and why? What are the important implications of what has been learned?

The focus is on the long-run availability of mineral commodities, or what is often called the mineral depletion problem or the mineral exhaustion problem. We do not address availability problems that arise for reasons other than mineral depletion. Strikes, cartels, price controls and other government policies, monopolies, adverse weather, accidents, booms in the business cycle, and even insufficient investment in exploration and mineral development can all for a time cause shortages of mineral commodities. Such shortages in almost all cases are temporary, lasting from a few days to perhaps a decade. Though they can cause considerable dislocation and hardship while they last, they fall outside the scope of this inquiry.

Terminology

Availability, as the term is used throughout this study, reflects the opportunity cost, or what has to be given up in terms of other goods and services, to obtain a mineral commodity. If availability is declining, this implies that over time more of other goods and services must be foregone to get an additional unit. With this definition, trends in availability reflect the extent to which mineral depletion is a growing threat to the long-run welfare of society. In practice, as Chapter 3 will discuss, there are many measures and definitions of mineral resource availability, all of which have their limitations.

Along with availability, we need to define what we mean by shortages and scarcity. These terms are often used to reflect an excess of demand over supply at the prevailing market price. Such situations are unusual, since normally when demand exceeds supply price rises bringing the two back into equilibrium. Of course, they can occur if governments or companies control prices. For our purposes, however, this definition is too narrow. When real prices are rising, the opportunity costs in terms of what we have to give up to get a mineral commodity are also rising. As a result, we use the terms shortage and scarcity to mean the opposite of availability. A growing shortage, for example, implies declining availability, and may occur even though demand and supply are in balance.

We also need to distinguish between mineral resources and mineral commodities, and between renewable and nonrenewable resources. Mineral commodities, such as copper, are produced from mineral resources, such as chalcopyrite and other copper-containing minerals. Mineral resources are the legacy of geological processes that took place over many thousands of years, often in the distant past. Since the time required for their formation is so vast from the perspective of any meaningful time scale for people,

mineral resources are considered nonrenewable. In contrast, many other resources, such as water, air, forests, fish, and solar energy, are considered renewable. One advantage of renewable resources is that their current exploitation need not result in less being available in the future. Just how significant the difference is between nonrenewable and renewable resources, however, is another issue, one we will return to in Chapter 7.

Organization

The presentation following this introduction is organized in the following manner. Chapter 2 examines the historical evolution of concerns over the long-run availability of mineral resources. It reviews the pioneering works of Thomas Malthus, David Ricardo, and Harold Hotelling, as well as the much more abundant literature since the 1970s.

Chapter 3 identifies different measures used to assess long-run trends in resource availability, and assesses their strengths and weaknesses. It considers physical measures, such as reserves and the resource base, as well as purely economic measures, such as real costs and real prices. It explores the concepts of user costs, economic and physical depletion, as well as Ricardian and Hotelling rents. It raises the possibility that mineral commodities may become more, rather than less, available over time.

Chapter 4, using measures described in Chapter 3, examines trends in resource scarcity over the past century. It covers the seminal work of Harold Barnett and Chandler Morse on production costs, along with the more recent work of Margaret Slade and others on mineral commodity prices. It finds that mineral resources, despite their widespread and accelerating use, have not become more scarce over the past century.

Chapter 5, acknowledging that past trends are not necessarily a good guide to the future, looks at the availability of mineral commodities over the near term (the next 50 years) and the more distant future. It examines the work of Brian Skinner on the geological nature of mineral deposit formation, and its implications for future scarcity. It also introduces the cumulative supply curve, a conceptual technique for categorizing the various factors shaping future trends in mineral resource availability. The chapter finds that the distant future with respect to mineral resource availability is at this time unknown, which helps explain why the debate over this issue continues. But it also suggests that society, if it wishes and is willing to cover the costs, can obtain considerable information on the prospects for future shortages by carrying out more research on the nature and incidence of sub-economic mineral deposits.

Chapter 6 turns to the environmental and other social costs associated with mineral exploitation, and assesses the threat they pose to the long-run availability of mineral commodities. It examines the ability of public policy to force mineral-producing firms to pay their full costs of production, particularly in light of the difficulties of measuring social costs and of regulating small-scale artisanal mining. It also assesses the ability of mineral-producing companies to reduce costs, assuming all social costs are internalized, by new technology and other means. This chapter ends by suggesting that economists and other social scientists are likely to play an increasing role in society's efforts to keep the adverse effects of mineral depletion at bay, complementing the important contributions that engineers and physical scientists have traditionally made.

Chapter 7, the final chapter, highlights the findings, and explores their implications for sustainable development, for green accounting, for the protection of

indigenous cultures and other social goods, for conservation, recycled materials, and renewable resources, and for global population. Among other things, this chapter suggests that the link between mineral resource availability and sustainable development is much looser than many presume. Declining resource availability need not prevent sustainable development, just as growing resource availability does not ensure it.

Chapter 2

EVOLVING CONCERNS

In an interesting little book, Maurice and Smithson (1984) examine a sample of resources crises confronting various civilizations at different points in history. The first and perhaps most significant was a food shortage some 10,000 years ago that led to the first agrarian revolution. Up to that point, the authors argue, the carrying capacity of the environment was sufficient to allow hunters and gatherers to survive and even prosper. At about 8000 BC, this changed, probably as a result of both population growth and adverse climate changes. Fortunately, some of our early nomadic ancestors responded by settling down, raising domesticated animals, and growing crops.

A second crisis, they contend, contributed to the end of the Bronze Age and the beginning of the Iron Age in ancient Greece around 1000 BC. The invasion of the Philistines, the Dorians, and others into the eastern Mediterranean at about this time interrupted trading routes, and for nearly a century cut Greece off from the traditional sources of tin it needed to make bronze. Out of necessity, the Greeks developed the means to produce iron.

These two developments suggest that resource shortages, and presumably concerns over resource availability, can be traced far back in time. For our purposes, however, it is sufficient to start with the Classical economists writing at the end of the 18th century and the beginning of the 19th century.

Classical Economists, 1798-1880

Among the Classical economists, Thomas Malthus is the best known for his views on resource availability and the human condition. His first published work, *An Essay on the Principle of Population*, appeared anonymously in 1798 and was republished under his name in five subsequent editions during his lifetime. In this influential treatise, he argues that population left unchecked tends to grow continuously while tillable land is limited. As more and more labor works the available land, output per worker falls until it reaches that level just sufficient to sustain life. At this point, misery or vice prevents further population growth. In his second edition, Malthus introduces the possibility that "prudential constraint" might limit population growth before living standards fell to the subsistence level. Despite this important qualification, the public generally associates Malthus with a very pessimistic view of the prospects for human welfare. Indeed, thanks in part to his writings, economics over the years has gained the reputation as the dismal science.

David Ricardo extends Malthus' analysis in his *Principles of Political Economy and Taxation*, first published in 1817. Most importantly, he takes into account quality differences in agricultural land. He assumes the best or most fertile land is worked first. As population increases and the demand for food rises, more land of poorer and poorer quality is brought into production. As food prices increase to cover the higher costs of farming the marginal fields, the owners of the more fertile lands earn a surplus, commonly referred to as economic rent or Ricardian rent. Output per worker also falls as

in Malthus' world. However, the reason for the decline is the inferior quality of the new lands brought into production, rather than the addition of more workers to a given amount of (similar quality) land.

While Malthus ignores mining and nonrenewable resources, Ricardo points out that mineral deposits vary in quality just like land. As a result, he claims, his analysis of land is equally applicable to minerals. He also recognizes that it is possible to discover new mineral deposits and to develop new mining technology. Interestingly, though, he does not consider the depletable nature of mines, and so fails to focus on what many consider to be the fundamental difference between nonrenewable and renewable resources.

In certain ways, Ricardo is both more and less pessimistic than Malthus. Resource availability in his analysis causes declines in labor productivity either immediately or at the time that poorer quality land is first brought into production. With Malthus, problems arise only after all the available agriculture land is in use. On the other hand, in Ricardo's world it is always possible to bring more land into production, as long as declining fertility is tolerated.

John Stuart Mill, the last of the Classical economists we consider, develops the views of both Malthus and Ricardo in his *Principles of Political Economy*, which first appeared in 1848. Mill argues that Ricardian scarcity, arising from the need to exploit land of poorer fertility, will likely occur long before all the land available for agriculture is brought into production. Indeed, he contends that the land available for agriculture is far more extensive than Malthus presumes. He also argues that the adverse effects of uncontrolled population growth may very well encourage people to constrain population

growth before living standards are driven down to subsistence. He recognizes as well that new technology could offset the tendency for resource scarcity to reduce living standards. For these reasons, his view of the human condition is more optimistic than those of Malthus and Ricardo.

The Conservation Movement, 1890-1920[1]

Widespread public concern over resource availability resurfaced toward the end of the 19th century in the Conservation Movement. Industrialization coupled with the closing of the American frontier and the rapid exploitation of once vast forest lands fostered this development, which was largely a political and social movement. Unlike Malthus, Ricardo, and Mill, the leaders of the Conservation Movement were not economists. Some, such as Theodore Roosevelt and Gifford Pinchot, were public officials. Many others were natural scientists.

As a result, the considerable literature associated with the Conservation Movement displays no coherent economic core. A reduction in physical supply is directly equated with a decline in resource availability, as the following frequently cited excerpt from *The Fight for Conservation* (Pinchot, 1910, pp. 123-24) so nicely illustrates:

> The five indispensably essential materials in our civilization are wood, water, coal, iron, and agricultural products. . . . We have timber for less than thirty years at the present rate of cutting. The figures indicate that our demands upon the forest have increased twice as fast as our population. We have anthracite coal for but fifty years, and bituminous coal for less than two hundred. Our supplies of iron ore, mineral oil, and

[1] This section is largely based on the interesting chapter (Ch. 4) on the Conservation Movement found in Barnett and Morse (1963), which in turn draws from Hays (1959).

> natural gas are being rapidly depleted, and many of the great fields are already exhausted. Mineral resources such as these when once gone are gone forever.

The Conservation Movement also viewed natural resources and nature as more multidimensional, with the various components more interdependent, and the whole far more complex than the Classical economists. Accordingly, mankind's critical dependence on nature is not just economic, but also psychological and even spiritual. Nature in its wonder promotes human values. Conservation is the "wise use" of resources, which goes far beyond the economist's concept of efficiency. It entails using where possible renewable resources in place of nonrenewable resources, more abundant nonrenewable resources in place of less abundant nonrenewable resources, and recycled products in place of primary resources.

While the Conservation Movement was largely concentrated in North America during the 1890-1920 period, similar concerns emerged in other industrializing countries and in other time periods. W. Stanley Jevons (1865), for example, warned Britain that its future industrial growth was threatened by the country's limited coal resources.

World War II and the Early Postwar Period, 1940-1965

During the 1930s the world was largely preoccupied with the Great Depression. Toward the end of this decade and throughout the first half of the 1940s, concerns over resource availability returned, but they focused on the short-run issue of securing adequate supplies for the war effort. Shortly after the war, however, the long-run availability of mineral resources once again rose to prominence as the world examined

the implications for resource use first for reconstruction and then for long-run economic development. In the United States, these concerns led to the creation of the President's Material Policy Commission, more popularly known as the Paley Commission after its chair, William S. Paley. The Commission, which published its hefty five-volume report in 1952, assessed the adequacy of the world's mineral resources to meet future needs. In the words of Volume I (President's Materials Policy Commission 1952, p. 2):

> The nature of the problem can perhaps be successfully over-simplified by saying that the consumption of almost all materials is expanding at compound rates and is thus pressing harder and harder against resources which, whatever else they may be doing, are not similarly expanding. This Materials Problem is thus not the sort of "shortage" problem, local and transient, which in the past has found its solution in price changes which have brought supply and demand back into balance. The terms of the Materials Problem we face today are larger and more pervasive.

The Paley Commission report encouraged the Ford Foundation in 1952 to provide the funding needed to establish Resources for the Future, a nonprofit corporation for research and education in the development, conservation, and use of natural resources. Over the next several decades, Resources for the Future sponsored a number of studies on the long-run availability of mineral resources, including the influential study by Barnett and Morse (1963), one of two seminal works that shaped the debate over the long-run availability of mineral resources during the latter half of the 20th century.[2] The other, discussed at the end of this chapter, is the article by Harold Hotelling (1931) on "The Economics of Exhaustible Resources."

[2] A sample of other studies on resource availability that Resources for the Future has sponsored over the years includes Adelman (1973), Bohi and Toman (1984), Darmstadter, Dunkerley, and Alterman (1977), Herfindahl (1959), Kneese, Ayres, and d'Arge (1970), Landsberg and Schurr (1968), Manners (1971), Manthy (1978), Potter and Christy (1962), and Smith (1979).

Barnett and Morse draw a sharp distinction between the physical availability of resources and economic scarcity. During the latter half of the 19th century, for example, the actual and potential supply of whale oil declined as many species of whales were hunted almost to extinction. The development of low-cost petroleum products and electricity, however, filled the needs previously satisfied by whale oil, and so prevented this physical decline from producing economic scarcity.

Using measures of economic scarcity, Barnett and Morse find that both renewable and nonrenewable resources, but in particular nonrenewable mineral resources, have become more, not less, available between 1870 and1957, the period they examined, despite the explosion in resource use during the 20th century. They attribute this favorable outcome largely to technological change, and its ability to offset the adverse effects of resource depletion. This surprising finding, which stood in stark contrast to the perceived wisdom of the time, stimulated a research boom in this area.[3] In Chapter 4, we will return to the Barnett and Morse study and the subsequent literature it spawned.

Limits to Growth and Social Costs, 1970-2000

In investing, it is often said, timing is everything. The same may hold, at least on occasions, for academic publications. In 1972, Donella H. Meadows and her fellow authors published their book *Limits to Growth*. Using an analytical technique called systems dynamics, they construct a model that generates scenarios of world futures. In

[3] Chapter 2 of Barnett and Morse (1963) entitled "Contemporary Views on Social Aspects of Resources" contains an interesting survey of the views of government and various disciplines (naturalism, ecology, demography, political science, and economics) prevailing at the time this book was written.

their base-case scenario, the one that they believe most likely to evolve barring corrective public policies, they foresee the collapse of per capita food and industrial output as a result of the exhaustion of mineral resources by the middle of the 21st century. While the study was severely criticized, it nevertheless was widely read and very influential, thanks in large part to its timing.

Shortly after the book appeared, the Middle East OPEC countries imposed an embargo on oil exports to the United States and the Netherlands for their support of Israel during the 1973 Middle East war. Simultaneously, OPEC as a whole engineered a three-fold increase in the world price of oil by withholding exports. Prices for many other mineral commodities also rose sharply in tandem with an economic boom in North America, Western Europe, and Japan.

Of course, temporary shortages caused by embargoes, cartels, and economic booms do not necessarily mean depletion is a problem. Still, the dislocations, though temporary, were painful, aggravated in part by market controls in some consuming countries that prevented commodity prices from rising to their market clearing levels. These problems focused public attention on resource availability in general and on *Limits to Growth* in particular. Many saw the disruptions of the early 1970s as an early warning that depletion and much more permanent and serious shortages were in the offing.

The widely expected scarcity, however, failed to emerge during the 1980s and 1990s as the real price of oil and many other mineral commodities actually declined. As a result, fears of resource depletion, though they did not evaporate completely, did subside. They were replaced by growing concerns over the environmental pollution and other social costs, such as the loss of biodiversity, indigenous cultures, and pristine wilderness,

associated with mineral extraction and processing. The following quotes, the first by an economist (Young 1992, p.100) and the second by a geologist (Kesler 1994, p iii), reflect this shift in concern:[4]

> Are we running out? Recent trends in price and availability of minerals suggests that the answer is 'not yet' . . . . The question of scarcity, however, may never have been the most important one. Far more urgent is, Can the world afford the human and ecological price of satisfying its voracious appetite for minerals?
>
> At the end of the twentieth century, we are faced with two closely related threats. First, there is the increasing rate at which we are consuming mineral resources, the basic materials on which civilization depends. Although we have not yet experienced global mineral shortages, they are on the horizon. Second, there is the growing pollution caused by the extraction and consumption of mineral resources, which threatens to make earth's surface uninhabitable. We may well ponder which of these will first limit the continued improvement of our standard of living. . . .

Another interesting example of this shift is *Beyond the Limits* (Meadows and others 1992), a sequel to *Limits to Growth*, written for the 20th anniversary of the latter's publication. Like the original volume, *Beyond the Limits* uses a systems dynamics model to generate scenarios of the future. The base-case scenario in both studies sees modern civilization collapsing during the 21st century. In *Beyond the Limits*, however, it is the environmental damage arising from the production and use of resources, rather than resource exhaustion, that causes the collapse.

Hotelling and the Theory of Exhaustible Resources

[4]There were earlier writers who anticipated the concern over the environmental constraint on resource exploitation of the 1990s. See, for example, Brooks and Andrews (1974).

While the preceding discussion brings us up to the present, it omits an important development that Harold Hotelling (1931) fathered with his article on "The Economics of Exhaustible Resources." In this piece, Hotelling explores the optimal output over time for a mine with a given amount of known resources. To simplify the problem, he makes a number of strong assumptions: (1) The mine's goal or objective is to maximize the present value of its current and future profits. (2) The mine is perfectly competitive and so has no control over the price it receives for its output. (3) There is no uncertainty, so the mine knows the size and nature of its resource stock as well as current and future costs and prices. (4) The mine's output is not limited by existing capacity or other constraints, allowing the mine to produce as little as nothing and as much as its entire remaining resource stock during any particular time period. (5) The mine's resource stock is homogeneous, so grade and other qualities do not vary. (6) There is no technological change.

Under these conditions Hotelling shows that firms exploiting an exhaustible resource stock behave differently than firms in other industries where all inputs are unconstrained. The latter, following the principles of any introductory economics textbook, maximize the present value of their profits by continuing each period to expand their output up to the point where the extra or marginal costs of producing one more unit just equal the prevailing market price.

Resource firms, on the other hand, have to take into account that each unit of output today means less profit in the future. In a world where ore is homogeneous, increasing output by one unit today results in a reduction of output by one unit in the final period of operation and the loss of the profits associated with that unit. In a world where

the ore is heterogeneous, an increase in output today means the future must exploit poorer quality resources, causing higher costs and lower profits.

So in addition to the marginal costs of producing an additional unit, there is an opportunity cost, commonly referred to as user costs, scarcity rent, or Hotelling rent, which equals the present value of the lost future profits. As a result, a resource firm has an incentive to expand its output during any particular period only up to the point where marginal costs plus user costs equal the market price. Figure 2.1 illustrates this difference. The firm with a fixed resource stock produces at Q_1. The firm without fixed inputs expands its output to Q_2.

Since user costs are the present value of the lost future profits associated with a unit increase in current production, they also reflect the present value of the extra future profits a firm would realize from having the additional resources needed to produce one more unit of output. This means that user costs measure the current value of an additional unit of mineral resource in the ground. Moreover, in the world of Hotelling where the mineral resource stock is homogenous, user cost multiplied by the available mineral resource gives the current value of the total stock of the mineral resource in the ground.

Hotelling also points out that mineral resources in the ground are assets, and so they must under his assumptions earn a rate of return (r) comparable to other types of assets with similar risks. If this were not the case, if the rate of return on mineral resources were lower than that of other comparable assets, it would pay their owners to extract and sell these assets as soon as possible, and invest the resulting profits in other assets whose returns were higher. This behavior, which would drive down mineral prices in the current period and raise them in later periods (when less would be available),

would continue until the rate of return from holding mineral resources in the ground just equals the rate of return on other comparable assets. Conversely, if the rate of return on mineral resources were higher than that of other comparable assets, the owners of mineral resources would be reluctant to exploit them. This would drive current prices up and future prices down, and in the process cause the rate of return earned by holding mineral resources to decline until it reached that of other assets.

This theoretical finding has important implications for mineral availability. Specifically, it anticipates that mineral resources in the ground should become less available as their value or price rises exponentially over time at the rate of r percent, where r is the rate of return on other comparable market assets.

For several decades Hotelling's article attracted little attention. Since the 1960s, however, some of the best minds in the field of economics have focused on this topic, attracted in part by the challenge of solving complex intertemporal optimization problems with new developments in advanced mathematics. The resulting literature, which is reviewed in Peterson and Fisher (1977), Bohi and Toman (1984), Krautkraemer (1998), and Neumayer (2000), relaxes many of Hotelling's assumptions. It also extends the scope from the optimal behavior for an individual mine to the optimal behavior for society as a whole in light of the finite nature of resources. These more recent works take into account exploration and the discovery of new mineral deposits, technological change from exploration to the reuse of mineral commodities, ore bodies with different grades and qualities, uncertainty and imperfect knowledge, market power that allows firms some control over price, and firm objectives other than maximizing the present value of current and future profits.

Relaxing Hotelling's assumptions, not surprisingly, alters his findings. No longer does the value of mineral resources in the ground have to rise at r percent over time. Indeed, with exploration and new technology, the value of mineral resources in the ground may even fall, implying that resource availability is increasing. Nevertheless, Hotelling's article and the subsequent work it stimulated play an important role in our understanding of the long-run availability of mineral resources. In particular, we will return to Hotelling and other works on the theory of exhaustible resources in the next two chapters.

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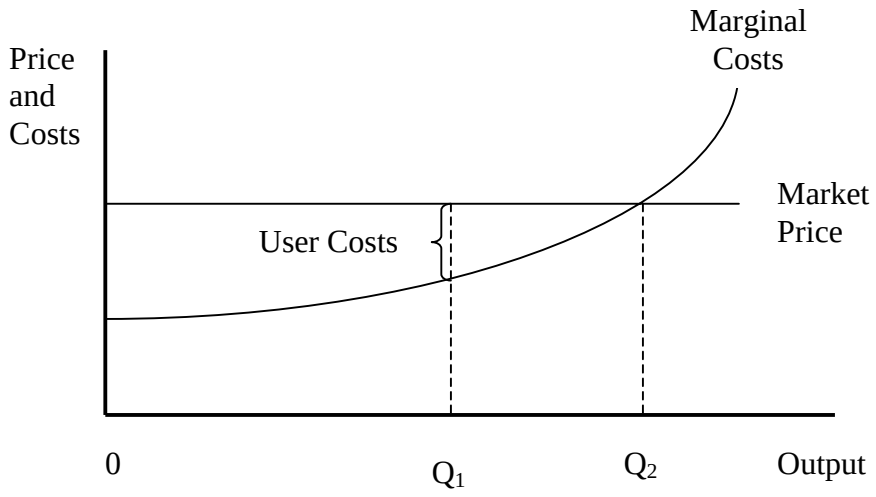
Figure 2.1. Market Price and Optimal Output For Mineral Commodity Producers



Chapter 3

IMPERFECT MEASURES

There are many ways to measure resource availability. While none are perfect, some are better than others. This chapter first considers measures that are entirely or largely physical in nature. These measures are frequently encountered in the literature and have considerable intuitive appeal. It then reviews measures that are economic in nature. While all the economic measures have shortcomings, we will see that they are more useful than physical measures for assessing the long-run threat from mineral depletion. In Chapter 4, as a result, we rely on economic measures to identify the historical trends in mineral commodity availability.

Physical Measures

The logic behind physical measures is both simple and appealing. As Chapter 1 notes, since the earth is finite, it contains a fixed amount of oil, coal, iron, copper, and any other particular substance. Consequently, the supply of all mineral commodities is a fixed stock. Physical measures attempt to assess the remaining stock at any point. The demand for mineral commodities, on the other hand, is a flow variable that continues year after year. So eventually demand must consume the available supply, causing the

physical exhaustion of the commodity. To assess how long the available stock will last—the life expectancy of the commodity—one has only to forecast trends in its future use.

This view of the depletion process, in large part because it is so logical, is frequently encountered. Over the years, as we saw in Chapter 2, it has greatly influenced the literature, from Malthus to the Conservation Movement to Hotelling (as well as many of the economists who have followed in Hotelling's footsteps by extending on the theory of exhaustible resources).

Reserves

Though the logic behind physical measures is simple, estimating the remaining available stock of a mineral commodity raises some difficult issues. The most common approach is to use reserves (or measures closely related to reserves). By definition, reserves are the quantities of a mineral commodity, such as oil or copper, found in subsurface resources (fields, deposits) that are both known and profitable to exploit with existing technology and prices.

Data on reserves for individual countries and the world as a whole are readily available from the U.S. Geological Survey, from similar government agencies in other countries, and from international organizations. Column 2 of Table 3.1 shows the world reserves in 1999 for a sample of mineral commodities. By themselves, they are not particularly enlightening, and normally one uses such data to calculate mineral commodity life expectancies. This, however, requires forecasts of future demand along with estimates of how much of the future production will come from primary production

and mining, and how much will come from secondary production and recycling. It is only primary production, of course, that depletes reserves.

Table 3.1 deals with this issue by showing life expectancies assuming primary production will grow at annual rates of zero, two, and five percent. The average rate of growth in primary production over the past 25 years for each mineral commodity is also shown in Table 3.1. In most cases, this average growth rate falls between zero and five percent. Lead and tin are the exceptions. Their growth has averaged a negative 0.5 percent annually.

Not surprisingly life expectancies vary greatly. The faster future demand and primary production are expected to grow, the lower they are, often by many years. For a few mineral commodities, such as magnesium (recovered from sea water) and potash, which are not shown in Table 3.1, reserves are sufficient to last for millennia at current rates of production. For most, however, the results are more disturbing, suggesting that many mineral commodities will be gone within a century or in a few cases even within a couple of decades.

This pessimistic scenario, however, presumes that reserves reflect the fixed stock of mineral commodities remaining to be exploited. This simply is not so. Reserves indicate the amount of a mineral commodity found in deposits that are known and profitable to extract with current technology and prices. While extraction over time is depleting reserves, the discovery of new deposits by exploration and the conversion of known but uneconomic resources into profitable deposits by new technology, both add to reserves. Indeed, even in a static world with no exploration or new technology, reserves

can increase as a result of rising mineral commodity prices or declining costs of labor, capital, and the other factors of production employed by the mineral industries.

Since exploration, new technology, and the other factors do increase reserves over time, reserves should not be thought of as long-run indicators of mineral availability, but rather as working inventories that energy and mineral companies can increase by investing in exploration and new technology. In many mineral industries, once reserves reach 20 to 30 years of current production, companies have little incentive to invest in developing their reserves further.

Some studies attempt to overcome the inherent problems of using reserves to measure mineral availability by increasing reserves in an arbitrary manner. *Limits to Growth* (Meadows and others 1972), for example, employs a multiple of reserves in its simulation efforts. Others use the concept of resources, rather than reserves, where resources include reserves plus the quantity of a mineral commodity contained in deposits that are either expected to be found or to become economic as a result of new technology or other developments within some foreseeable future. All these attempts, however, suffer from the same fundamental problem as reserves; namely, the resulting figures are ultimately not fixed stocks reflecting the remaining availability of mineral commodities.

Resource Base

An alternative physical measure that comes much closer to measuring the total amount of various mineral commodities found in the earth is the resource base. This measure encompasses all of a mineral commodity contained in the earth's crust. It includes reserves, resources, as well as the contents of all other subsurface occurrences,

whether or not they are known or likely soon to become so, and whether or not they are currently economic to exploit or likely soon to become so. The relationship between reserves, resources, and the resource base is shown in Figure 3.1, a modification of the well-known McKelvey box.

Table 3.2 shows the resource base for a number of mineral commodities, along with their life expectances assuming the demand for primary production grows at zero, two, and five percent annually. The most striking finding is the sheer magnitude of the figures. At current rates of primary exploitation, all the mineral commodities for which we have resource base estimates would last for millions of years, some for billions of years! Given that our solar system is only about five billion years old and that homo sapiens have existed as a species for only several hundred thousand years, these are large numbers. They suggest that society might have more pressing problems than mineral depletion.

However, Table 3.2 also shows that assuming a continuous growth in primary production of only two percent annually reduces the life expectancies of the resource base from millions and billions to hundreds and thousands of years. While these figures are small enough to perhaps cause some concern, they like the larger figures are not very useful indicators of the long-run availability of mineral resources for several reasons.

First, many mineral commodities are not destroyed after they are extracted and used. Ignoring the trivial amounts that have been shot into space, the world today has as much copper, lead, and zinc as it ever has had. Some past production of these metals has been degraded and discarded. Recovering and reprocessing this material may be expensive, but this is a issue of costs, not of physical availability.

Second, while recycling is not an option for the energy resources, their ultimate scarcity is constrained by substitution opportunities and backstop alternatives. Coal, natural gas, petroleum, hydropower, uranium, wind, and solar power, for example, can all produce electricity. The mix of these resources used at any particular time depends largely on their relative costs.

Of course, certain energy resources, such as petroleum, have unique characteristics that at the present time make substitution difficult or impossible in some applications. The automobile with its internal combustion engine, for instance, depends on petroleum as it requires a mobile energy source. However, the opportunities for resource substitution are growing in many important end-use energy applications. Nowhere is this more evident than with the automobile, where new technology is rapidly advancing the prospects for using electricity, fuel cells, and other alternative fuels to power the car of the future. Such alternatives are now technically feasible; their widespread adoption is largely a question of costs.

In light of such substitution opportunities, the depletion of a particular resource poses a problem only if all the alternatives are similarly suffering from growing scarcity. While the resource base for many of the nonrenewable energy minerals is unknown (and may be smaller or larger than often assumed), the availability of renewable energy resources, particularly solar power, is for all practical purposes unlimited.[1]

[1] The availability of solar power reaching the earth's upper atmosphere equals the solar constant times the area of the earth presented to the sun. The solar constant (SC) is the rate of arrival of energy per unit area perpendicular to the sun's rays at earth's location. This equals 1350 watts per square meter (Giancoli 1997). The area of the earth presented to the sun equals $\prod R^2$, where R is the radius of the earth (6.38×10^6 meters) and $\prod$ is the well-known ratio of the circumference of a circle to its diameter (3.14159). So the solar power reaching the upper atmosphere is $SC \prod R^2 = 1350 \times 3.14159 \times (6.38 \times 10^6)^2 = 1.73 \times 10^{17}$ watts. Since only about 50 percent of this energy reaches the ground (Ristinen and Kraushaar 1998), the total solar power reaching the earth's surface is half of this figure, or 9×10^{16} watts. Multiplying this figure by

Third, the resource base ignores the possibility of extracting mineral commodities from beneath the earth's crust or from space. While such activities seem far-fetched at the present time, there are on-going discussions of mining on the moon and on near-earth asteroids. History suggests that many activities that seem implausible today may be commonplace in a century or two.

Fourth, and perhaps most important, before the world extracts the last drop of oil or the last molecule of silver from the earth's crust, rising costs would completely eradicate demand. This means that economic depletion would threaten the availability of resources long before the physical exhaustion of the resource base would occur.

For these reasons, costs and prices, properly adjusted for inflation, provide a better early warning system for long-run resource scarcity than the available physical measures. This brings us to the economic measure of availability.

Economic Measures

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the number of hours in a year (24 x 365) and then dividing by 1000 (to convert from watts to kilowatts) indicates that 79 x 10^{16} kilowatt-hours of solar energy reach the earth's surface annually.

To comprehend the magnitude of this figure, we can compare it to the energy derived annually from global petroleum production. The amount of energy in a barrel of oil varies. For the United States it averages about 5.8 million Btu's (U.S. Energy Information Administration, 2001a), or the equivalent of 1.7 thousand kilowatt-hours. As shown in Table 3.1, annual global crude oil production averaged 23.7 x 10^{9} barrels over the 1997-1999 period. At 1.7 thousand kilowatt-hours per barrel, this output contains 4 x 10^{13} kilowatt-hours of energy, or approximately 0.005 percent of the solar power reaching the earth's surface every year.

According to the U.S. Energy Information Administration (2001b), crude oil production accounts for 40 percent of global energy output. So total energy output currently equals 0.012 percent of the available solar power. This means that the physical availability of solar power is some 8,000 times greater than current energy production. The point is not to suggest that some day the world may use all of its available solar power. The costs, including the environmental costs, of solar power presumably would rise sufficiently to make the additional use of solar power uneconomic long before the world was completely covered with solar panels. The point rather is simply that it is costs, and not physical availability, that ultimately determines the availability of energy commodities.

There are three widely recognized economic measures of the long-run availability of mineral commodities—the marginal costs of extraction and processing, the market price of the mineral commodity, and user costs. As pointed out in Chapter 2 (see Figure 2.1), mineral commodity producers have an incentive to expand output up to the point where marginal production costs plus user costs just equal the market price. So these three economic measures are related.

Figure 3.2 illustrates the nature of this relationship. The vertical axis shows the market price for a mineral commodity, and the production costs for the various (discovered) deposits from which mineral companies can produce the commodity. Production costs differ because deposits vary in quality. Some are high grade, easy to process, and located close to cheap ocean transportation with needed infrastructure already in place. Others are not. The column marked A in Figure 3.2 identifies the lowest cost (highest quality) deposit. It can produce an output of OA annually at a per unit cost of OC_1. Column B indicates that the next best deposit can produce AB a year at a per unit cost of OC_2. Column C represents the third best deposit, and so on.

The figure indicates that the market price is P and user costs are C_mP per unit of output. It also assumes that per unit production costs vary little within any given ore body or deposit, at least compared to the differences in costs between deposits. For this reason, production costs are portrayed as a horizontal line for each deposit.

Assuming that mining companies develop and mine deposits if, and only if, the market price covers their production costs plus user costs, a long-run industry supply curve can be constructed by adding user costs (C_mP) to the height of each column (the production costs) in Figure 3.2. At the market price P, the industry will produce the

output OM from the first M deposits. The ores contained in these deposits are reserves. Columns N and higher represent deposits that are not profitable to exploit at the price P. The minerals they contain are resources but not currently reserves.

The production costs plus user costs for deposit M are just equal to the market price, and it is this deposit that illustrates the relationship between market price, marginal production costs, and user costs—our three economic measures of resource availability. Intra-marginal deposits, those in categories A through L, enjoy production costs plus user costs that are lower than the market price, and so they earn an additional profit as a result of their superior quality. This extra profit, as noted in Chapter 2, is commonly called Ricardian rent. As Figure 3.2 shows, while only deposits A through L enjoy Ricardian rents, they as well as deposit M earn user costs.

While Figure 3.2 highlights the relationship between price, costs, and user costs, these three indicators of resource availability measure different things. The market price reflects the opportunity cost (in the sense of what has to be given up) of obtaining another unit of the mineral commodity—a barrel of crude oil or a ton of refined copper, for example.

User costs reflect the opportunity cost or the value of the oil or copper ore in the ground. Under certain conditions, user costs approximate the additional costs of finding one more unit of marginal quality (category M) reserves.[2] Higher quality reserves normally are more costly to discover.

Extraction and processing costs reflect the value of the labor and other inputs required to extract resources from the ground and to convert them into crude oil, refined

[2] This follows when firms have an incentive to expand their exploration efforts up to the point where the cost of finding another unit of reserves just equals the value of that unit.

copper, or other mineral commodities ready to be sold in the marketplace. These differences mean that the three economic measures may provide different signals regarding the long-run availability of mineral commodities.

In a static world where no discovery or new technology occurs and where the existing ore is all of the same quality, Hotelling (1931) has shown that user costs rise at r percent a year (the rate of return on other assets similar to mineral resources in the ground). Extraction and processing costs remain constant. As a result, the marginal cost of producing the last unit of output is the same for each period, and equals the average costs across all output. In this situation, the market price rises at the same absolute rate as the user costs. Unless extraction and processing costs are zero, however, the percent increase in the market price is less than r percent, the rate for user costs. In this situation, user costs and to a lesser extent market prices indicate growing scarcity, while production costs show no change in resource availability.

Allowing for technological change in the extraction and processing of mineral commodities introduces the possibility that production costs may decline over time. Such a decline may more than offset the rise in user costs, allowing the market price to decline. This favorable trend may not continue indefinitely, however, as over time user costs account for a growing portion of the market price. As Chapter 4 points out, this possibility has led Slade (1982) and others to hypothesize that real mineral commodity prices follow a U-shape curve over time, first declining and then rising.

Going one step further, and allowing not only for technological change in extraction and processing but also for new discoveries and mineral deposits of varying qualities, introduces the possibility that user costs as well as production costs may fall

over time, permitting market price to decline indefinitely. To illustrate this possibility, consider Figure 3.2 once again and assume that there are many large deposits with the same production costs as deposit N. In this case, production costs, once they reached those of deposit N, would stabilize. User costs would decline, as the lost future profits associated with increased output today would not arise for many years, not until deposit N and all other similar deposits were exhausted. The present value of these lost profits as a result would likely be far lower than the present value of the lost future profits associated with increasing current production prior to the exploitation of deposit N.

Such situations may arise where backstop technologies exist. Should the cost of producing natural gas, for example, rise sufficiently so that solar energy becomes economic, the user costs associated with energy production from natural gas would fall to zero.

Challenges to Economic Measures

Our economic measures (price, marginal production costs, and user costs) of mineral resource availability, though now generally accepted as superior to the physical measures (reserves, resources, and the resource base), are not perfect. Mineral commodity prices, for example, may at least in the short run be more influenced by cyclical fluctuations in the business cycle, accidents, strikes, and other factors than trends in long-run availability. They can also be distorted by a variety of market imperfections, including cartels and other forms of market power, government price controls, public subsidies, and environmental and other social costs that producers and consumers do not

pay. The sharp rise in oil prices in the early 1970s, for example, reflected more the market power of OPEC and short-run fluctuations in the business cycle than rising long-run availability problems.

Similarly, market imperfections and short-run disturbances, again particularly in the short run, may distort extraction costs on the margin. The jump in oil prices in the early 1970s, for example, stimulated investors to develop high-cost wells that previously were uneconomic. An additional shortcoming of extraction costs is their failure to anticipate the future. While current mineral commodity prices will rise in anticipation of future shortages, extraction costs depend on the quality of the resources currently being used rather than the quality of those the future will use.

User costs are particularly easy to interpret when extraction costs are constant. When extraction costs are rising, however, we have seen that user costs can decline as society moves to poorer quality but more abundant resources. This reflects a reduction in the future threat of resource shortages, but does not reflect past trends very well. If extraction costs focus too much on the past, user costs suffer from the opposite problem.

Another shortcoming of our economic measures of scarcity is that they can provide quite different indications of resource availability trends. New technology, for example, may over time drive production costs down while depletion may be pushing user costs up. Mineral commodity prices in such situations may be rising, falling, or constant, and the implications for trends in mineral commodity availability are ambiguous.

Ecological economists and others also challenge the use of our economic indicators on the grounds that they are mere reflections of a fundamentally flawed market process. Here the case against economic measures encompasses several concerns.

First, the economic system, it is argued, is just a part or a subsystem of a finite global ecosystem. The economic system extracts resources from and jettisons waste back into the ecosystem. While the world economy was small, the ecosystem absorbed these interactions with little or no costs. With the growth in the global economic system over the past century, however, this has changed, and as a result large environmental and social costs associated with current economic activities are not reflected in the costs that producers incur or the prices that consumers pay. In a debate with Julian Simon, Norman Myers (Myers and Simon 1994, p. 185) advanced this view:

> The goods we purchase have often been produced at a concealed cost of pollution during the production process, and when we consume them or throw them away after use, still more pollution ensues, for instance, acid rain, ozone-layer depletion, and global warming. This is pollution for everybody today and tomorrow, not just for the purchaser. Yet the social costs are far from reflected in the prices we pay: the economic externalities are rarely internalized, even though they should be if prices are to serve as realistic indicators. Externalities are nothing less than larcenous costs imposed on other people.

Traditional economists would agree that all costs, including the environmental and other social costs, of producing mineral commodities should be internalized if prices and costs are to reflect true trends in resource availability. The critics, however, believe that external costs are very large and pervasive. They question whether society has the ability or the will to force producers and consumers to pay these costs. They also contend

that the prices and costs recorded for mineral commodities in the past would be much higher and increasing much faster if these costs were taken into account.

Second, the marketplace provides reliable indicators of scarcity only if participants determining mineral commodity prices, extraction costs, and user costs are themselves properly informed. As Norgaard (1990, pp.19-20) has suggested: "If resource allocators are not informed, the cost and price paths their decisions generate are as likely to reflect their ignorance as reality."

Third, a small percentage of the world's population unduly determines the demand for mineral commodities due to the very skewed distribution of global income and wealth. Again, according to Myers (Myers and Simon 1994, p. 185):

> In any case, market indicators . . . reflect the evaluation only of those people who can register their money votes in the marketplace—an option that, as we have seen, is almost entirely denied to two people out of five worldwide. What would be these people's reaction to . . . assurances that spending power is steadily enhance through declining prices—or that the Waldorf is increasingly open to all?

Distortions in demand bias the trajectories of prices and the other economic indicators of resources availability. A more equitable distribution of income and wealth would allow the bottom third of the world's population to increase greatly their demand for housing, food, and other basic necessities. Of course, the richest third would have to reduce its demand for goods and services, but overall such a transformation would likely increase appreciably the demand for materials and energy. This in turn would generate a different, perhaps very different, pattern of mineral commodity prices and production costs than that produced by the highly inequitable market system that currently exists.

Fourth, the market system also fails to give adequate weight to the interests of future generations, as it is the living alone (and not their yet-to-be-born descendents) who interact in the marketplace and shape the public policies that determine commodity prices. If the voices of future generations were taken into account, the critics claim, we would discount future profits less and raise current commodity prices in order to tilt the consumption of resources more toward the future.

Fifth, the marketplace is anthropocentric and takes into account only the interests of people. Yet other species, it is argued, have intrinsic value as well. The market and public policy consider their interests only to the extent that people are prepared to champion them. This market imperfection again calls into question the validity of the economic measures of resource availability, and raises the possibility that both the level and trends in commodity prices might be far higher if the welfare of all living creatures, rather than just people, were properly considered.

These challenges to the economic measures of resource availability raise important issues, which deserve more attention. The first contends that the true costs of mineral production (and many other economic activities) far exceed the costs that producers incur and in turn the prices consumers pay. This implies a massive failure of public policy to internalize the environmental and other social costs. Few would argue that public policy is perfect. Vested interests and widespread ignorance can and often do promote sub-optimal policies. The issue here, however, is how convincing a case can be made for massive failure over an extended period of time, particularly for those countries where governments are ultimately accountable to their citizens.

The second concern—that the ignorance of market participants cripples our economic measures of resource availability—highlights the complications introduced by uncertainty and imperfect information. To what extent these complications undermine the usefulness of economic measures, however, depends on (a) the use to which they are put and (b) the pervasiveness of the ignorance. If the objective is to forecast accurately on the basis of current indicators, and if one believes that current participants in the marketplace are ill informed, then the economic measures are of questionable use. On the other hand, if current participants are thought to be reasonable savvy, one should have more confidence in the trends portrayed by economic measures. In either case, as Krautkraemer (1998, p. 2008) points out, economic indicators reflect the ". . . available information about scarcity at a particular time and that information changes over time." So economic indicators should reflect the collective wisdom of the market about how resource scarcity is changing. While this collective wisdom is imperfect, the critical question is whether it runs counter to the best evidence available on future resource scarcity over an extended period of time.

The other challenges to the economic measures of resource availability raise even more fundamental philosophical issues, regarding not just how to measure resource availability, but more importantly, the values we hold individually and collectively as a society, and thus consider when allocating resources and making decisions. Ultimately, however, these challenges are relevant only to the extent that they influence those individuals whose decisions and behavior matter, as the following quote from Stokey and Zeckhauser (1978, p. 262) so colorfully argues:

> Our main point is that it's people, and only people, that count. This means that redwoods and bluebirds and Lake Baikal and the Old

> Man of the Mountain are worth saving only if people believe them worth saving. Abstractly considered, the rights of nonhuman entities may seem a valid criterion for policy. But in fact these rights are meaningless unless championed by people; neither the redwoods nor the bluebirds can speak for themselves. If this judgment strikes you as unduly hard-nosed, look at the other side of the coin. How many voices are raised on behalf of that vanishing species, the smallpox virus? And who speaks for the boll weevil? There is ample pragmatic support for an anthropocentric approach. All philosophical justifications to the contrary, unless human beings care about redwoods, the redwoods will be destroyed.

While many thoughtful individuals would like to see a more equitable distribution of global income and wealth, it matters little for resource availability (or anything else for that matter) until such concerns actually affect the purchasing power of the economically disenfranchised. Similarly, the interests of future generations or of other species, regardless of the arguments on their behalf, affect the present only to the extent that the current generation of humans takes them into account. To say trends in resource availability would have been less favorable if public policy had been different (better) may be interesting, but it in no ways alters the actual trends.

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Figure 3.1. Reserves, Resources, and the Resource Base

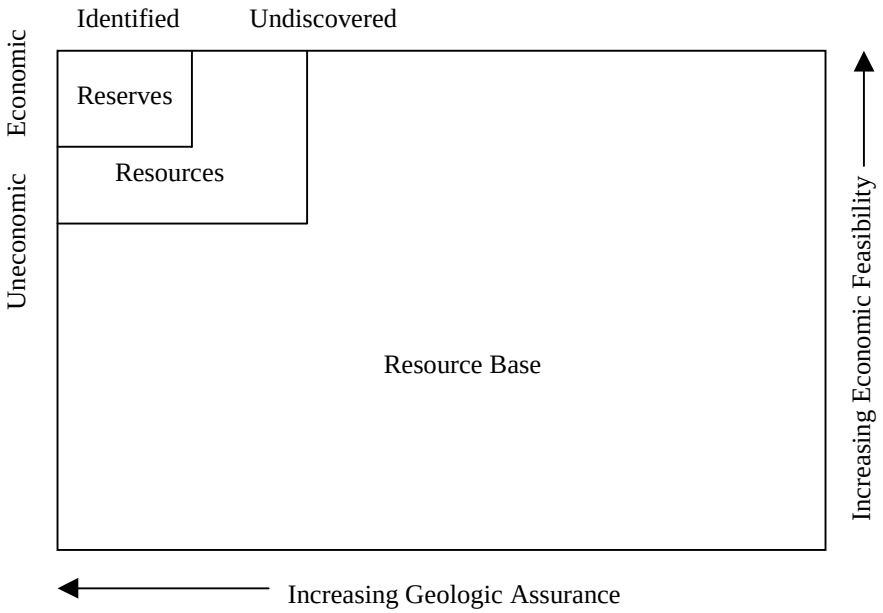

Figure 3.2. Market Price, Production Costs, User Costs, and Ricardian Rents

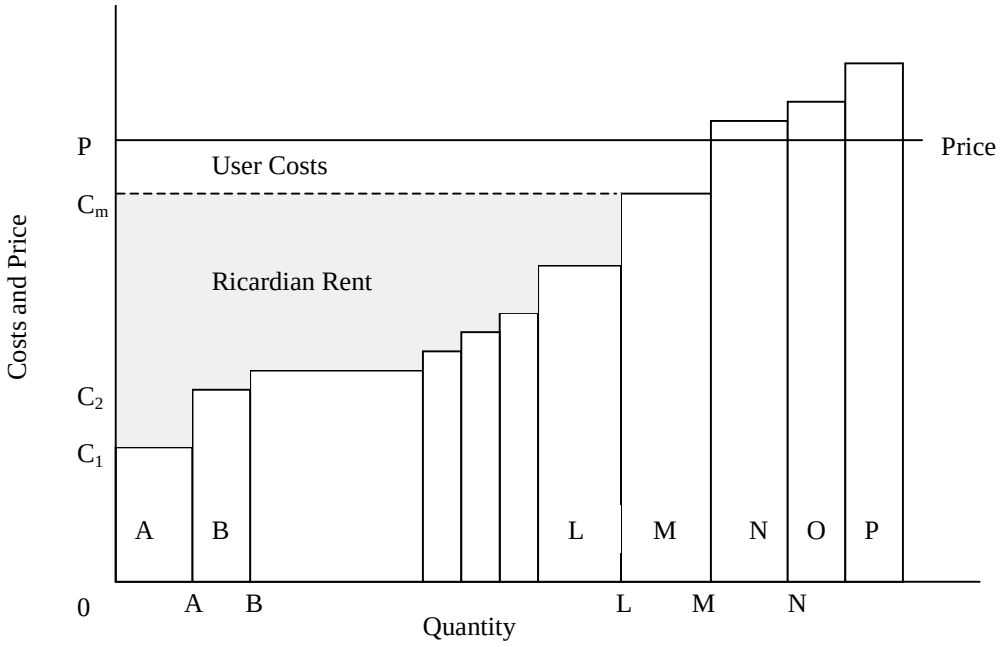

Table 3.1. Life Expectancies of World Reserves, Selected Mineral Commodities

Mineral Commodity[a]	1999 reserves[b]	1997-1999 average annual production[b]	Life expectancy in years, at three growth rates[c]			Average annual growth in production, 1975-1999 (percent)
			0%	2%	5%	
Coal	987×10^9	4561.3×10^6	216	84	49	1.1
Crude Oil	1035×10^9	23.7×10^9	44	31	23	0.8
Natural Gas	5145×10^{12}	80.5×10^{12}	64	41	29	2.9
Aluminum	25×10^9	123.7×10^6	202	81	48	2.9
Copper	340×10^6	12.1×10^6	28	22	18	3.4
Iron	74×10^{12}	559.5×10^6	132	65	41	0.5
Lead	64×10^6	3070.0×10^3	21	17	14	-0.5
Nickel	46×10^6	1133.3×10^3	41	30	22	1.6
Silver	280×10^3	16.1×10^3	17	15	13	3.0
Tin	8×10^6	207.7×10^3	37	28	21	-0.5
Zinc	190×10^6	7753.3×10^3	25	20	16	1.9

Sources: U.S. Bureau of Mines (1977), U.S. Geological Survey (2000a); U.S. Geological Survey (2000b); American Petroleum Institute (2000); BP Amoco (2000); International Energy Agency (2000).

Notes:

[a]For the metals other than aluminum, reserves are measured in terms of metal content. For aluminum, reserves are measured in terms of bauxite ore.

[b]Reserves are measured in metric tons except for crude oil, measured in barrels, and natural gas, measured in cubic feet.

[c]Life expectancy figures were calculated before reserve and average production data were rounded.

Table 3.2. Life Expectancies of Resource Base, Selected Mineral Commodities

Mineral Commodity	Resource base[b] (metric tons)	1997-1999 average annual production	Life expectancy in years, at three growth rates			Average annual growth in production, 1975-1999 (percent)
			0%	2%	5%	
Coal[a]	n/a	4561.3×10^6	n/a	n/a	n/a	1.1
Crude Oil[a]	n/a	23.7×10^9	n/a	n/a	n/a	0.8
Natural Gas[a]	n/a	80.5×10^{12}	n/a	n/a	n/a	2.9
Aluminum	2.0×10^{18}	22.4×10^6	89.3×10^9	1065	444	2.9
Copper	1.5×10^{15}	12.1×10^6	124.3×10^6	736	313	3.4
Iron	1.4×10^{18}	559.5×10^6	2.5×10^9	886	373	0.5
Lead	290.0×10^{12}	3070.0×10^3	9.4×10^6	607	261	-0.5
Nickel	2.1×10^{12}	1133.3×10^3	1.8×10^6	526	229	1.6
Silver	1.8×10^{12}	16.1×10^3	111.8×10^6	731	311	3.0
Tin	40.8×10^{12}	207.7×10^3	196.5×10^6	759	322	-0.5
Zinc	2.2×10^{15}	7753.3×10^3	283.7×10^6	778	329	1.9

Sources: The data on the resource base are based on information in Brobst and Pratt (1973, pp. 22-23) and Lee and Yao (1970, pp. 778-86). The figures for the 1997-1999 average annual production and the annual percentage growth in production for 1997-1999 are from Table 3.1 and the sources cited there.

Notes:

[a]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, rather than assessments of the resource base.

[b]The resource base for a mineral commodity is calculated by multiplying its elemental abundance measured in grams per metric ton times the total weight (24×10^{18}) in metric tons of the earth's crust. It reflects the quantity of that material found in the earth's crust.

Chapter 4

THE BENEVOLENT PAST

This chapter looks backward, back to the end of the 19th century and the beginning of the 20th century. It examines the research others have conducted to identify the historical trends in resource availability over this period. Ultimately, we are concerned about the future, not the past, and past trends, of course, may not continue into the future. Nevertheless, an understanding of the past should prove useful when we turn our attention toward the future in Chapter 5.

This chapter is organized around our three economic measures of resource availability. It looks at trends in the costs of producing mineral products first, then in mineral commodity prices, and finally in user costs. The last section attempts to draw some general conclusions about past trends in resource availability and to explain some of the inconsistencies among the three measures.

Production Costs

Mineral producing companies do not generally make their production costs available to the public. Some consulting firms, government agencies, and even producing companies collect and estimate this information, primarily for what are called cash costs

(which approximate variable costs, and thus exclude capital costs).[1] These series, however, go back at best only several decades.

As a result, efforts to measure production costs have focused on trends in the inputs used to produce mineral commodities.[2] This, for example, is the approach taken by Barnett and Morse (1963) in their pioneering book *Scarcity and Growth*, which Chapter 2 briefly notes. Using data compiled by Potter and Christy (1962) and Kendrick (1961), they construct indices of the labor used per unit of output and of the labor plus capital used per unit of output for all extractive industries. They also compute the same indices for agriculture, for minerals, for forestry, and for a number of specific industries within these economic sectors. Their study, which looks just at the United States, covers the period from 1870 to 1957.

It is important to note that Barnett and Morse measure the average labor and capital costs of resource production across all producers, and not the costs of marginal producers as one would ideally like. As a result, they tend to underestimate the labor and capital required by the marginal producers. This, however, may not greatly affect their results and findings. Since they are looking at trends over time, trends in an index of average costs may closely follow the trends in an index of marginal costs.

Table 4.1 shows their results when production costs are measured in terms of labor and capital inputs per unit of output. At the time the Barnett and Morse study appeared, these results created considerable surprise. They indicate that the labor and capital inputs needed to produce extractive resources in general declined dramatically—

[1] See, for example, U.S. Bureau of Mines (1987) and Torries (1988, 1995).
[2] When physical measures of inputs are used, such as number of employees, this procedure does have the advantage that the results are not influenced by changes in wages and other input prices, whose movements presumably do not reflect resource scarcity.

by over 50 percent—during the nearly 90-year period examined, despite the dramatic growth in their consumption. Moreover, the pace of decline was greater after 1919 than before, suggesting not only that resources were becoming more available over time, but that they were doing so at an accelerating rate. Finally, the fall in production costs was even greater for the mineral sector—over 75 percent—although this sector unlike agriculture and forestry relies upon nonrenewable resources.

Barnett and Morse attribute these favorable trends largely to technological change. New technologies lower the costs of finding new resources. New technologies allow the exploitation of previously known but uneconomic resources. New technologies permit the substitution of less scarce resources for more scarce resources. New technology reduces the amount of resources needed to produce final goods and services. Moreover, according to Barnett and Morse (1963, pp. 9-10):

> These developments . . . are not essentially fortuitous. At one time they were, but important changes have occurred in man's knowledge of the physical universe over the past two centuries, changes which have built technological advance into the social processes of the modern world. . . . Not only ingenuity but, increasingly, understanding; not luck but systematic investigation, are turning the tables on nature, making her subservient to man. And the signals that channel research effort, now in one direction, now in another—that determine innovational priorities—are usually the problems calling loudest to be solved. Sometimes the signals are political and social. More often, in a private enterprise society, they are market forces.

The Barnett and Morse study, in large part because of its surprising findings, did not go unchallenged. Indeed, the study fostered a wave of research on resource extraction and processing costs that continues down to the present. Some writers (Cleveland 1991) question the focus on just labor and capital inputs, arguing the results might be quite

different if energy and other inputs were also taken into account. Others, including Barnett (1979) himself, raise the possibility that production costs could be falling in the United States, thanks to that country's increasing reliance on imports, while rising for the world as a whole. Still others note that the rising environmental costs associated with resource production were not included in their figures. Finally, some commentators (Johnson and others 1980, Hall and Hall 1984) claim that extending the Barnett and Morse analysis beyond 1957 might uncover a reversal in the downward cost trend.

While all the above are legitimate concerns, the Barnett and Morse results have proven remarkably robust. Subsequent research (Barnett 1979, Johnson and others 1980, Slade 1988, Slade 1992, and Uri and Boyd 1995) on the costs of resource extraction has for the most part supported the Barnett and Morse conclusion that production costs have fallen since the late 1800s for resources in general, and particularly so for nonrenewable mineral resources.[3]

Mineral Commodity Prices

Mineral commodity prices enjoy two important practical advantages over the two other economic indicators of resource availability. First, they are readily available and easy to obtain. Second, they are reasonably reliable. This is particularly true for mineral prices set on commodity exchanges, such as the London Metal Market. As a result, there is a rich history of studies of mineral commodity prices.

This section looks first at the early studies undertaken in the 1960s and 1970s. It then focuses on the attempts to model the historical trends in mineral commodity prices

that began in the 1980s. These early modeling efforts in turn fostered a number of more sophisticated models, in some instances employing new advances in time series analysis. They are considered toward the end of the chapter.

Early Efforts

Potter and Christy (1962) provide one of the first systematic analyses of price trends for natural resource commodities. This work covers a variety of agricultural, mineral, and forestry products in the United States. It spans the period 1870 to 1957, and was subsequently updated to 1973 by Manthy (1978). Nominal prices are converted to real prices by using the U.S. producer price index (PPI) to adjust for inflation.[4]

Figure 4.1, reproduced from Potter and Christy, shows the long-run price trends for all resources, and for the agricultural, mineral, and forestry sectors separately. It indicates that mineral prices fell by over 40 percent between 1870 and 1957. All this decline, however, took place during the first decade of this period. Since 1880, mineral prices display considerable short term fluctuations in response to wars and other disturbances, but the long term trend is quite stable. The data for all minerals, however, hide major differences in price trends among individual commodities. For example, the real prices of coal, lead, and lime rose over the 1870-1957 period, while those for iron, zinc, copper, petroleum, and phosphate rock fell.[5]

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[3] For an exception, see Hall and Hall (1984).

[4] The U.S. wholesale price index became the producer price index in 1978. To avoid confusion, this chapter refers to both by the current name, the producer price index, or by its abbreviation, PPI.

[5]Potter and Christy provide price data for four energy commodities (petroleum, natural gas, bituminous coal, and anthracite coal), for fourteen metals (iron ore, pig iron, steel, ferroalloys, ferromanganese, nickel, tungsten, copper, lead, zinc, bauxite, aluminum, tin, and magnesium), and for fourteen non-metallic minerals (dimension stone, crushed and broken stone, portland cement, lime, sand, gravel, clays, structural clay products, building brick, gypsum, phosphate rock, potash, sulfur, and fluorspar).

Barnett and Morse (1963) also examine the price data collected by Potter and Christy, deflating these data by the prices of non-extractive goods, rather than the PPI. Abstracting from short-run movements, they find mineral prices have remained quite constant since the last quarter of the 19th century. These findings are similar to those of Potter and Christy, and stand in sharp contrast to the dramatic decline Barnett and Morse find in the production costs of mineral commodities over the same period. Nevertheless, Barnett and Morse contend that trends in prices like those for production costs provide no support for the hypothesis that mineral depletion is causing resource scarcity

Writing a decade later, Nordhaus (1974) does find substantial declines in the long-run price trends for many important mineral commodities. Between 1900 and 1970, for example, his work shows a price drop of 97 percent for aluminum, 90 percent for petroleum, 87 percent for copper, lead, and zinc, 84 percent for iron, and 78 percent for coal. Nordhaus uses the cost of labor to deflate the prices of mineral commodities, which largely explains why his results differ from Potter and Christy and from Barnett and Morse. Over the years labor costs have risen much more rapidly than the prices of wholesale goods or of non-extractive goods.

These findings highlight the fact that long-run price trends may vary considerably depending on the deflator used to adjust for inflation. Nordhaus's deflator—labor costs—has the advantage that it shows trends in the number of hours of labor that one could buy for the price of various mineral commodities, a measure of opportunity costs that is easy to comprehend. On the other hand, labor costs have risen in part because of investments in human capital (more education, improvements in on-the-job training, better health), which have little or nothing to do with trends in mineral resource availability.

Econometric Models

Smith (1979) provides one of the earliest attempts to model mineral price trends. Relying primarily on the data of Potter and Christy (1962), as updated and modified by Manthy (1978), he postulates the following simple linear time trend over the 1900-1973 period for the real prices of four categories of natural resources (total extractive goods, mineral commodities, forestry products, and agricultural goods):

$$P_t = \alpha_0 + \alpha_1 t + \varepsilon_t \quad \ldots \quad 4.1$$

Where P_t is the average price in year t for each of the natural resource categories deflated by the U.S. producer price index, t is the time trend (t = 1, 2, . . .74), ε_t is the stochastic error in year t, and α_0 and α_1 are unknown parameters, which are assumed to remain constant over the period.

Smith uses regression analysis to estimate the parameters, and finds that the estimates for the parameter of the trend variable (α_1) are statistically significant (in the sense that they differ from zero with a probability of 90 percent or more) only in the case of forest products. These results at first blush appear to support the conclusions of Potter and Christy and of Barnett and Morse that aside from the forestry sector there has been no significant trend over the long term in the real prices of natural resource products.

Smith, however, argues that this conclusion is warranted only if the parameters in his model (α_0, α_1) remain constant over the entire 1900-1973 period. Using two alternative statistical techniques,[6] he shows that this is highly unlikely. In the case of

[6] The first is the Brown and Durbin cusum test, and the second the Quandt log-likelihood ratio.

minerals, his findings suggest that the estimate for the time trend parameter (α_1) was negative and rising toward zero over the decade from 1910 to 1920, implying that prices were falling over this period but at a slower and slower pace. The time trend parameter then turns positive during the 1920s and 1930s, implying that prices were rising over these years. It becomes negative again during the 1940s, 1950s, and early 1960s, and thereafter remains very close to zero until 1973, the end of the period examined.

These findings, he suggests, should not be surprising. Over the years 1900-1973 many changes affecting resource price trends were occurring. The nature of the U.S. economy was evolving, causing substantial shifts in the relative importance of individual commodities within the aggregate categories. Petroleum, for example, was becoming much more important both within the mineral sector and within the extractive goods sector as a whole.

Smith contends that these changes mean the long-run time trends that real resource prices are following have changed over the 1900-1973 period. As a result, the failure of real resource prices to rise over the long run may obscure more recent evidence covering a shorter period of time that may reflect growing resource scarcity. For this reason, he questions the conclusions of Potter and Christy and of Barnett and Morse.

Slade (1982), in an influential empirical study, argues that the true relationship between real resource prices and time is U-shaped.[7] In support of this hypothesis, she notes that the prices for mineral commodities should, under competitive market conditions, equal their marginal production costs plus user costs (as shown in Figures 2.1 and 3.2).

[7] This possibility is also suggested by Pindyck (1978) and Heal (1981).

User costs according to Hotelling (as we saw in Chapter 2) should be increasing over time. Production costs, however, may be rising or falling. Slade contends that technological change tends to push extraction and processing costs down over time, while the need to exploit lower grade and poorer quality deposits tends to drive production costs up. For a time, the beneficial effects of technological change may offset the adverse effects of poorer quality deposits as well as the rise in user costs. In this case, production costs will fall by more than user costs rise, allowing real price to decline.

This favorable trend, however, cannot continue indefinitely. Over time production costs account for a smaller and smaller share of the sum of production costs and user costs, and so the rise in user costs must eventually more than offset the decline in production costs. Slade believes this reversal will be reinforced by natural limits on new technology that eventually cause even production costs to rise.

Figure 4.2 portrays the expected scenario. At the beginning of the period under analysis (T_0), user costs are quite small compared to marginal production costs. Early in the period, thanks to technological change, production costs fall sufficiently to offset the upward trend in user costs. This favorable trend continues until time T_1, after which the rise in user costs exceeds the decline in production costs, causing price to rise. Eventually, at time T_2, the downward trend in production costs is also reversed as the rise in costs caused by the decline in ore grade and deposit quality offsets the effects of new technology.

Slade tests this hypothesis for eleven important mineral commodities—three fuels (coal, natural gas, and petroleum) and eight metals (aluminum, copper, iron, lead, nickel,

silver, tin, and zinc). She assumes the hypothesized U-shaped relationship between price and time can be captured by the following quadratic function:

$$P_t = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 4.2$$

Where P_t is the average price in year t for each of the eleven mineral commodity deflated by the U.S. producer price index, t is the time trend (t = 1, 2, . . .), ε_t is the stochastic error in year t, and α_0, α_1, and α_2 are unknown parameters.

For each commodity, Slade uses price data from 1870 (or the first year data are available) to 1978 and regression analysis to estimate the parameters (α_0, α_1, α_2) of equation 4.2. For comparison purposes, she also estimates the linear relationship, shown in Equation 4.1, between prices and time.

Her assumed U-shaped relationship between prices and time anticipates that the estimate for α_1 will be negative and the estimate for α_2 will be positive, a result that she finds holds for all eleven mineral commodities. Moreover, except for lead, the estimates for α_2, which indicate a non-linear relationship, are positive with probability levels that exceed 90 percent. These results provide strong support for Slade's hypothesis that mineral prices tend to fall and then rise over time. Moreover, in all cases she finds that the minimum point on the estimated relationship between price and time is reached before 1973. This, she concludes, ". . . indicates that nonrenewable natural-resource commodities are becoming scarce" (Slade 1982, p. 136).[8]

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[8] The results for the linear equation compared with those for the quadratic equation suggest that the latter more accurately reflects the true relationship between mineral prices and time. First, as noted, all but one of the estimated parameters for square of time variable in the quadratic equation are positive at the 90 percent probability level. If the true relationship between prices and time were linear, this parameter would be zero. Moreover, all of the estimated linear relationships considerably underestimate mineral prices toward the end of the period covered, which is not the case for the estimated quadratic relationships. Interestingly, the

Recent Developments

In large part because of its important implications for the long-run availability of mineral commodities, Slade's study has received considerable attention. Subsequent studies have raised a number of concerns or caveats about her analysis:

1. As we saw earlier, Smith questions whether one can assume the parameters of the simple linear model are constant over time. The same question can be raised for Slade's quadratic relationship.

In her article, Slade (1982, pp. 129,136) actually addresses this issue in passing. If the true relationship is as she assumes a quadratic function, with prices first declining but eventually rising, Smith should find the estimated parameter on the time variable when his linear equation is used to be negative in the early years of his sample, but declining toward zero. Eventually, it should turn positive, as real prices bottom out and start to increase. Slade claims this is what Smith's results show. A close look at his results for the mineral sector indicates that this is true for the period up to 1920, but not thereafter. This is not what we would expect if the quadratic equation with invariant parameters applied over the entire 1870-1978 period that Slade examines. Berck (1995) and Pindyck (1999) provide further evidence that the long-run relationship between mineral prices and time changes over time.

This is troubling, for its suggests efforts to estimate empirically such relationships are shooting at moving targets. Any given effort, particularly if it covers a long span of time, is likely to reflect a hybrid curve that reflects several different true relationships,

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results for the linear equation provide much less support for the conclusion that mineral resources are experiencing increasing scarcity. Only seven of the eleven estimated parameters on the time variable were

each relevant over different periods with no guarantee that estimated results even closely approximate the current long-run relationship.

2. A related challenge comes from modern time series analysis, much of which was not available to Slade in the early 1980s when she wrote her original article. The statistical properties of her results, which so strongly support her hypothesis regarding the long-run trend in mineral prices, depend on mineral prices being what is called trend stationary. This means that the prices of mineral commodities will revert back to the same long-run trends if disturbed by a short-run shock, such as a strike or a war. If this is not the case, then prices follow a stochastic trend, and the parameters (α_0, α_1, α_2) change over the period examined in response to short-run shocks.

Several scholars (Agbeyegbe 1993, Berck and Roberts 1996, Ahrens and Sharma 1997), including Slade (1988), have subsequently carried out tests to determine if the price series for the mineral commodities she considers are trend stationary. The results vary, in some cases the trends are stationary, in other cases they are stochastic.

3. Slade's analysis ends in 1978. As Krautkraemer (1998) shows in some detail, the prices for many energy and other mineral commodities fell during the 1980s and 1990s. This raises the possibility that her findings might be quite different if the study were carried out today.

Howie (2001) has recently updated Slade's data, and the results are shown in the Appendix to this study. He also re-estimates her equations, using the same regression techniques and commodities. The results provide somewhat mixed support for Slade's original findings. The quadratic function does a better job of tracking the long-run trends in mineral prices than the linear function for some but not all of her eleven commodities.

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positive, and only four of these at a probability of level of 90 percent or more.

Howie also finds that the price trends for certain commodities are stochastic not stationary.

4. Like most other scholars analyzing long-run price trends, Slade assumes that a commodity's price equals its marginal production cost plus user costs. Implicitly, she and others assume that the marginal production costs reflected in prices are those that prevail over the long-run, not the short run, for long-run production costs are what are relevant for measuring the long-run availability of mineral commodities.

We know that in the short run (a period so short that firms cannot change their capacity), when the demand for mineral commodities exceeds the available capacity, marginal production costs can for a time far exceed their long-run levels. On the other hand, when the economy is depressed and the mineral industries suffer from excess capacity, marginal production costs are likely to fall below their long-run levels. By examining mineral prices over a number of decades, Slade and others presume that such short-run deviations of production costs and prices from their long-run values more or less cancel out.

A more troubling problem arises when prices are not the outcome of the interaction of supply and demand in a competitive market. This can occur when producers acting individually or collusively exercise market power and control the market price. It can also occur during wars and other emergencies, when governments impose price controls on mineral commodities. Such market distortions have occurred with some frequency in the past, as Figure 4.3 illustrates for copper. During such periods, price is a biased indicator of availability, overestimating scarcity when cartels and other

collusive activities maintain the price at artificially high levels and underestimating scarcity when price controls keep prices from reaching their market clearing levels.

Slade (1982, footnote 14) raises the possibility that the OPEC cartel and the increases in energy prices it produced after 1973 might account for the subsequent upturn in mineral prices. She dismisses this possibility, however, by noting that the estimated curves for all of the mineral commodities she examines reached their minimum point before 1973.

While the general public is well aware of OPEC's efforts to control the price of oil since 1973, less well known are the frequent attempts to control the price of copper, nickel, tin, and numerous other mineral commodities over the past century. Most of these efforts lasted for only a few years, but unlike the short-run impact of the business cycle on prices, there is no tendency for the effects of market power on price to cancel out over the long run.[9]

The available literature, unfortunately, provides few studies that systematically examine how market power alters the long-run trends in commodity prices. We do know that over the past century many non-fuel mineral markets have become more competitive as the costs of transporting bulk commodities have fallen and the demand for mineral commodities has grown. This suggests that long-run prices may underestimate trends in scarcity. Thanks to OPEC and its effects on oil and other energy prices since the early 1970s, just the opposite may be true for the energy markets.

Some years ago, Herfindahl (1959) conducted an interesting study of copper prices and costs, and found that the effects of market power can be substantial. Carefully examining the period 1870 to 1957, he identifies the years during this period that were

abnormal, in the sense that collusion, wars, or depression seriously distorted the copper price (see Figure 4.3). He also divides the years before World War I from those after, since a revolutionary change in technology at around that time caused a one-time drop of some 37 percent in real prices. Of particular interest for our purposes, he finds that the copper price deflated by the producer price index (PPI) declined over the 1870-1918 period by five percent a year when the abnormal years were excluded, compared with four percent a year when they were included. For the 1918-1957 period, the difference was much greater: real prices increased by 0.2 percent a year when the abnormal years were excluded compared with 0.6 percent when they were included.

Herfindahl's work calls into question, at least for copper since 1918, the premise advanced above that a decline in market power over time has introduced a downward bias in our price measures of scarcity for the non-fuel mineral commodities. It also raises the possibility that long-run trends in the real prices of mineral commodities may contain breaks, or abrupt downward shifts, and thus fail to follow the smooth continuous trends so often assumed in studies (especially econometric studies) of mineral commodity prices. Finally, the Herfindahl study shows that systematic efforts to purge the distortions introduced by market power and other factors that cause prices to deviate from their market clearing values are possible.

5. Slade uses the PPI to deflate the nominal prices of mineral commodities. While this index is widely used, rarely is it justified beyond mentioning the need to eliminate the effects of inflation. There are, of course, other deflators one might use. As we have seen, Barnett and Morse (1963) find the prices of non-extractive goods most appropriate

[9] For studies of cartels in the mineral and energy industries, see Eckbo (1976) and Schmitz (1995).

for their purposes. Nordhaus (1974) uses the cost of labor, and Krautkraemer (1998) the consumer price index (CPI). Another candidate is the GDP deflator.

Conceptually, the deflator used should depend on how we want to measure resource scarcity. This is done by considering the sacrifice, usually in terms of some basket of goods, that society has to give up to obtain an extra ton of copper or barrel of oil. If the desired sacrifice is a representative sample of all the goods and services that comprise the economy, then the GDP deflator is the most appropriate. If the desired sacrifice is a representative sample of all consumer goods and services, then the CPI should be used.

While either of these two baskets of goods is probably more appropriate than a basket of producer goods, the PPI, which Slade and many others use, has the advantage that it is available over an extended period of time. In addition, there is little to suggest that the long-run trends in real mineral prices would be significantly altered if the GDP deflator or CPI were used instead.

We do know from our earlier discussion of Nordhaus (1974) that using the cost of labor makes a big difference. Since labor costs have risen much more than the costs of most goods and service, deflating by labor costs produces real mineral prices that distinctly trend downward over the long run. Deflating by the cost of labor is appropriate when one desires to measure the sacrifice in terms of how much labor (leisure) one can buy for the price of an additional unit of a mineral commodity. As noted earlier, however, it suffers from the fact that the cost of labor has risen over time for reasons that have nothing to do with trends in resource scarcity. In addition, it implies that the appropriate

basket of goods for measuring the opportunity costs contains just one good, labor services.

Perhaps a more serious shortcoming of the PPI, and of other commonly used deflators as well, arises from their tendency to overestimate inflation. Several years ago a Congressional Advisory Commission estimated that the U.S. CPI overestimates inflation by 1.1 percent a year (U.S. Senate, Committee on Finance 1966, Boskin and others 1998, Moulton and Moses 1997). Most of this bias (0.6 percent) is attributed to the introduction of new goods and improvements in the quality of existing goods. The rest reflects the failure of the consumer price index to account properly for consumer substitutions in response to price changes (0.4 percent) and for discount stores and other improvements in retailing (0.1 percent).

While these exact percentages may not apply to the PPI, there is no doubt that it too overestimates inflation for the same set of reasons. This would not be a problem if the reported prices for mineral commodities were similarly biased, but this is clearly not the case. Appropriate adjustments for quality changes, new products, and user substitutions would not significantly alter the long-run price for a particular grade of crude oil or for other mineral commodities. As a result, deflating nominal mineral prices by the PPI or any of the other common price indices generates long-run series of real prices that underestimate the true trends (Svedberg and Tilton, forthcoming).

Figure 4.4 provides some indication of the magnitude of this bias. It shows the real price of crude oil over the 1870-1998 period, deflated first by the PPI, then by the PPI minus 0.75 percent per year, and finally by the PPI minus 1.25 percent per year. The price for petroleum properly adjusted for inflation presumably lies somewhere between

the last two curves. Not surprisingly, making this adjustment changes the course of long-run prices, causing them to trend significantly upward. A comparable change in the long-run trends for other mineral commodities occurs when their prices are similarly adjusted.

The above reservations about the Slade model raise legitimate concerns. What is less clear is how they, particularly when combined, affect her findings and the implications for the long-run availability of mineral commodities. We will revisit this issue at the end of this chapter.

User Costs

Our third economic measure of long-run trends in resource availability is user costs. As chapters 2 and 3 point out, user costs are the present value of the future profits that a mine loses as a result of increasing current output by one unit. Moreover, it is important to stress that the relevant mine is the marginal producer, as the current market price just covers its extraction costs plus user costs. Intra-marginal mines enjoy relatively low extraction costs thanks to particularly good ore or other considerations. So expanding current output by one unit causes intra-marginal mines to suffer a greater loss of future profits than marginal producers, but this loss reflects both user costs and the Ricardian rent associated with the quality of reserves (see Figure 3.2).

While Hotelling, Slade, and others anticipate on the basis of theory that user costs will rise over time at some fixed percentage rate, this result holds only under a fairly restrictive set of conditions, as Hotelling explicitly notes.[10] For example, Hotelling assumes only one homogenous ore (hence no differences in grade or other characteristics)

and no technological change. Relaxing either of these assumptions allows user costs to follow other trends, including a decline over the long-run. Should the development of cheap solar power, for example, make the production of coal and natural gas uneconomic, the user costs associated with coal and natural gas production would fall to zero, since there would be no loss of future profits as a result of producing more today.

Thus, there is a need to measure trends in user costs. Not surprisingly, marginal mines do not report (and probably are not even consciously aware of) the expected net present value of the loss in future profits they incur by increasing their output an additional unit today. This means indirect measures of user costs are necessary. Assuming resource markets are competitive and certain other conditions, user costs reflect the in situ value (the value in the ground before extraction) of the reserves that the marginal mine owns and is exploiting. This in turn, again under the proper conditions, approximates the costs of finding such reserves. As a result, three indirect methods exist for estimating long-run trends in user costs for mineral commodities—the difference between their market price and marginal costs of production, the in situ value of marginal reserves, and the expected exploration costs of finding new marginal reserves.

None of these measures is easy to estimate over long periods due to the dearth of data and other problems. As a result, published studies on user costs are far less numerous than those on mineral prices. Moreover, the studies that do exist come to different conclusions. A few (Fisher 1981, Stollery 1983, Sadorsky 1991) find evidence of increasing user costs. Halvorsen and Smith (1991) fail to find any significant trend. Others (Farrow 1985, Pesaran, 1990, Lasserre and Ouellette 1991) conclude user costs are falling.

[10] For a complete list of these conditions, see Chapter 2.

This somewhat confusing state of affairs is confounded further by other evidence, which suggests that user costs, while a fascinating intellectual construct, may be of little or no significance in practice. In particular, it is difficult, if not impossible, to find instances where mine managers have deliberately reduced profitable production on the grounds that the resulting increase in future profits, properly discounted, more than makes up for the loss in current profits. Indeed, it is rare to find mine managers who are even familiar with the concept of user costs.

The uncertainty created by new technology and other unexpected developments may simply make user costs largely or entirely irrelevant in the real world. Radetzki (1992), for example, points out that Sweden benefited greatly from the exploitation of its iron ore deposits from the beginning of the 20th century through the 1950s. However, the ability of these mines to compete, which was largely based on their close proximity to the steel industries of Europe, was undermined during the 1960s and 1970s by the technological revolution in the ocean transport of bulk commodities. Had Sweden decided to save these deposits in the hope of realizing even larger (discounted) profits in the future, the country would likely have reaped no benefits. In retrospect, the user costs of mining Swedish iron ore in the first half of the 20th century apparently were zero.

An Overview

The three economic measures just reviewed, as Chapter 3 points out, reflect different aspects or sources of scarcity. User costs focus on the availability of the resource in the ground. Marginal costs focus on the production process and its impact on

availability. Prices reflect the combined effects of both trends in in situ availability and in production.

The available evidence on production costs indicates that the cost-reducing effects of new technology have more than offset the cost-increasing effects of the decline in the quality of the resources being exploited. As a result, production costs have fallen substantially for mineral commodities over the past century.

Historical trends in user costs and mineral commodity prices, on the other hand, are far less clear. In the case of user costs, obtaining reliable data over an extended period is quite difficult. This is not a problem for mineral prices, but interpreting the trends is. Some studies see long-run price as stationary, and conclude growing scarcity is not a problem. Others find trends following a U-shaped curve over time, and conclude that scarcity is on the rise. To this, one must add the problems of identifying the appropriate price deflator and the uncertainties they introduce.

Despite such inconsistencies, the available evidence does permit two general conclusions. First, over the past century, a period when the demand for mineral commodities exploded and the world consumed more mineral resources than all previous history combined, the depletion of mineral resources has not produced serious scarcity problems. The consumption of most mineral commodities today is as high as it has ever been. While the long-run trends in mineral prices may be confusing, they have clearly not forced the world to curtail its mineral consumption. As Krautkraemer (1998, p. 2091) has pointed out:

> Economic indicators of nonrenewable resource scarcity do not provide evidence that nonrenewable resources are becoming significantly more scarce. Instead, they suggest that other factors of nonrenewable supply, particularly the discovery of new deposits, technological progress

> in extraction technology, and the development of resource substitutes, have mitigated the scarcity effect of depleting existing deposits.

Second, the evidence from the past also strongly suggests that the long-run trends in mineral prices, and more generally in the availability of mineral commodities, are not fixed. Rather they shift from time to time in response to changes in the pace at which new technology is introduced, in the rate of world economic growth, and in the other underlying determinants of mineral supply and demand. This not only complicates the task of identifying the long-run trends that have prevailed in the past, but cautions against using those trends to predict the future. Since the trends have changed in the past, they presumably can do so as well in the future.

The lessons to be learned from the past, it seems, are nicely summarized by Neumayer (2000, p. 309) when he states:

> So far, the pessimists have been wrong in their predictions. But one thing is also clear: to conclude that there is no reason whatsoever to worry is tantamount to committing the same mistake the pessimists are often guilty of—that is the mistake of extrapolating past trends. The future is something inherently uncertain and it is humans' curse (or relief, if you like) not to know with certainty what the future will bring. The past can be a bad guide into the future when circumstances are changing. That the alarmists have regularly and mistakenly cried 'wolf!' does not *a priori* imply that the woods are safe.

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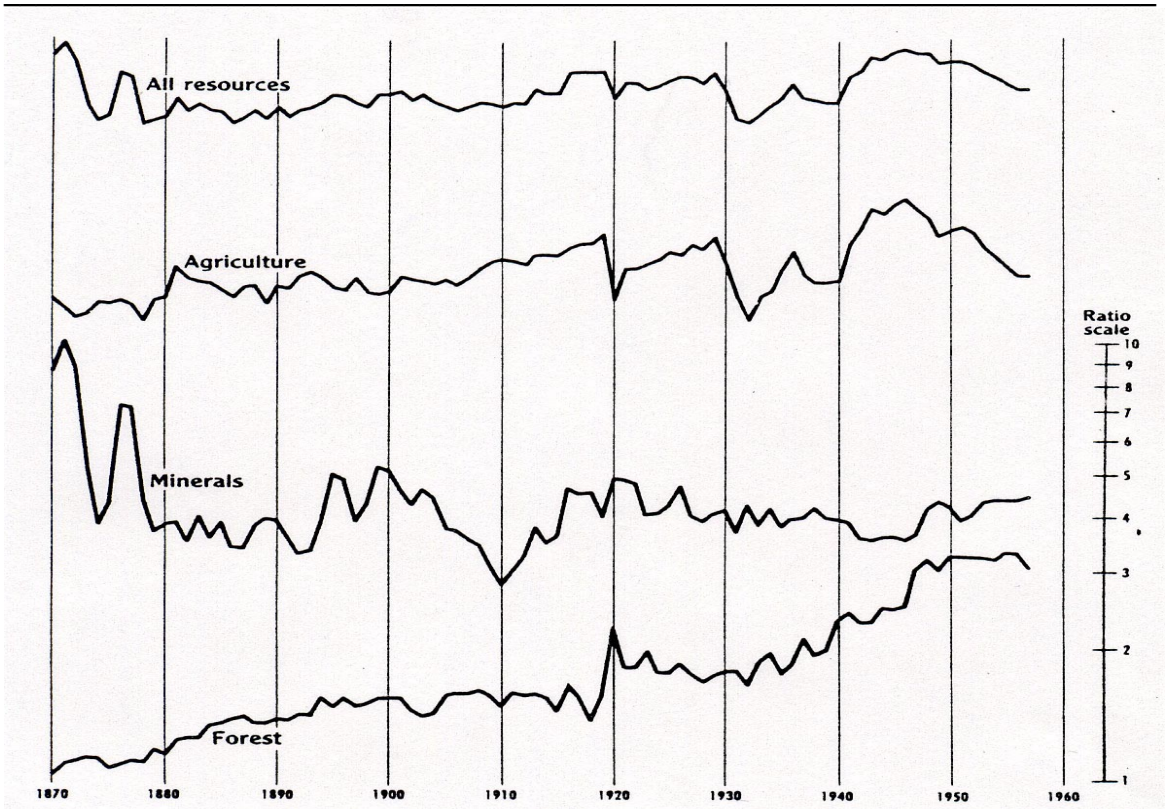
Table 4.1. Indices of Labor and Capital Inputs Per Unit of Output for the U.S. Extractive Industries as a Whole, for Agriculture, for Minerals, and for Forestry, 1870-1957
(1929 = 100)

	Total Extractive	Agriculture	Minerals	Forestry
1870-1900	134	132	210	59
1919	122	114	164	106
1957	60	61	47	90

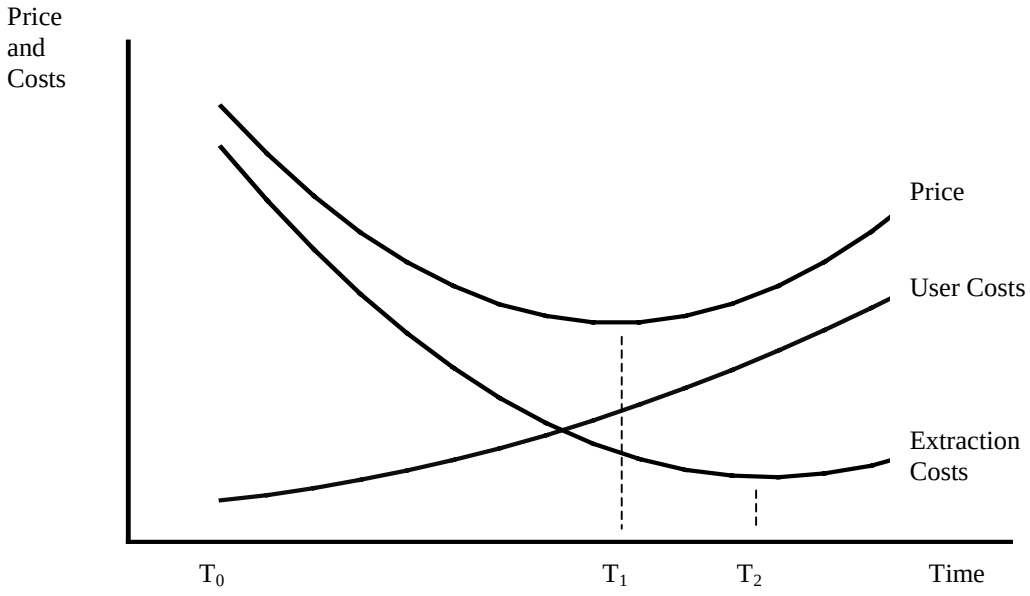
Source: Barnett and Morse (1963), p. 8.

Figure 4.1. Real Prices for All Resources and for the Agriculture, Minerals, and Forest Sectors



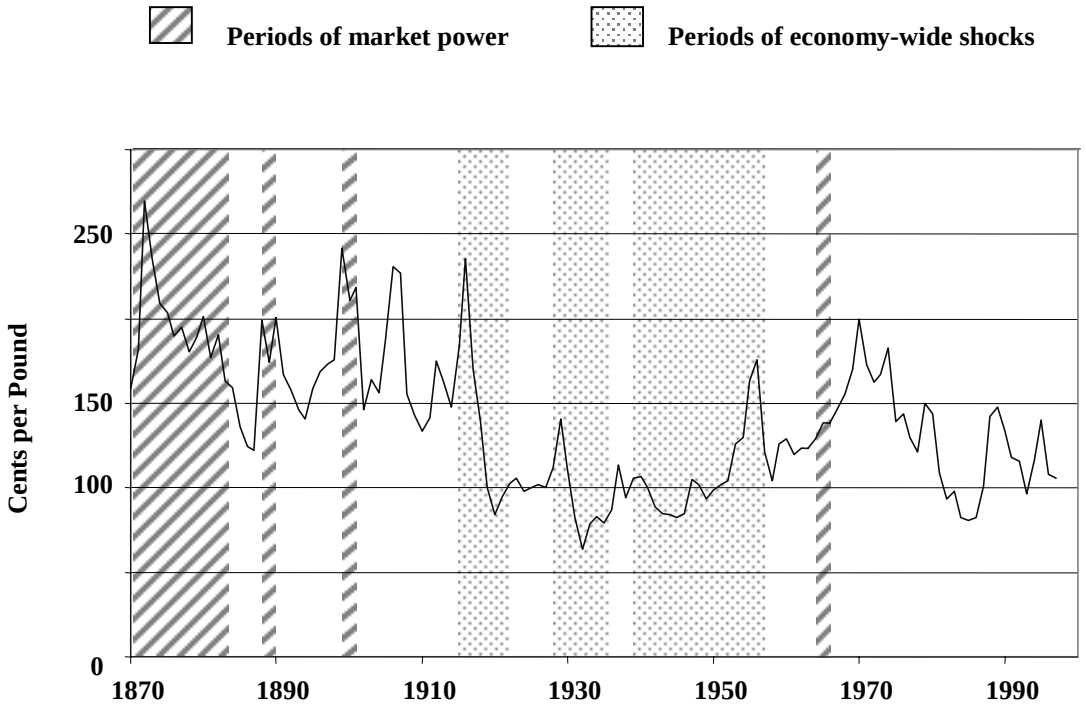
Source: Potter and Christy (1962), Chart 1.

Figure 4.2. Hypothesized Trends in User Costs, Production Costs, and Prices for Mineral Commodities



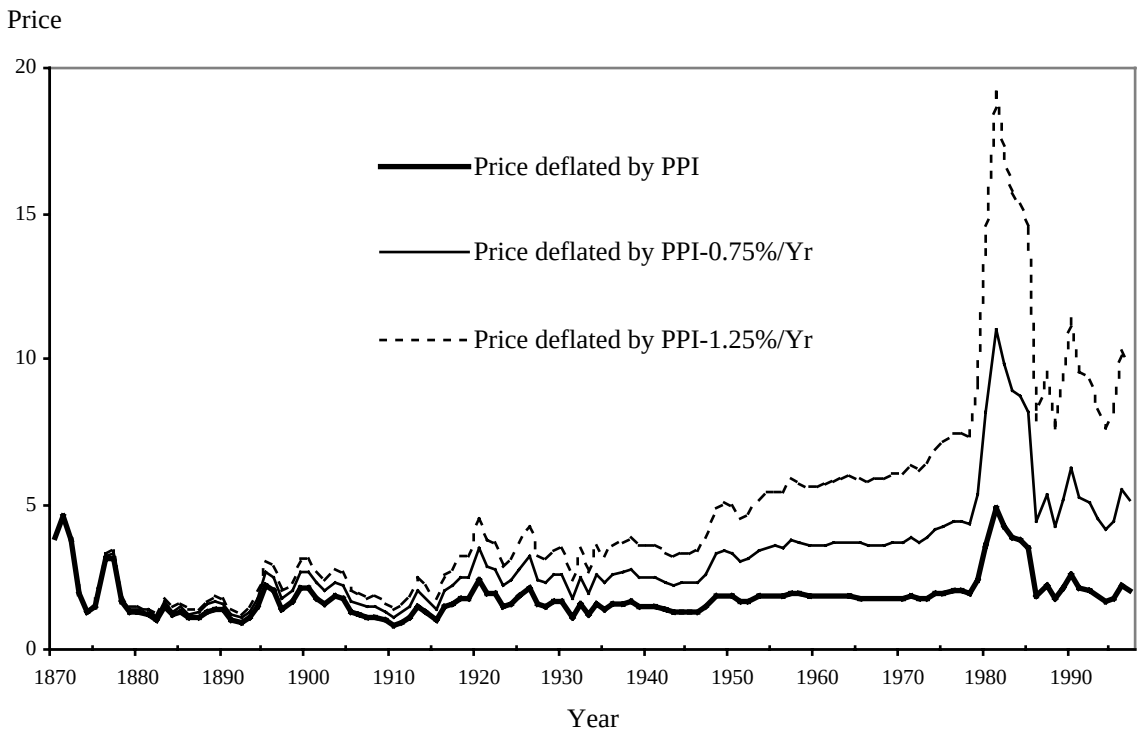
Source: A modification of Figure 1 in Slade (1982).

Figure 4.3. Real Copper Prices in 1997 Dollars Per Pound from 1870 to 1997 With Occurrences of Cartels, Wars, Major Depressions, and Other Market Distortions



Sources: Herfindahl (1957) and Mikesell (1979) as updated by Howie (2001)

Figure 4.4. Real Price of Petroleum Deflated by (a) the PPI, (b) the PPI Minus 0.75 Percent per Year, and (c) the PPI Minus 1.25 Percent per Year, 1870 – 1997, in (1870) Dollars per Barrel



Sources for oil prices deflated by the PPI: Potter and Christy (1962), Manthy (1978), Slade (1978), as updated by Howie (2001)

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

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[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.

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[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

$Q = Pop \times (Y/Pop) \times (Q/Y)$ 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.

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[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.

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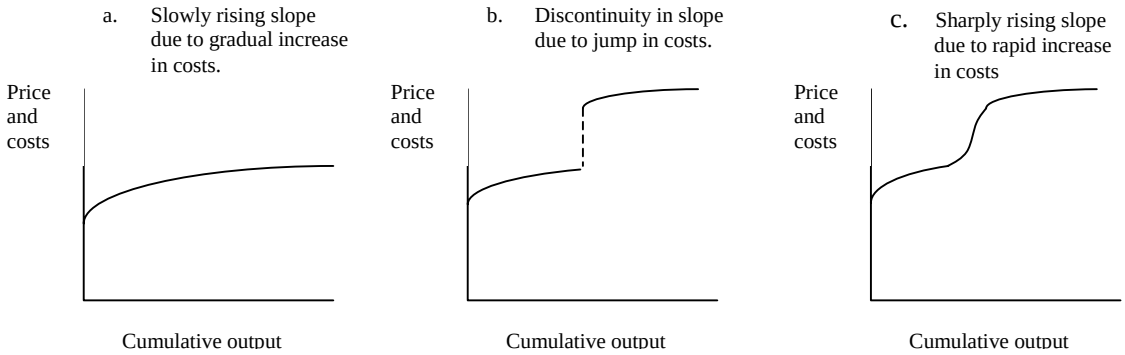
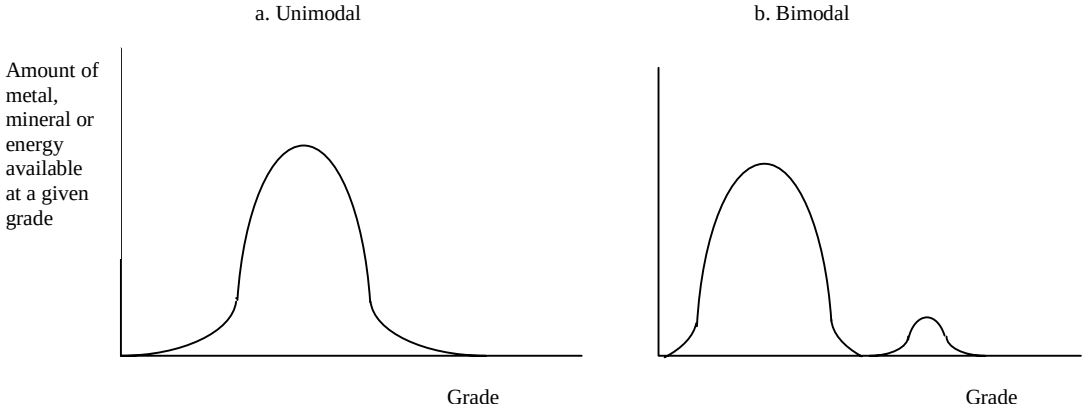
Figure 5.1. Illustrative Cumulative Supply Curves



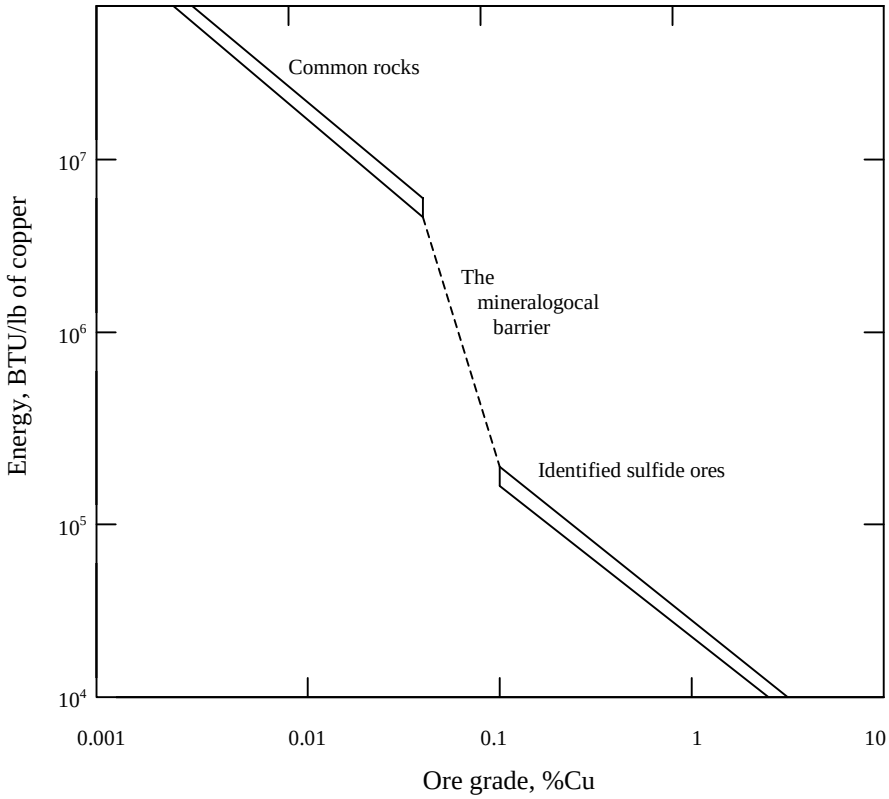
Source: Tilton and Skinner (1987).

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



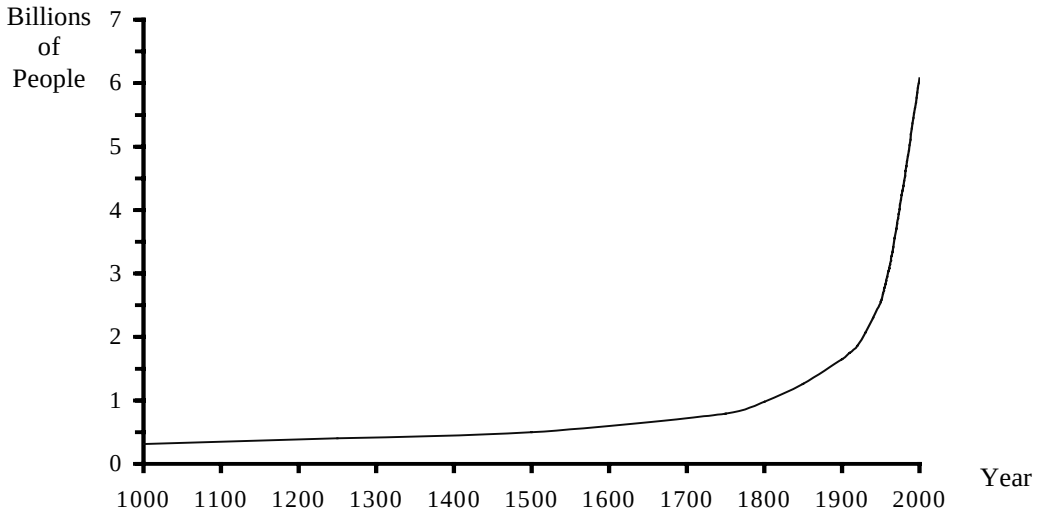
Source: Skinner (1976).

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



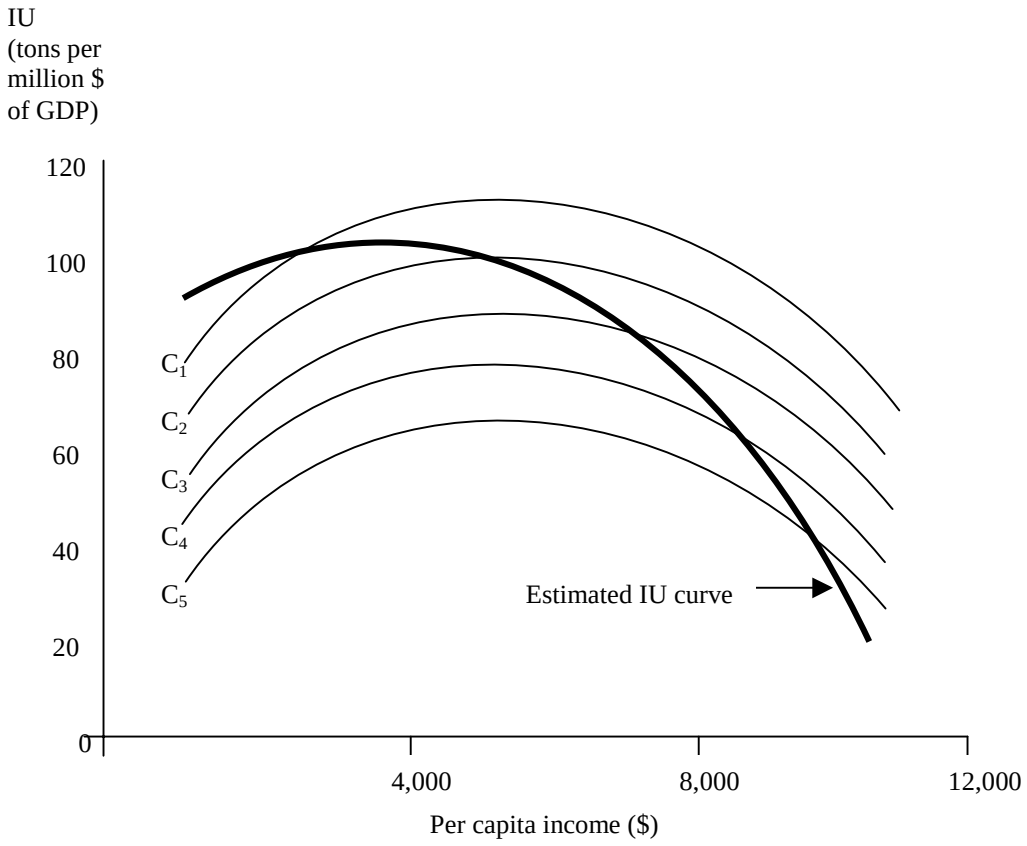
Source: Skinner (1976).

Figure 5.4. World Population, 1000-2000



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

Figure 5.5. Intensity of Use Curves



Chapter 6

THE ENVIRONMENT AND SOCIAL COSTS

As Chapter 2 points out, the 1990s witnessed a shift in the debate over the long-run availability of mineral commodities. Fears that the environmental and other social costs incurred in the extraction, processing, and use of mineral commodities might severely constrain their future availability pushed aside the more traditional concerns over mineral depletion. Even if new technology allows the exploitation of poorer deposits without any significant increase in the real price, the environmental damage inflicted on society and the other social costs that the producer and consumer do not pay, it is argued, may soon preclude the widespread use of mineral commodities.

Social costs cover all the costs associated with a particular activity. They include those costs for which the producing firm and in turn the consumer pay, such as the costs of labor, capital, and materials. These are called internalized costs, since the firm or party that uses these resources pays for them.

Social costs also include any external costs, or what are often referred to as simply externalities. These are costs that are borne by members of society other than the firm and the consumers who cause them. When the generation of electric power spews particulates and other pollutants into the air, unless the firm is charged or fined, it and ultimately consumers do not pay all the costs of power generation; some are inflicted on people who live down wind from the power plant.

Externalities create problems. Society in effect subsidizes goods with external costs, since their market price does not reflect their full costs of production. This results in greater production than is optimal. Producers, moreover, have no incentive to conserve on environmental and other resources for which they do not pay. So these valuable resources are overused. In addition, long-run trends in costs and prices are no longer reliable indicators of resource availability.

Figure 6.1 illustrates these distortions, and shows the optimal use of environmental resources from the perspective of society. The horizontal axis reflects the consumption of environmental resources, or alternatively the amount of environmental damage along with any other social costs incurred (E). These costs may in some instances be measured by an appropriate proxy. Mandonça (1998) and Mandonça and Tilton (2000), for example, contend that deforestation is a reasonable proxy for the environmental damage arising from iron ore mining in the Amazon region. If the use of environmental resources (deforestation) rises in direct proportion with output (iron ore production), the horizontal axis also reflects the output (Q) of the good causing the damage to the environment. When this is the case, a second line showing output (Q) can be drawn beneath the horizontal axis (E). The vertical axis measures benefits and costs associated with using the environmental resource measured in dollars or some other currency.

The MNB curve shows the additional or marginal net benefit derived from using one more unit of the environmental resource (the deforestation of one more hectare). This in turn depends on the extra profits the mining company can earn as a result (that is, on the difference between the firm's costs and its revenues). Since profits per unit of output tend to fall as output increases, the curve slopes downward. The MEC curve shows the additional or marginal external costs—the environmental costs that society but not the

mining companies must bear—as a result of using one more unit of the environmental resource (again, for example, from the deforestation of one more hectare). Since the unit value of the remaining environmental resource is likely to rise as its supply declines, this curve slopes upward.

For society, the benefits from mining in the Amazon are maximized when the additional costs of using one more hectare of land just equal the additional benefits. This occurs where the two curves cross at a mine output of Q_1 and land deforestation at E_1. In this situation some use of the environment, that is some environmental damage, is desirable. Of course, this need not be the case. In some instances, the curve MEC may lie above the curve MNB across all levels of output and environmental resource use. This means that the social costs of production exceed the social benefits for all outputs, and so any production would detract from, rather than add to, the well-being of society as a whole.

In either case, however, the mining company has an incentive to continue to produce until the MNB curve reaches zero, as it does not pay the environmental costs that the curve MEC reflects. Without some sort of government intervention it will continue to produce and pollute until output reaches Q_2 and environmental resource use E_2. The result is both too much output and too much pollution.

The remedy most policy analysts recommend for this problem is for the government to limit output or pollution to its optimal levels. For example, the government can regulate mining by permits and other means, and in the process either restrict the amount of output permitted to Q_1 or the amount of pollution to E_1. Since output is good, while pollution is bad, restricting pollution rather than output has the advantage that it encourages mining companies to increase output (the good) to the extent they can and still limit their pollution (the bad) to its socially optimum level (E_1).

Another possibility is for the government to impose a tax on companies, often referred to as a Pigovian tax, after Arthur Pigou, the British economist, who first recommended this solution to the problem of externalities. Placing a tax of OC dollars, for example, either on output or pollution would encourage producers to restrict their output and pollution to the desired levels. Again, a tax on pollution is preferable, since it is pollution not production that society wants to discourage.

Historically, governments have relied primarily on command and control regulations rather than on taxation and other economic incentives to correct the problems and distortions caused by environmental and other external costs. The past several decades, however, have seen growing support for economic incentives. By forcing companies to pay for the environmental resources they consume, they encourage companies to strive just as hard to reduce their pollution as to conserve on the labor, capital, and other inputs they employ. This is a big advantage, as over time it permits more production with less pollution and other social costs.

In the case of mining iron ore in the Amazon, for example, a tax of OC dollars per hectare of land deforested would encourage the socially desirable amount of pollution (E_1). It would also provide an incentive to find ways to reduce the environmental damage associated with mining, allowing iron ore output to increase with little additional deforestation. The price of iron ore would also reflect the full costs of production and so the true scarcity value of this resource.

The preceding suggests that the threat to the long-run availability of mineral commodities due to environmental and other social costs may be mitigated or completely eliminated by forcing producers and consumers to pay for these costs. Once this is done, new technology, just as it has reduced the labor, capital, and other internalized costs of

resource production in the past, should reduce the erstwhile external costs associated with mining and mineral processing.

For this to happen, however, requires, first, that public policy has the ability and the will to force firms to pay the environmental and other social costs associated with their production. Then, once these costs are internalized, firms must possess the capability to generate the requisite technologies. This chapter examines these two necessary conditions, starting with the second.

Technology and Environmental Costs

A century ago, even 50 years ago, mineral producing firms faced few environmental restrictions. The environment was largely viewed as a free good, for firms and others to use as they wished. As a result, there was little or no incentive to reduce environmental costs. Sulfur dioxide, particulates, and other pollutants were pumped into the air. Other wastes were dumped on land or into nearby streams. Mines were abandoned with little or no reclamation.

This situation has changed greatly over the past several decades, as governments around the world have imposed regulations and other controls on mineral producers and other firms. One interesting byproduct of this development is the accumulating evidence indicating that firms can substantially reduce their environmental costs when they have the incentives to do so. Environmental costs, it appears, are just as amenable to the cost-reducing effects of new technology as capital and labor costs, perhaps even more so since efforts to reduce environmental costs were so modest until recently.

A comprehensive review of this evidence is to our knowledge not yet available, and in any case is not necessary here. Several examples should suffice. A particularly interesting case is the lead industry in the United States. Figure 6.2 provides a life cycle analysis for this commodity, first for 1970 and then for the years 1993-94. While consumption grew by about 15 percent over this period, primary domestic production and net imports declined as recycling and secondary production more than doubled. Despite rising consumption, lead discarded back into the environment fell by more than 50 percent. Government policies that regulated the recycling of motor vehicle batteries and that curtailed or eliminated for health reasons the use of lead in paints and gasoline deserve most of the credit for these favorable developments.

The aluminum industry in Canada provides another example. As Figure 6.3 shows, it managed between 1972 and 1995 to reduce its emissions of particulates, fluoride, and polycyclic aromatic hydrocarbons[1] (PAHs) by 67, 69, and 86 percent respectively, all while more than doubling its output.

Yet another interesting case is the Chuquicamata copper smelter in northern Chile. As Figure 6.4 illustrates, over the 1980-1999 period this smelter increased the amount of recovered arsenic emissions from 35 to 90 percent, and the amount of recovered sulfur dioxide emissions from zero to 80 percent. Codelco, the state enterprise that owns Chuquicamata, spent over $600 million to realize these improvements. While this is a formidable sum, Chuquicamata nevertheless managed to remain one of the world's largest and lowest cost copper producers over this period.

[1] Polycyclic aromatic hydrocarbons (PAHs) arise from the incomplete combustion of carbon compounds, and are largely the result of forest fires and the burning of wood. In the aluminum industry, the baking of pitch found in the anodes causes PAHs emissions. In newer smelters using Soderberg anodes, PAHS emissions are almost zero.

While the reduction in sulfur dioxide emissions at Chuquicamata is impressive, the technology exists today to capture more than 99 percent of these emissions. As a result, smelters in countries with very stringent environmental standards—in Japan, for example—remove all but one or two percent of their sulfur dioxide emissions. Unfortunately, at the other end of the spectrum a significant number of smelters still allow 100 percent of their emissions to escape into the atmosphere.

Thus, the impact of new technology on sulfur dioxide pollution is substantial where public policy internalizes these environmental costs and far less impressive elsewhere. Today the best smelters are producing a hundred tons of copper with less sulfur dioxide pollution than smelters generated in producing just a single ton several decades ago. In addition, about a fourth of the world's copper is now produced by a new hydrometallurgical process, solvent extraction electrowinning, which completely bypasses the smelting stage of the traditional process. As a result, the copper it creates generates no sulfur dioxide emissions.

There are instances where environmental or other concerns may preclude mineral exploitation, where mining is simply incompatible with preserving environmental resources and other assets that society values highly. Activities that diminish the natural beauty of national parks, the pristine wilderness of remote areas, the culture and mores of indigenous people, and biodiversity are often cited examples. Considering Figure 6.1 once again, these are situations where the MEC curve lies above the MNB curve across all possible outputs.

In these situations, no amount of technological change may reduce the costs to acceptable levels, and public policy may quite appropriately place certain sites off-limits to

mineral exploitation.[2] This, in fact, has been the case for some time in most countries. While making it more difficult for the cost-reducing effects of new technology to offset the cost-increasing effects of depletion, such exclusions, even when growing in magnitude, are not incompatible with falling resource costs, as recent history shows. We will return to this issue in Chapter 7.

Internalizing the Externalities

According to the preceding section, the technology currently exists to capture all or almost all the sulfur dioxide emissions arising from copper smelting. Yet, this technology has diffused quite unevenly around the world, largely reflecting the success or failure of public policy in internalizing environmental costs. This brings us back to the first of the conditions necessary to avoid an environmental constraint on the long-run availability of mineral commodities: namely, that public policy must force firms to pay the environmental and any other external costs associated with their activities. This, in turn, requires (a) that governments are able to identify and measure these costs, and (b) that they possess the means and the will to force firms to pay them.

Valuing Environmental and Other Social Goods

Market prices provide a good starting point for assessing the value of the labor, capital, and the other inputs used in the extraction and processing of mineral commodities.

[2] It does not necessarily follow that exploration too should be excluded from all such sites. Exploration typically entails far less environmental damage than mine development and operation. It also provides information that permits a more accurate assessment of the potential benefits (the MNB curve) from mining in a particular area. While this point may trouble those concerned about preserving wilderness areas, the fact that

Unfortunately, many social goods, including clean water, wilderness, indigenous cultures, and biodiversity, are not traded on markets, and so alternative means are needed to assess their value. Over the past several decades, economists and others have devoted considerable effort to devising the necessary techniques.

One approach, a fairly recent social experiment, entails the actual creation of markets for environmental goods. For example, the government has for some years now allowed U.S. coal-powered electric power utilities to trade sulfur dioxide permits. Those companies that can reduce their sulfur dioxide emissions at a cost less than the going permit price have an incentive to sell their permits. Where the opposite is true, companies have an incentive to buy permits. So the market price for permits reflects the lowest possible cost to society of reducing sulfur dioxide emissions by one additional ton. Assuming the total number of permits reflects the optimum level of sulfur dioxide pollution, their price provides a good measure of the social costs associated with an additional ton of sulfur dioxide emissions, and of more importance forces firms to internalize these costs.

A second approach depends on inferences from actual consumer behavior. Hedonic pricing, for example, compares the value of similar houses close to and away from an airport to assess the social cost, measured by what people are willing to pay in additional housing costs, of the noise pollution created by arriving and departing airplanes. Travel cost studies measure the value users place on a lake, stream, or other recreational facilities from the travel and other expenses people incur to use these facilities.

A third approach, contingent valuation, arose primarily to value a class of environmental goods prized for their non-use or existence value. Many people, for

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few if any private interests are likely to have an interest in conducting exploration where the probability of being permitted to develop a successful discovery is low or zero should provide some consolation.

example, may place a positive value on the rain forests of the Amazon, the pristine wilderness of Alaska, or the indigenous culture of the Bla'an people who live on the island of Mindanao in the Philippines.[3] This may be true even though they themselves never plan to visit the Amazon, Alaska, or the Philippines. Such non-use value has in practice proven particularly difficult to measure. Contingent valuation attempts to do so by asking people, typically in structured manner governed by recommended procedures, how much they would pay to preserve these resources. It has been used in the United States, particularly in legal cases for resource damage assessments, and elsewhere as well. It is generally considered the only available method for valuing environmental and other social assets with non-use value.

Contingent valuation is, however, controversial, in part because it is not based on or even related to actual behavior. Those polled do not actually have to pay what they say they would pay. Among the experts, there is widespread agreement that poorly designed contingent valuation studies—where, for example, the respondents are inadequately informed or the questions leading—can produce highly flawed results. There is much less agreement, however, over the reliability of well-designed studies.

In addition, public acceptance, or rather the lack of it, is a serious concern. Cox (1994) provides an interesting example in his analysis of the public dispute in Australia over the proposed gold, platinum, and palladium mine at Coronation Hill. Largely because this deposit lies within the Kakadu Conservation Zone in the Northern Territory, the Australian government carried out an extensive cost-benefit analysis of the proposal. The study used contingent valuation to estimate the value of preserving the area. The analysis

[3] For an interesting description of the efforts by a mining company to preserve the Bla'an culture, see Davis (1998).

was conducted with considerable care, with the assistance of experts from abroad, and in accordance with accepted procedures. It found that Australians feel strongly about the possible environmental damage from mining in the Conservation Zone, but the methodology created such a fierce backlash that the government removed all references to the contingent valuation effort from its final report.

Critics fault contingent valuation at two very different levels. First, many claim that the methodology (asking people what they would pay) simply does not produce reliable responses for a host of reasons. Here, the complaint is that contingent valuation does not produce the information it purports to, namely, true willingness to pay.

Second, several critics (Humphreys 1992 and 2000, Sagoff 2000, Soderholm and Sundqvist 2000) question the use of contingent valuation for more fundamental philosophical or ethical reasons. For them, even if contingent valuation does elicit reliable responses, adding the willingness to pay across all individuals in society is not the appropriate way for society to place a value on social goods.

They argue for an alternative approach, which recognizes that biodiversity, native cultures, pristine wilderness, and other social goods with substantial non-use value are public goods, just like national defense or safe municipal drinking water. Governments decide how much to spend on national defense through a political process that reconciles the various competing interests of society, not an artificially constructed simulation of the marketplace.

The political process allows a public debate. This provides individuals and organizations with the opportunity to make their own views known, as well as to become better informed about the issues and the views of others. The political process also more readily accommodates the fact that individuals may make decisions about the purchase of

private goods in a different way using different criteria than the decisions about public goods. As citizens, for example, individuals may support policies (such as higher taxes for education) that have no impact or even a negative impact on their own well-being. The political process, it is argued, is much more likely to take into account and reflect such support than contingent valuation.

Finally, both approaches give the wealthy a greater say in the provision of public goods (since the rich have more dollars to spend on questions posed in contingent valuation studies and more dollars to spend influencing the political process). With the political process, however, every individual no matter how poor ultimately has one vote in electing public officials. This may leave the poor feeling less disenfranchised.

This review of various techniques for valuing environmental resources is far from comprehensive or complete, yet it suffices to show that measuring the full social costs associated with mineral exploitation is complex and difficult. While our tools in this area have advanced considerably over the past several decades, much progress is still needed before reliable measures of environmental resource values are available, particularly for those resources with non-use value.

The current debate over global warming and climate change, unfortunately, provides an excellent illustration of the need for progress in this area. After years of discussion, there is now a growing consensus that global warming is a reality, and that carbon dioxide and other greenhouse gases are largely responsible. Still hotly disputed are the pace of climate change, the consequences and costs, the contribution of people as oppose to nature, and the benefits of curtailing industries and other human activities that generate greenhouse gases. These uncertainties make it difficult, if not impossible, to assess the external costs associated with global warming that coal producers and other mineral commodity industries

generate, which is necessary to determine suitable public policies to internalize these externalities by an appropriate carbon tax or other measures.

The Means and the Will

Once the environmental costs are known, governments need the means and the will to force producers to pay these costs. Clearly, the means exist. Indeed, as noted above, the on-going debate is over which set of tools or means governments should rely upon. Command-and-control regulations, probably the most common instrument, can require the use of certain technologies or equipment, and set ceilings on the permissible amounts of given pollutants. However, economic incentives, such as pollution taxes, have in recent years found increasing favor as they often lower the costs of reducing pollution. With both command-and-control regulations and economic incentives, there are enforcement problems, but these do not appear any greater than in many other areas of public policy, such as worker health and safety or taxation compliance.

The great differences noted earlier in the recovery of sulfur dioxide emissions found among copper smelters suggest the will of governments to internalize costs may be a more serious problem. Some of these differences may simply reflect the lower environmental costs associated with copper smelting in more remote and less inhabited regions. In addition, over time as old smelters are replaced, state-of-the-art environmental control technologies are likely to be used more widely. So some of the current discrepancies among smelters may be temporary, though given the long lives of many copper smelters, temporary may mean decades.

In addition, the sorry environmental legacy of state-owned mining enterprises in Russia and other former centrally planned states raises some troubling concerns. Clearly

where the government has a conflict of interest, where it owns and operates mineral enterprises and is also responsible for ensuring that they adhere to acceptable environmental practices, the environment often suffers from a lack of will on the part of the government to internalize environmental and other social costs.

Another serious and possibly more permanent problem, given the recent trends away from central planning and toward the privatization of state-owned enterprises, entails artisanal or informal mining. This is very small-scale mining—often illegal—by individuals or groups using the simplest and most primitive equipment. According to the International Labor Organization (1999), some 13 million people along with 100 million dependents worldwide depend on small-scale mining for their livelihood. While some of these workers are engaged in small-scale mechanized mining, many are employed in the artisanal sector. The number of workers in small-scale mining rivals that of the formal mining sector, and has been growing at 20 percent a year over the past five years, a rate far faster than that for the formal mining sector.

The World Bank (Barry, 1996, p. 3) estimates that artisanal mining accounts for 20 percent of the gold, 40 percent of the diamonds, and nearly all the gemstones produced in Africa. Somewhat less than half of Brazil's gold production comes from such operations, down from 70 percent just a few years ago. In addition to gold, diamonds, and gemstones, artisanal miners produce copper, silver, tin, zinc, and coal.

These mines are highly inefficient, often leaving in the ground ore that better-run operations would exploit. They are more dangerous, and often employ women and children. They are also far more damaging to the environment per unit of output. Many gold operations, for example, discharge mercury into the surface and ground water. Acid mine

drainage, soil erosion, deforestation, and river silting are also common problems. Sites are typically abandoned with little or no reclamation.

In many respects, artisanal mining is resource exploitation at its worse, but it does provide a subsistence existence to millions of individuals with few if any alternatives. Governments as a result are reluctant to close down these operations or even in many cases to impose environmental and other regulations. In short, artisanal mining represents a major social and political problem whose resolution largely awaits major new initiatives to eliminate the poverty and the dearth of economic opportunities, which are largely responsible for these marginal activities so damaging to the environment.

Global warming provides one final illustration of the problems society can encounter in its struggle to deal effectively with externalities. Even without the uncertainties noted earlier, creating the political will on an international basis to curb greenhouse gases in a world of many independent nation states is daunting. Developing countries claim that they did not create the problem, and should not now have to slow their growth to reduce greenhouse emissions. The developed world argues that selective cutbacks by only a few countries will not be effective. Still other countries may benefit from a warmer climate, or believe they may benefit, and so are not greatly inclined to support efforts to abate or reverse global warming. And all countries are reluctant to bear more of the costs than they believe is their fair share, which invariable is less than other countries propose. The possibilities for stalemate are obvious.

Conclusions

The shift in the on-going debate over the long-run availability of nonrenewable mineral resources during the 1990s raises some interesting issues by focusing on the potential constraint that the environment and other external costs may impose of resource exploitation. In the past, scientists and engineers have successfully generated the new technology and other innovations needed to offset the cost-increasing effects of depletion.

In the future, if environmental and other social costs become a more important component of the total cost of mineral resource production and use, as seems likely, the favorable trend toward greater mineral resource availability can continue, as we have seen, but only if two conditions are satisfied. First, mineral producers with the assistance of science and technology must be able to continue to offset the upward pressure on their costs due to depletion. Second, public policy must internalize the environmental and other social costs of mineral production so that producers have the same incentive to reduce these costs as their other costs.

Of the two, the second condition appears the most challenging. The pursuit of this condition will involve policy analysts, economists, political scientists, and other social scientists in the struggle to ensure the long-run availability of mineral commodities. Indeed, their role could turn out to be even more difficult than that of their colleagues in engineering and natural sciences, for the problems of valuing environmental resources and the problems of ensuring that governments have the will to internalize all the social costs may prove more troubling, perhaps far more troubling, than the more traditional technical challenges.

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Figure 6.1. The Optimal Use of Environmental Resources

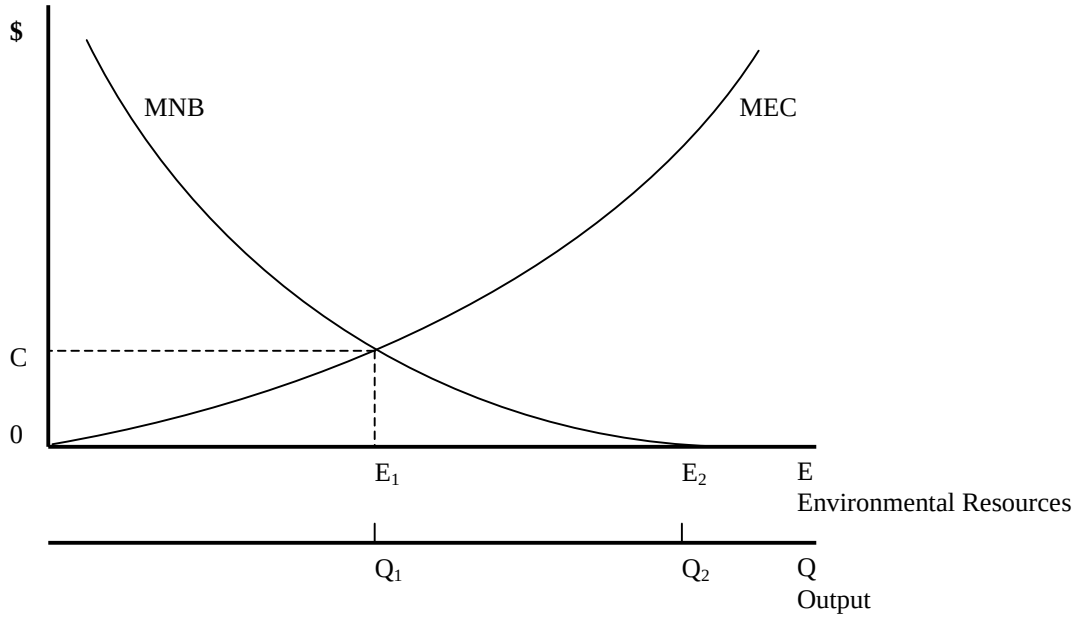
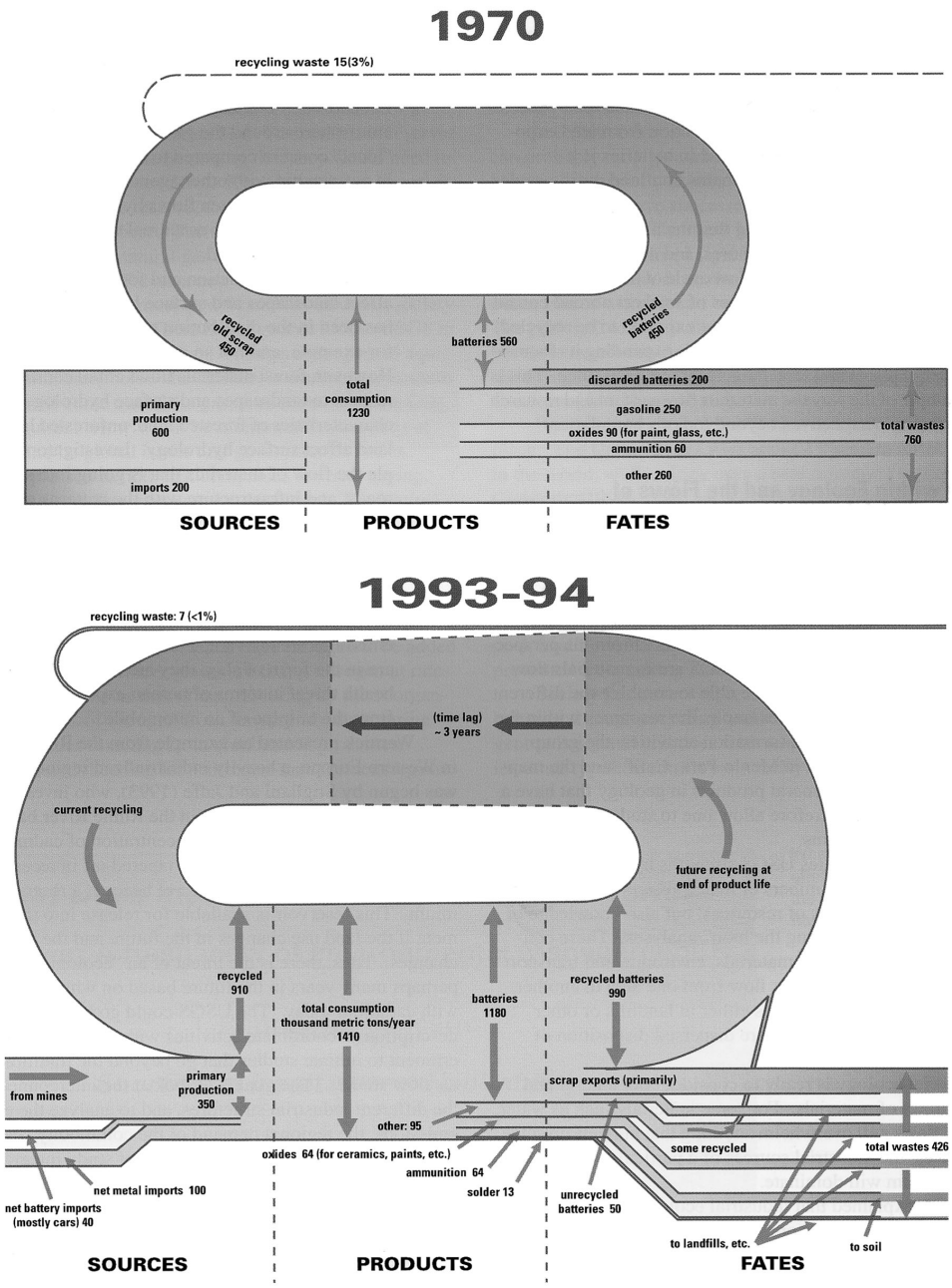
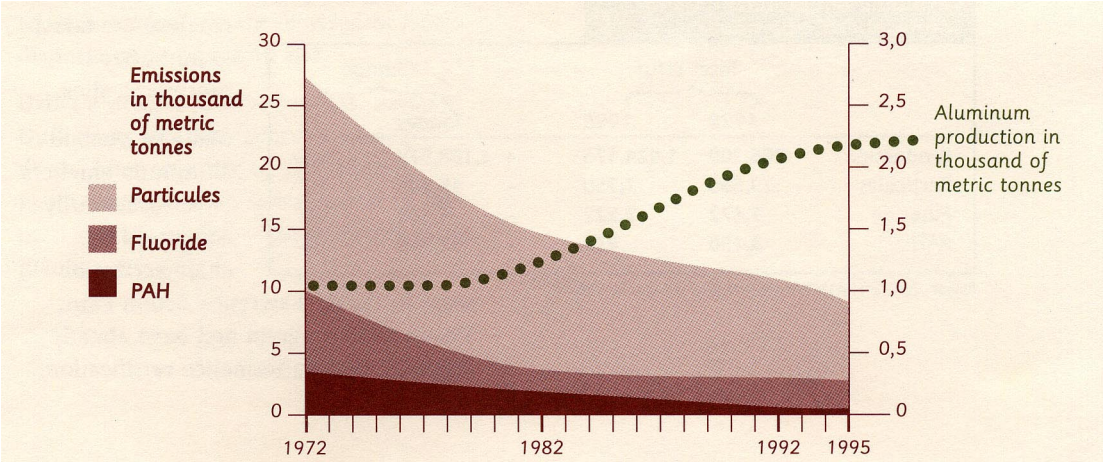


Figure 6.2. Lead Flows in the United States, 1970 and 1993-94.



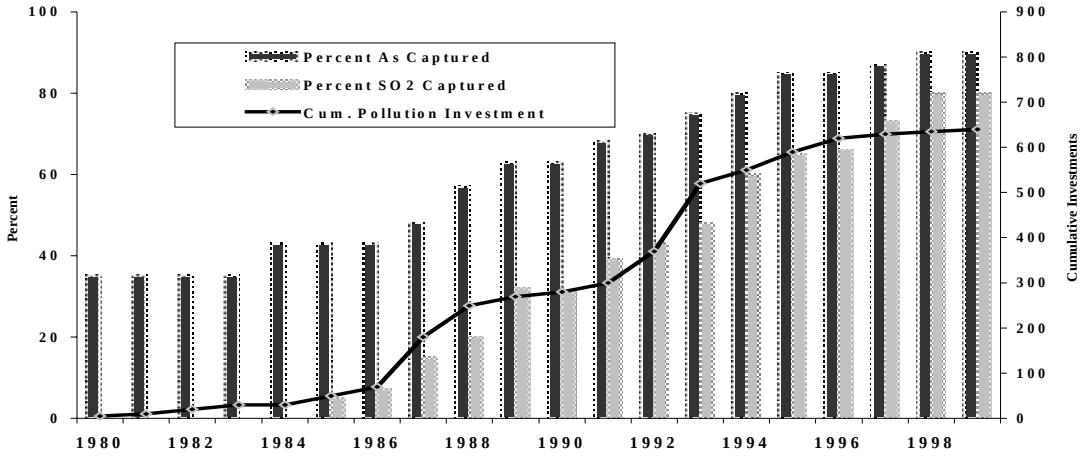
Source: The Interagency Working Group on Industrial Ecology, Material and Energy Flows as reproduced in U.S. Geological Survey (2000, p. 14).

Figure 6.3. Production and Air Emissions for the Canadian Aluminum Industry, 1973-1995



Source: Ministère de l'Environnement et de la Faune du Québec as cited in Aluminium Industry Association (1997).

Figure 6.4. Percentage of Arsenic and Sulfur Dioxide Emissions Captured and Cumulative Investment in Pollution Abatement at the Chuquicamata Smelter, 1980-1999



Note: Figures for the years after 1995 are projections.
Source: Corporacion Nacional del Cobre de Chile (Codelco).

Chapter 7

FINDINGS AND IMPLICATIONS

Over the past several decades, we have learned a great deal about the long-run availability of mineral commodities, thanks in large part to the lively debate among scholars over this important issue. We now know, for example, that the world is not likely to wake up one day to find the cupboard bare or the well dry. We will not run out of mineral commodities the way a car runs out of gasoline. One minute speeding along the highway, the next completely stranded on the berm. Depletion, if it becomes a serious problem, will do so by raising the real costs of finding and producing mineral commodities slowly but persistently over years and decades. Signs of pending scarcity will appear long before serious shortages actually arrive on the scene.

This is because the mineral resources that satisfy the needs of society for materials and energy vary greatly in quality. The high quality, low cost resources currently being exploited account for only a fraction of the total. Once they are gone, large amounts of lower quality resources will remain, which in the absence of offsetting technological change would be more expensive to find and exploit. Long before the lowest quality resources—the last ounce of silver in the earth's crust or the last watt of incoming solar energy—are used, costs would become prohibitive.

So depletion raises the specter of a world where resources are too costly to use rather than a world with no resources. This means that the opportunity cost paradigm

rather than the fixed stock paradigm is the appropriate way to assess the long-run availability of mineral commodities. This finding leads to two important corollaries.

First, depletion is no longer inevitable. While over time depletion tends to drive the costs and prices of mineral commodities up, new technology tends to mitigate this tendency. Indeed, mineral commodities can become more available over time if the cost-reducing effects of new technology more than offset the cost-increasing effects of depletion.

Second, measures of availability should reflect the sacrifice that society makes to obtain additional quantities of mineral commodities. Possible indicators of the sacrifice include user costs, production costs, and prices, with prices being the most common measure encountered in part because price data are readily available and in part because prices encompass both user costs and production costs. While these three measures suffer from various shortcomings, and may even at times move in opposite directions, they provide far more useful insights regarding availability trends than fixed stock measures, such as the life expectancies of the reserves or the resource base.

We also now know that new technology has over the past 130 years kept the adverse effects of depletion at bay despite an unprecedented surge in both population and the consumption of mineral commodities. Real production costs and prices for many mineral commodities have actually fallen, implying their availability has increased.

Of course, there have also been shortages. Indeed, shortages have occurred with some regularity for a number of reasons—wars, strikes, economic booms, cartels, insufficient investment in new mines and processing facilities, perverse government

policies—but depletion is not among them. This is fortunate, and is why the shortages the world has so far experienced have not for long endured.

Two clouds or caveats, however, cast a shadow this fairly rosy picture. First, we know that the past is not necessarily a good guide to the future. While the current levels and rates of accumulation of mineral reserves augurs well for the next several decades, the more distant future is much harder to discern. We simply do not have the tools to forecast the future course of technological change with any semblance of the accuracy needed to know whether it will suffice to offset the adverse effects of depletion.

Second, our measures of availability take into account only the costs that producers incur and the prices that their customers pay. Environmental and other external costs associated with the production and use of mineral commodities are not considered. At any point in time, this omission imparts a downward bias in our availability measures, causing them to underestimate the true costs and price of mineral commodities.

How it affects trends over time, however, is less clear. The tendency for environmental costs to grow in importance and as a percentage of total costs causes our availability measures increasingly to overestimate availability and to underestimate scarcity. On the other hand, the considerable efforts that governments around the world have made over the past several decades to force companies and consumers to pay for more of what were formerly external costs has partially, perhaps totally, offset this upward bias.

As for the future, some believe that environmental and other social costs may preclude the widespread production and use of mineral commodities. We have seen that this need not be the case, but only if public policy internalizes the external costs, and if

society can continue, as it has in the past, to generate the technology needed to keep mineral commodity costs (which would now include all social costs) from rising.

Unfortunately, satisfying both of these two necessary conditions is neither easy nor certain. Recent history suggests that environmental and other social costs, once firms are required to pay them, are just as amenable to the cost-reducing effects of new technology as other costs. However, internalizing these costs may prove far less tractable for two reasons. First, considerable progress is still needed to develop acceptable techniques for measuring the value of the environment, indigenous cultures, and other social goods. This is particularly so for those goods with substantial non-use value, and where different groups within society hold conflicting value systems that lead to greatly different preferences. Second, the political will to force firms to pay for all the social assets they use may falter, in regions where unemployment and poverty are already widespread, and elsewhere as well.

So, despite all that we have learned about the long-run availability of mineral commodities, the central question remains unanswered. We simply do not know whether or not coming generations face a future of mineral commodity shortages. Those who argue otherwise ask the rest of us to share their faith, or lack of faith, in technology. This is why the debate continues.

More geologic information on the incidence and nature of mineral deposits, particularly sub-economic mineral deposits, could be acquired that would go a long way to resolving this critical issue. The needed knowledge, however, is not currently available, nor is it likely to soon become available, largely because little economic

incentive exists to learn more about deposits whose profitable exploitation at best lies many years in the future.

Despite this somewhat frustrating state of affairs, important implications still flow from what we do know about the long-run availability of mineral commodities—implications for sustainable development; for green accounting; for indigenous cultures and other social goods; for conservation, recycling, and renewable resource use; and for population, poverty, and discrimination.

Sustainable Development

Sustainable development is a term of many meanings. The World Commission on Environment and Development (1987), better known as the Brundtland Commission after its chair, in its report *Our Common Future*, is widely credited with introducing the term sustainable development into the public lexicon. It defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Since then, as Toman (1992) and other writers have noted, many other definitions have surfaced. For some, sustainable development means protecting a particular ecosystem, for others preserving biodiversity, for still others protecting an indigenous culture or a local community from the development of a nearby mine. Then there are those who see sustainable development as helping a mining community remain economically viable after the ore is gone and the mines are closed. In yet another use, sustainable development is the equitable distribution of income, goods, and resources

among different countries and people today, and so is void of any intertemporal dimension.

Here we use sustainable development to mean that the present generation behaves in a way that does not preclude future generations from enjoying a standard of living at least comparable to that of our own. This definition is fairly common among economists. Like the original definition of the Brundtland Commission, it has a macro orientation, focusing on changes in the welfare of society as a whole over time rather than the well-being of a particular ecosystem or local community.

Our concern is specifically on the possibility that the current consumption of mineral commodities may force future generations to accept a lower standard of living. Though sustainable development has emerged as a popular concern only over the past decade or two, fears of resource exhaustion as we have seen date back at least to the 18th century writings of Thomas Malthus and the Classical economists. We care about the long-run availability of mineral commodities for many reasons, but the primary reason is presumably the widespread belief that growing scarcity could threaten the welfare of future generations.

Upon some reflection, however, the link between the long-run availability of mineral commodities and sustainable development turns out to be much looser than one might at first suspect. This is because the potential for future generations to enjoy a standard of living equal to that of the present generation depends on all the assets that we pass on. Abundant low-cost mineral resources are just one of these assets. Others include man-made capital (houses, factories, schools, office buildings, roads, bridges, and other infrastructure), human capital (a healthy and well-educated populace), natural capital (a

clean environment, pristine wilderness, and rich biodiversity), political and social institutions (stable and democratic government, a well-developed legal system, a tradition of resolving conflict by peaceful means), culture (music, art, dance, theater), and of course technology.

As a result, increasing the availability of mineral commodities may make sustainable development somewhat easier to achieve, but certainly does not ensure it. A generation that fails to invest in new technology, that despoils the environment, and that perpetuates widespread poverty in order to husband its stock of mineral resources for future use is not likely to achieve sustainable development, and is even less likely to earn the gratitude of future generations.

On the other hand, sustainable development is possible even with declining long-run availability of mineral commodities. This simply requires an offsetting increase in the other assets passed on to future generations. Indeed, future generations may even benefit from an increase in the current exploitation of mineral commodities where this allows today's generation to spend more on infrastructure, education, research and development, and other types of investments.

Going one (big) step further, some economists (Solow 1974, Hartwick 1977, Dasgupta and Heal 1979) have argued that sustainable development is even possible with the complete exhaustion of nonrenewable mineral commodities, using models with strong substitutability assumptions. These assumptions allow the substitution of other inputs for nonrenewable mineral resources in the production of all critical goods. Models with weak substitutability assumptions, which allow for some substitution but not the complete elimination of mineral commodities in the production of goods and services, not

surprisingly find the complete exhaustion of mineral resources incompatible with sustainable development. Advocates of the latter set of models (Daly 1996, Ruth 1995, Neumayer 2000) argue with some persuasion that the strong substitutability assumption defies the laws of nature.

However, the debate over strong and weak substitutability, while of some intellectual interest, may be of questionable practical relevance. As pointed out earlier, physical exhaustion is not the issue. We will not literally run out of resources. Scarcity may push the costs of some mineral commodities sufficiently high to preclude their widespread use, but resources will remain in the ground, and so will be available at some price.

In any case, the pace of mineral extraction appears at best to be but a modest determinant of sustainable development. Much more important is how much the current generation spends of its available income on its own consumption and how much it invests.[1] Over the past century the production of mineral commodities has exploded, yet their long-run availability has increased thanks largely to the investment in research and development that has generated a continuing flow of new technologies. This investment coupled with society's other investments has left each succeeding generation better off than that of its parents, at least in developed countries.

This raises two intriguing issues. First, though sustainable development has become the holy grail by which much public policy and behavior is currently judged, is it perhaps too modest a goal? Do we not want the generation of our children and grandchildren to be substantially better off than we are, just as our generation is

[1] Of course, how much it squanders on needless mismanagement, corruption, wars, and other welfare-reducing activities also matter.

substantially better than those of our parents and grandparents? Have we perhaps set our sights too low?

Second, how much should the present generation be saving and how much should it be investing? While it is easy to point to instances of profligate consumption by others, particularly by those richer than we, poverty is also widespread. A large portion of the world's current population does not have adequate food, housing, medical care, or education. How do we in deciding how much of our current income to invest for future generations weigh and compare intergenerational and intra-generational equity? The issue is further complicated by the fact that providing food, housing, medical care, and education to today's poor is also an investment in the future. We will return to this important issue when examining the implications of resource availability for population.

Green Accounting

Among the great economic inventions of the 20th century are modern national income and product accounts. Income accounts, such as the well-known gross domestic product (GDP), measure the total income and output of a nation over a year or some other period. Asset accounts indicate the assets, liabilities, and net worth of a nation at a particular point in time.

National income and product accounts provide a useful report card on a country's economic performance. Is output growing? Is the ratio of investment to consumption rising or falling? How does this ratio compare with that of other countries? Are the country's total assets growing? Are some regions expanding faster than others? How is

total income divided between labor, capital, and other resource owners? Such information is of intrinsic interest, and invaluable for the formation of public policy.

National income and product accounts do, however, suffer from a number of deficiencies. With a few exceptions, for example, they have traditionally considered as income and output only sales and purchases that occur in the marketplace. They thus take account of the services provided by a paid maid or housekeeper, but not the services of an unpaid housespouse.

Another important shortcoming concerns their treatment of natural resources and the environment. They currently take into account the production of mineral commodities and their flows through the economy, but completely ignore changes in the stocks of mineral assets in the ground. So while the accumulation and depreciation of physical assets, such as plant and equipment are counted, the discovery of new mineral reserves and their depletion over time are overlooked. This anomaly is troubling since mineral resources are often important inputs into the production of goods and services, just like labor and capital. The treatment of environmental assets is even more of a problem. Not only are changes in these important assets ignored in the asset accounts, they are largely overlooked in the income and product accounts as well.

These shortcomings mean that a country could be enjoying strong apparent economic growth based on the exploitation of its natural resources and environmental assets, which was unsustainable and actually impoverishing the country. A full reckoning of the costs and benefits would reflect a country not growing stronger economically, but rather living off its natural resource and environmental assets.

Green accounting encompasses the efforts over the past several decades in the United States and abroad to augment the traditional treatment of the environment and natural resources in national income and product accounts. In the case of mineral resources, these efforts have produced various procedures for estimating the value of reserves in the ground. These techniques, described in some detail in Nordhaus and Kokkelenberg (1999, ch. 3), attempt in various ways to estimate the value of the user costs (or Hotelling rent) plus the Ricardian rent associated with existing reserves, as illustrated in Figure 3.2.

These efforts indicate that U.S. mineral wealth has changed little over the past several decades. This means that the value of reserve additions plus any revaluation of reserves due to price changes have more or less offset the value of reserve depletions over time. This provides little support for the view that the country is in the midst of an unsustainable mineral resource consumption binge, though several decades is perhaps too short a period of time for assessing this proposition.

Another interesting result flowing from this work concerns the relatively modest contribution of mineral resources to the total wealth of the United States. The value of U.S. mineral resources are estimated at but three to seven percent of the country's tangible capital stock (Nordhaus and Kokkelenberg 1999, p. 104). Adding in other assets, such as human capital, would further reduce these figures.

Even of more interest is the somewhat perverse relationship between a country's mineral wealth and the long-run availability of mineral commodities. While logic would suggest that an increase in mineral availability should tend to increase mineral wealth, this is rarely the case. Again, referring back to Figure 3.2, we can see that an increase in a

mineral commodity's price, a sign of growing mineral commodity scarcity, increases the Ricardian rents associated with existing reserves, and hence the value of mineral reserves in the ground.

Alternatively, consider the impact of a new technological development that made it possible to capture BTUs from solar energy more cheaply than from mining and burning coal. The costs of BTU production, which previously might be reflected by the step function in Figure 3.2, would now be replaced by a horizontal line located below the costs of the lowest-cost coal mine. Coal deposits would no longer have any value, and solar energy would enjoy neither Ricardian rents nor user costs (Hotelling rents) since the available supply would have a common cost of production and would be limitless for all practical purposes. While greatly improving the long-run availability of energy, this dramatic development would completely wipe out the mineral wealth once enjoyed by the owners of coal deposits. Nor would this loss be offset by new mineral wealth since the new source of energy, solar power, would create neither Ricardian rents nor user costs.

Perhaps a more realistic example concerns the discovery and development of high grade, low-cost copper deposits in Chile over the past couple of decades. By keeping the world price of copper below what it otherwise would have been, these new mines have reduced the value of copper reserves in the United States and elsewhere. While the increased value of the reserves in Chile may or may not have offset the losses elsewhere, the new mines in Chile by reducing the world price have clearly increased the long-run availability of copper worldwide.

Mineral Extraction and Incompatible Social Goods

Indigenous cultures, biodiversity, and pristine wilderness are all examples of social goods that many contend are simply incompatible with the extraction of mineral commodities. Where this is true, internalizing the costs of these social goods more than merely reduces the optimal output of mineral resources, it reduces it to zero. How then can society protect these goods without at the same time ensuring the long-run scarcity of mineral commodities?

As Chapter 6 noted, public policy has for years prohibited mineral production in certain areas, such as national parks and military reservations. Moreover, the total size of these areas has expanded greatly over the past several decades, while simultaneously the availability of many mineral commodities has increased. This suggests that the protection of social goods incompatible with mining is possible without necessarily causing scarcity, though clearly the more territory withdrawn from mineral extraction the greater the difficulties new technology faces in the struggle to keep mineral costs and prices from rising.

The challenge for public policy is not to choose between biodiversity, pristine wilderness, and indigenous culture on the one hand and the availability of mineral commodities on the other. It is not an either/or issue, a case of black or white, but rather a question of the appropriate tradeoff. How much biodiversity, wilderness, and indigenous culture does society want to preserve? As the amount increases, so does the price to society in terms of the long-run mineral availability sacrificed. At the same time, as the amount increases, the additional or marginal benefits to society will fall, assuming the

most valuable sites for biodiversity, wilderness, and indigenous culture are selected for protection first.

This suggests that public policy should continue to preserve these social goods, and exclude mining from the areas required, up to the point where the marginal costs (in terms of the resource availability sacrificed) just equals the marginal benefits to society. Such a policy may or may not give rise to the scarcity of mineral commodities in the long run, but if it does, the policy still promotes the welfare of society as a whole.

Moreover, some economists and policy analysts (Krutilla and Fisher 1975, Dasgupta and others 1999) urge a cautionary policy, one that requires governments when weighing the benefits and costs to take account of the fact that once mining or other activities destroy such social goods, the damage is often irreversible. Moreover, as population and per capita income increase over time, the demand for these goods is likely to grow more rapidly than the demand for most other goods. Unlike other commodities, it is difficult or impossible to produce goods that consumers widely consider as close substitutes for biodiversity, indigenous cultures, and pristine wilderness.

Such concerns coupled with the vast quantities of marginal resources known to exist for many mineral commodities suggest that a prudent policy at least for the present would preclude mineral development wherever important social goods are threatened. For example, the troubled history of the Panguna mine on Bougainville Island in Papua New Guinea in retrospect indicates that the central government and private companies should have paid more attention to the concerns of the local people. Some might even argue that the mine should never have been developed, as it is simply too disruptive to the indigenous culture. Despite the attractive nature of this deposit, had this been the

case, the effect on the long-run evolution of costs in the world copper industry would have been negligible. Indeed, given the large number of known but undeveloped porphyry deposits that could produce copper at costs close to many of today's operating mines, a number of mines could have been excluded from development with little effect on the long-run costs of producing copper.

Conservation, Recycling, and Renewable Resources

Concern over the long-run availability of mineral commodities has fostered, and continues to foster, widespread support for public policies and other activities that encourage conservation, recycling and secondary production, and where possible the greater use of renewable resources. Even if the long-run availability of mineral commodities is unknown, such policies, it is argued, are desirable as useful insurance in the event future shortages do arise.

Others contend that these activities—conservation, recycling, and increasing reliance on renewable resources—are inevitable. The world, they argue, is in the midst of what has to be a temporary period, as it exploits at an unprecedented rate its stocks of nonrenewable mineral resources. Once this era of profligate use draws to an end, as it must, there will be no choice. The world will have to rely far more on conservation, recycling, and renewable resources, and rising mineral commodity prices will provide the incentives to do so.

While both of these positions are at times advanced as self-evident and uncontroversial, they do raise a number of issues. The remainder of this section looks

first at conservation, and then turns to recycling and the substitution of renewable resources.

Conservation

Conservation can be an elusive concept. To most people, it simply means using less. But this loose definition raises the question: how much less? At one extreme, which few conservationists would advocate and which in any case would garner little public support, conservation could mean doing completely without.

At the other extreme, conservation could mean using mineral commodities efficiently without needless waste. If mineral commodities are properly priced, then the marketplace should ensure they are used efficiency. In this case, no public policies or extra efforts to reduce mineral commodity use should be necessary. In practice, as Chapter 6 points out, prices for mineral commodities often do not include all the costs that their production and use impose on the environment and other social goods. In such cases, public policy is needed to ensure that these external costs are internalized. Here again, few are likely to object, at least in principle, to such efforts.

Conservation becomes more controversial when it entails reducing the use of mineral commodities below the levels that market efficiency dictates. Now society is paying a price for conservation in terms of less output and slower growth. As noted above, one might justify these costs as an insurance premium against the risk of future resource scarcity. This presumes, however, that more cost-effective methods of buying insurance do not exist. This may not be the case. The prospects for adequate future

supplies might be enhanced much more by devoting the income that would be lost as a result of conservation to research and development.

Another possible reason for reducing current income to promote conservation rests on the belief that much of today's materialistic lifestyle in the rich countries is not only unnecessary but undesirable, particularly as it may increase the likelihood of future mineral shortages. Thus, a decline in income that discourages undesirable consumption can be accommodated at little or no cost to society as a whole.

Despite some intuitive appeal, this argument raises a number of difficult issues. First, how do we decide what are necessary and desirable expenditures, once individual preferences as expressed through the marketplace are rejected as appropriate indicators? Do we make such decisions collectively through the political process? If so, if current consumption patterns are truly perverse, why has public policy not already introduced luxury taxes or other measures sufficient to correct the situation? Second, once this issue is resolved and we identify which expenditures are unnecessary and undesirable, might it not be preferable to divert the resources used to produce them to other contemporary needs, such as housing, food, and medical care for the poor?

Third, as we have seen, natural capital in the form of mineral resources is just one of many assets the current generation will pass on, affecting the welfare of future generations. If we are concerned about intergenerational equity and the welfare of future generations, public policy should encourage the current generation to consume less and invest more. Investments might be made in education and human capital, in the strengthening of social and cultural institutions, or in the body of scientific knowledge and technology. Only under special conditions is the best investment likely to entail

preserving mineral resources by conservation. Finally, as also noted before, it is not clear that equity is served by augmenting the welfare of future generations at the expense of the current generation, given the widespread poverty that currently afflicts large parts of the globe and the tendency over the past century in the developed countries for each succeeding generation to be better off than its predecessor.

Pulling together these various thoughts, we can make a strong case for conservation, when conservation means using mineral commodities efficiently up to the point where the costs (including all the social costs) of using another unit just equal the benefits to society. Moreover, so defined, the marketplace should encourage the efficient level of conservation as long as government policy forces producers and consumers to pay for all the costs. Over time, if scarcity drives the prices of mineral commodities up, conservation will cause their use to decline. Alternative, if scarcity should decline, allowing prices to fall, conservation so defined will dictate an increase in the optimal use of mineral commodities.

When conservation means something other than the efficient use of mineral commodities, as was the case, for example, with the Conservation Movement described in Chapter 2, it becomes more difficult to justify and more controversial.

Recycling and Secondary Production

Recycling and secondary production constitute an important source of supply for many metals, and are often perfect substitutes for primary output. So by increasing recycling, society can slow the rate at which primary mineral resources are exploited.

This does not mean, however, that all the metal in products coming to the end of their useful lives should be recycled. The lead once added to gasoline is still about, and in theory could be recycled. In such dissipated uses, however, scrap metal is prohibitively expensive to recycle.

What then is the optimal amount of recycling that society should undertake, and to what extent is government intervention in the marketplace needed to achieve this optimum? One position, which parallels the efficiency criterion for conservation, contends that the output of copper, lead, tin, or any other metal should be divided between primary and secondary production so that total production costs are minimized. This means continuing to recycle up to the point where the cost of obtaining one more ton of metal from recycling just equals the costs of producing one more ton from mining. Again, in both instances, the costs should include all costs, including the environmental costs.

Some scholars (Page 1977) who favor this view argue that public policy needs to encourage recycling since primary production gets more subsidies in various forms and imposes more external costs on society than secondary production. This is not easy to actually demonstrate, particularly in light of the many efforts over the past decade or two to promote recycling. However, to the extent public policy does discriminate in favor of primary production, a strong case can be made for eliminating this discrimination and thus for promoting more recycling.

Others contend that public policy should go further. Whether recycling is economic or not, they point out, often depends on the behavior of consumers. If the latter are conscientious and sort their waste, separating out, for example, metal cans, recycling

becomes much more competitive. Educating consumers, like education in general, is a type of public good. By reducing the costs of recycling it provides benefits to society that at best recycling firms can capture only in part. Where such external benefits exist, markets will fail, providing less of a good or service than is optimal from the point of view of society. This, of course, is the primary rationale for government support for research and development and for education. As a result, the argument goes, the government has a legitimate role to play in encouraging consumer behavior that promotes recycling.

The same rationale can be employed to justify government support for research and development that reduces the cost of recycling and so promotes secondary production. Here, however, the argument of market failure supports government support for research and development that reduces the costs of primary production as well. So whether optimal public support for research and development would favor secondary or primary production is unclear.

Perhaps the most common and problematic case for policies favoring recycling contends that secondary production buys society time. According to this argument, as the world moves, as it must, from a cowboy economy based on nonrenewable resources to a spaceship economy based on renewable resources and secondary production, secondary production slows depletion. This extends the period available for the world to navigate this difficult transition period, and reduces the resulting dislocation and hardship.

We have seen, however, that depletion is not a question of the physical availability of mineral resources, but rather of costs. Should depletion eventually drive the costs of primary production up greatly, then the world will have to make the transition

from nonrenewable primary resources to renewable resources and secondary production. However, forcing society to incur these costs now can be questioned for at least two reasons. First, while primary mineral commodities may become scarce in the long run, this is not certain. Why pay to alleviate a problem that may not arise? Why not pay when and if the problem actually occurs?

Second, even if scarcity were certain, the income lost by pushing recycling beyond the point that minimizes the total production costs for mineral commodities might be better spent in other ways. Promoting technologies that reduce the costs of finding and producing mineral commodities or that develop suitable alternatives, for example, may be a far more effective strategy for mitigating the impact of depletion. More generally, investing these funds by attacking poverty, strengthening institutions, reducing corruption, and enhancing political stability may, as we have seen, pay far greater dividends to future generations, as compensation for our possible failure to maintain the long-run availability of mineral commodities.

The above, it is important to note, does not necessarily preclude public support for recycling. It does imply, however, that the case for such support is not self-evident, but rather requires empirical verification.

Renewable Resources

Solar power, biomass, and other renewable resources are replenishable on a time scale of relevance to humanity, and so can be used indefinitely. Does this mean, as is

sometimes argued, that society should where feasible promote the use of renewable in place of nonrenewable resources?

The answer to this question closely parallels the preceding discussions of conservation and recycling. A strong case for market failure and government intervention favoring renewable over nonrenewable resources exists if the production and use of nonrenewable resources imposes greater external costs, or in other ways receives subsidies that exceed those bestowed on the production and use of renewable resources. Of course, should careful analyses of the relative subsidies document that renewable resources are actually favored, then government policy should tilt in the opposite direction.

Government policies that favor the use of renewable resources beyond such measures are more difficult to justify, since they reduce income and wealth. This cost helps mitigate a problem that may in the end not arise. In addition, the income and wealth given up by the current generation might if spent in others ways enhance the welfare of future generations even more.

This seems particularly so since renewable resources can also suffer from depletion if use exceeds sustainable levels. A cursory glance at the resources generating the greatest concerns at the beginning of the 21st century finds the focus largely on renewable resources—climate, the ozone layer, water, air, soils, whales, and biodiversity in general. The general perception that renewable resources are sustainable while nonrenewable resources are not is clearly incorrect. Indeed, with renewable resources physical exhaustion is in some instances a real threat, as the extinction of many animal species over the past century illustrates. This raises the possibility that the distinction

between renewable and nonrenewable resources is misleading. Both can suffer from depletion, and in the case of renewable resources depletion may entail more than just rising costs.

Population, Poverty, and Discrimination

This final section explores the fascinating relationship between the long-run availability of mineral commodities and the world's population. In particular, it focuses on two issues. The first concerns the influence of resource availability on population, and addresses the question: To what extent does the availability of mineral commodities impose an upper limit or ceiling on the world's population? The second examines the influence of population on resource availability, and considers the question: Is a growing population a threat to the long-run availability of mineral commodities?

The Population Ceiling

At any particular time, available world resources do impose an upper limit on the number of people the world can support. Malthus and other Classical economists, as we saw in Chapter 2, recognized this fact over two hundred years ago. According to the law of diminishing returns, as more of a variable input (people) is added to a fixed input (land or resources in general), the additional return or output from adding one more unit of the variable input must at some point decline. Eventually, this decline will push the average output per person down until it just equals the subsistence level. At this point, which

Malthus recognized was not a pleasant situation, the world reaches the upper limit on the number of people it can sustain.

Several aspects of this scenario, however, deserve further consideration. First, for most people the optimal population level is significantly below the maximum possible. There are many reasons for this, including the fact that a world where everyone just barely manages to survive is not particularly enticing.

Second, it is clear the world possesses sufficient supplies of mineral commodities to support its current population of six billion plus people, and probably can support the nine to ten billion people expected by the middle of this century when current forecasts see the world's population peaking. Less clear is how far the developing countries can move toward the high living standards currently prevailing in the developed countries in light of these population figures and the long-run availability of mineral commodities. This, however, is a concern more relevant to the optimum level of population, than the ceiling. Moreover, while economic development is still poorly understood and appears to depend on the fortunate confluence of many factors, the long-run availability of mineral commodities does not appear to be of great importance. Korea, Hong Kong, Singapore, Malaysia, Chile, and more recently China have all enjoyed rapid rates of economic growth over the past several decades, while many other developing countries have not, even though in a growing global economy all have more or less equal access to needed mineral commodities.

Third, renewable as well as nonrenewable resources impose a ceiling on population. Indeed, the availability of land, water, and other renewable resources may well constrain population growth long before nonrenewable resources, the latter's finite

nature notwithstanding. If so, the mineral constraint on population is non-binding, and hence largely or totally irrelevant.

Fourth, the population ceiling arising from mineral commodities is not stationary but rather shifts over time responding to changes in their long-run availability. If new technology continues to offset the cost-increasing effects of depletion, the population ceiling could rise indefinitely. Growing scarcity would have the opposite effect.

So the answer to the first question is: Yes, the availability of mineral commodities does impose a limit on the world's population. Though true, and of some interest, this fact has limited significance in practice, in part because the ceiling is constantly changing, in part because renewable resources may dictate an even lower population limit, in part because the ceiling is above the current level of population and above those levels likely to prevail over the foreseeable future, and most importantly because the desired or optimum level of population is far below the ceiling and set largely by other considerations.

The Population Threat

This brings us to the second question: Is population growth a significant threat to the long-run availability of mineral commodities? Here again the conventional wisdom, that the answer to this question is yes, is at best only partially correct. It is true that an increase in population, everything else remaining the same, tends to increase the demand for mineral commodities and so drives society up its cumulative supply curve at a faster pace than would otherwise be the case. However, as Julian Simon has so persistently

argued, people influence the supply as well as the demand for mineral commodities. The more people, the more minds to develop the innovations and new technologies that shift the cumulative supply curve down over time. Whether more people on balance promotes or impedes the long-run availability of mineral commodities is an open question requiring empirical evidence for its resolution. Simon contends that a growing population thanks to the ingenuity and resourcefulness of people increases availability; others are less sanguine.

While controlled experiments of the kind so common in physics, chemistry, and other natural sciences are difficult to replicate in the social sciences, the past century does in a way provide a laboratory for an empirical test. Between 1900 and 2000 world population more than tripled, rising from under two billion to over six billion. Yet according to the measures reviewed earlier, resource availability did not significantly decline. This provides little support for the hypothesis that population growth seriously threatens the long-run availability of mineral commodities. While the future could be a different story, those who advocate slowing population growth in order to preserve the long-run availability of mineral commodities need at least to ponder the possibility that they may unwittingly be pushing counterproductive policies.

The influence that people have on the supply of mineral commodities via their ingenuity and influence raises some other intriguing and even paradoxical issues. Poverty and discrimination, for instance may be a far more serious challenge to the availability of mineral commodities than population per se. The United Nations (2001) estimates that poverty afflicts one in four people living in the developing world, or some 1.2 billion individuals, where poverty means living on less than one dollar a day. Without adequate

housing, food, health care, and education, these individuals simply do not have the opportunity to develop the skills and talents needed to promote the technologies that push the cumulative supply curve down over time, or to contribute back to society in other ways.

This reflects a loss that makes the entire world, developed as well as developing, poorer than it otherwise would be. How many Leonardo DaVincis, Thomas Edisons, and Albert Einsteins have lived and died in the slums of Calcutta, Rio de Janeiro, and New York lacking the means to develop their extraordinary talents? How much better off would the world in general be without poverty, and how much more available would mineral commodities be in particular?

Discrimination poses an equally troubling problem. Around the world, women and minorities are denied opportunities to obtain the education and experience needed to pursue productive professional careers. Like poverty, discrimination affects us all, not just those afflicted. Like poverty, it does so in a particularly insidious way, by preventing what might have been. As a result, those who are not directly affected have little or no idea of the magnitude of the losses they suffer. Indeed, many are unaware that poverty and discrimination impoverishes them too.

While there is no way to assess accurately these costs, they must be huge. Between a third and a fourth of humanity currently is unable to contribute to the welfare of society as a result of poverty and discrimination. If these or higher figures apply to the past as well, not an unreasonable assumption, they suggest that the benefits the world enjoys from the stock of existing technology (to say nothing of the those flowing from the arts and humanities) might now be 20 to 40 percent greater. In the case of mineral

commodities, such an additional infusion of new technology would have accentuated the tendency over the past century toward increasing availability, and enhanced the prospects for the continuation of this favorable trend in the future.

These issues suggest that the frequent accusations leveled by many against the developed countries, and in particular against the United States, that their profligate use of mineral commodities is inequitable and unjust may be misguided. While the per capita consumption of mineral commodities in India, Nigeria, China, and other developing countries is quite low, the widespread poverty in these countries means they can contribute only modestly to the on-going struggle to offset the cost-increasing effects of depletion. The developed countries on the other hand, despite their apparent profligate use, are in a far stronger position to foster the long-run availability of mineral commodities. If profligate use helps generate the income that supports the development of new cost-reducing technologies, it may actually benefit the developing countries despite the claims to the contrary.

Some may find this idea disturbing. They can, perhaps, take comfort in the fact that its underlying logic also leads to the conclusion that the developed countries should help fight poverty and discrimination around the world, not out of charity, or at least not solely out of charity, but because it is also in their own self interest to do so.

Of course, discrimination, poverty, and population growth may not be independent. In particular, population growth may contribute to poverty. Where this is so, the case for limiting population growth as a means of promoting the future availability of mineral commodities is easier to make. Where population growth does not aggravate

poverty, however, if is far less clear that mineral commodity availability is a valid justification for curbing population growth.

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Appendix

REAL PRICES FOR SELECTED MINERAL COMMODITIES, 1870-1997

by

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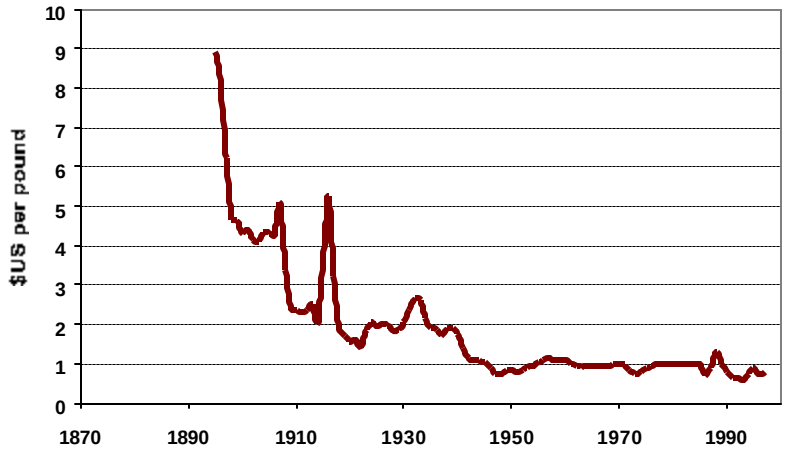
The figures below show the prices for aluminum, copper, pig iron, iron ore, nickel, lead, silver, tin, zinc, petroleum, natural gas, and bituminous coal deflated by the U.S. producer price index over the period 1870 to 1997. They are an update of the price data that Robert S. Manthy provides in his 1978 book, *Natural Resource Commodities—A Century of Statistics*. This book, in turn, updates the 1962 book by Neal Potter and Francis T. Christy, Jr., entitled *Trends in Natural Resource Commodities*. Both volumes, published by Johns Hopkins for Resources for the Future, contain a wealth of other data on mineral output, consumption, trade, and employment.

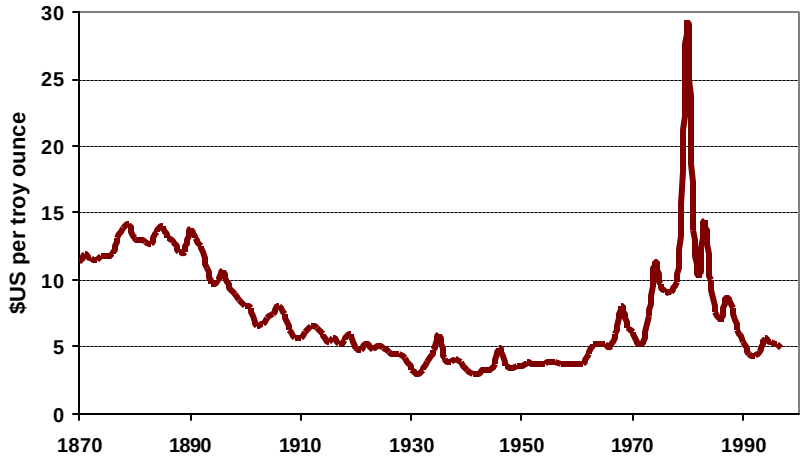
It is important to note that the prices shown are for the United States. Many mineral commodities are sold in global markets, and so trends in U.S. prices closely track prices abroad. However, this is not always the case. For example, the iron ore price shown is for iron ore from the Mesabi Range in northern Minnesota sold at ports on Lake Erie. This price does not fully reflect the decline over the past several decades in the prices of iron ore shipped from Brazil and Australia, which are currently the world's largest producers and exports of iron ore.

The section on data sources following the figures identifies the nature of the prices quoted along with their original sources.

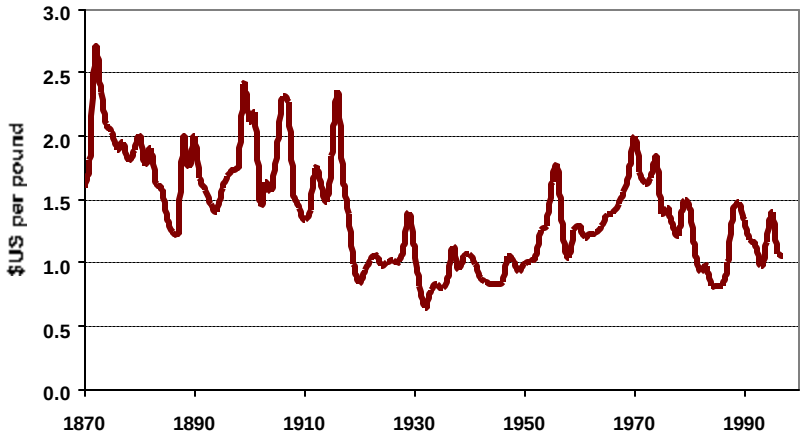
Real Prices Al Ingot ($US/lb), $1997



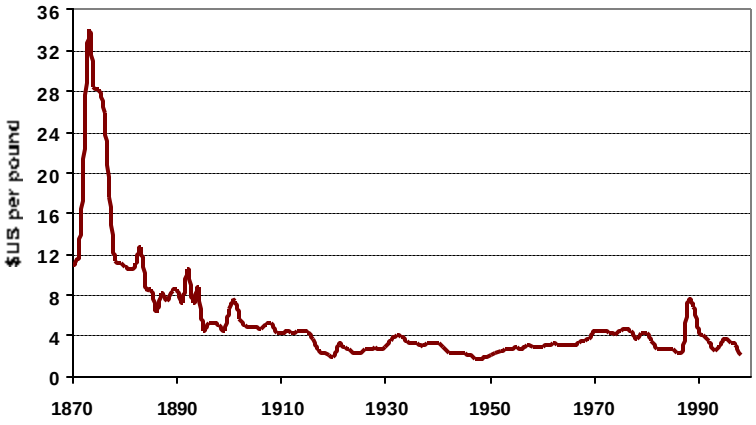
Real Prices Ag ($US/troy ounce), $1997



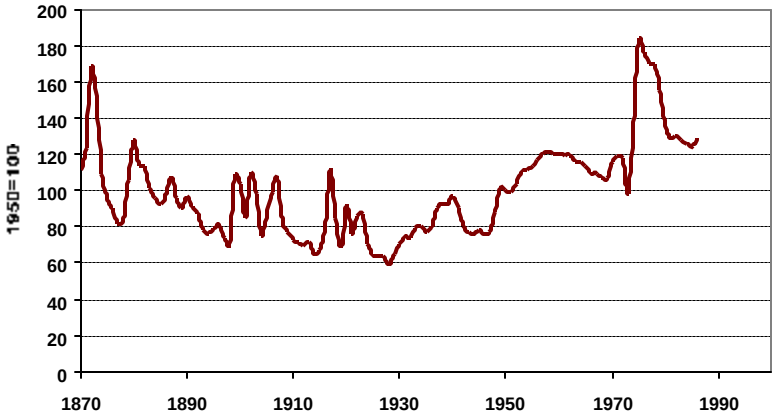
Real Prices Cu ($US/lb), $1997



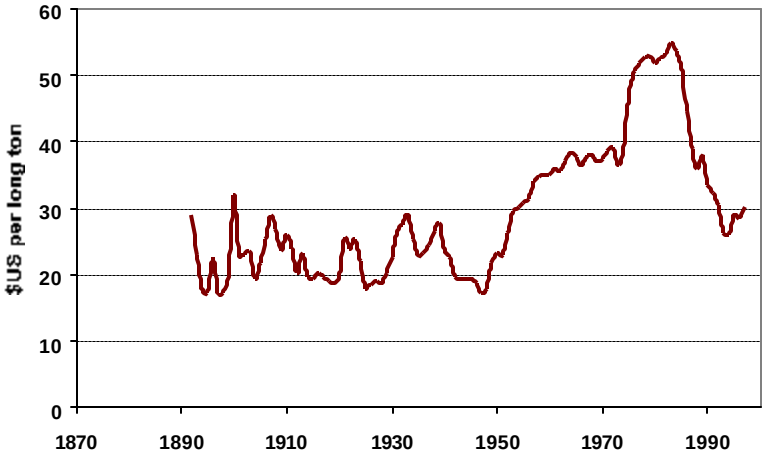
Real Prices Ni ($US/lb), $1997



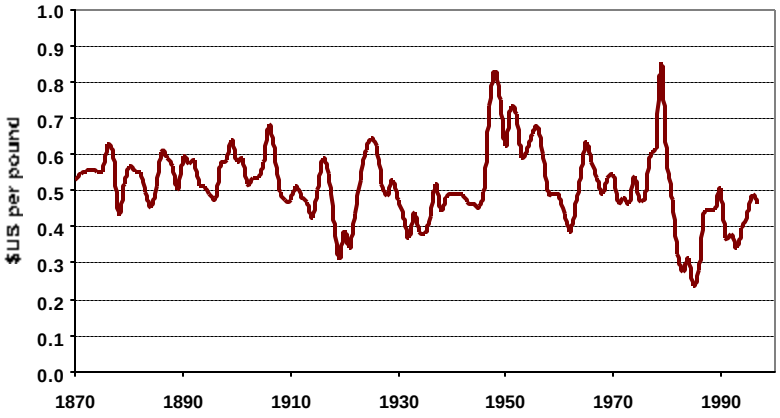
Real Prices Pig Iron (1950=100)



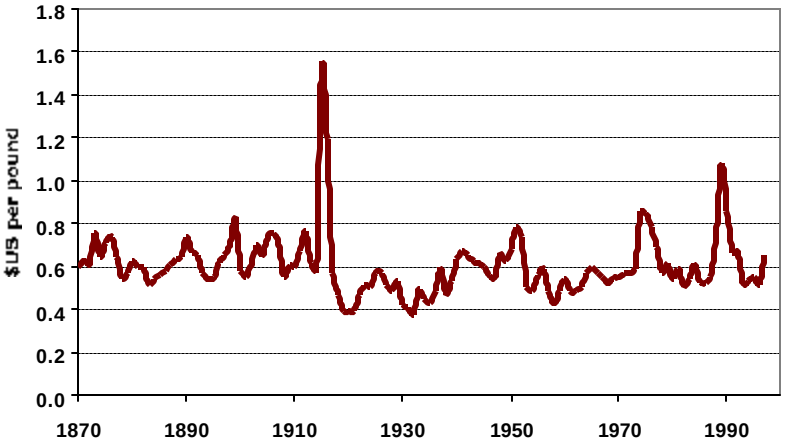
Real Prices Iron Ore ($US/long ton), $1997



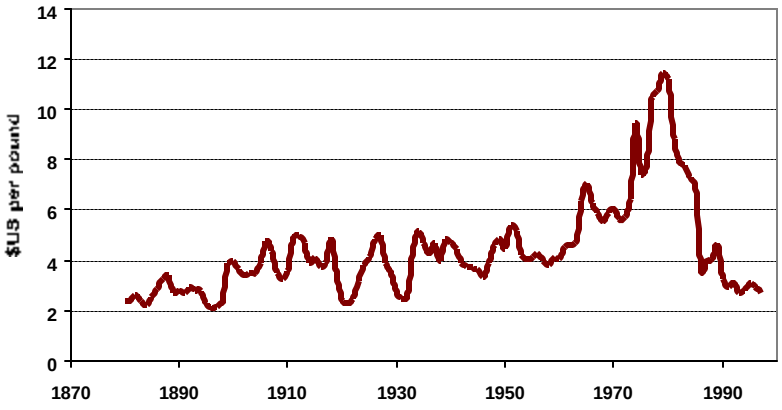
Real Prices Pb ($US/lb), $1997



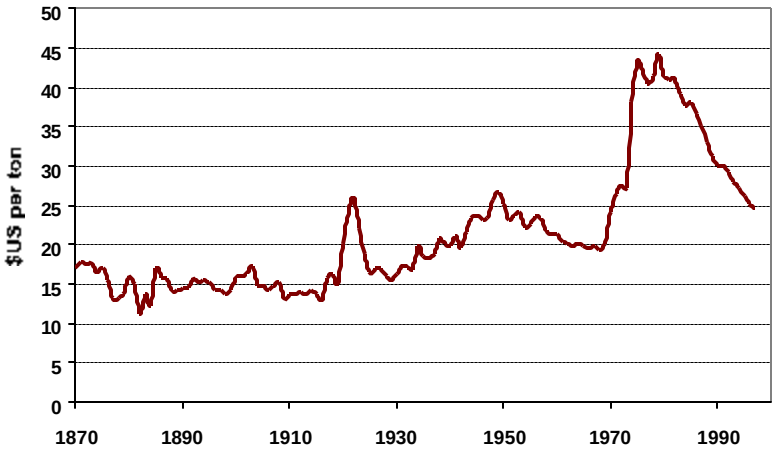
Real Prices Zn ($US/lb), $1997



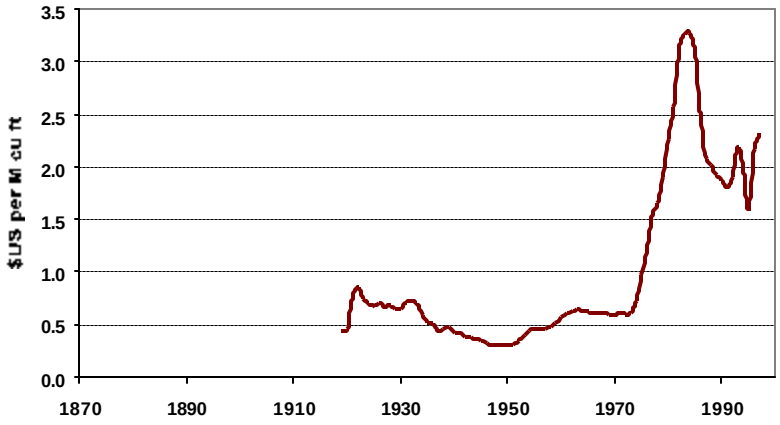
Real Prices Sn ($US/lb), $1997



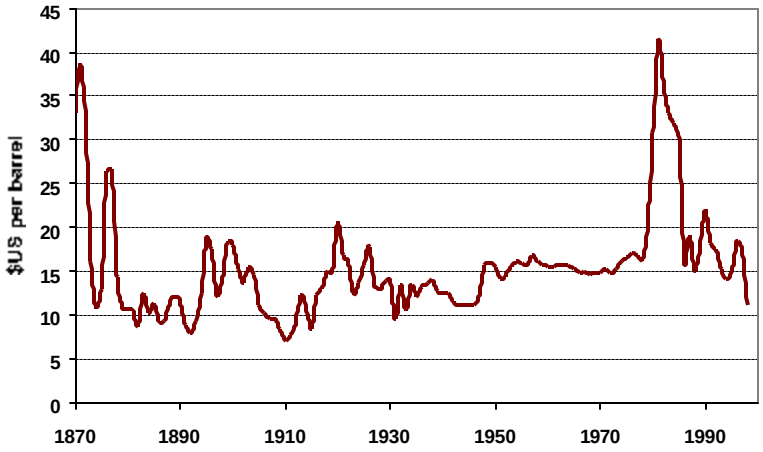
Real Prices Bituminous Coal ($/ton), $1997



Real Prices Natural Gas ($US/ M cu ft), $1997



Real Prices Petroleum ($US/barrel), $1997



Nature of Data and Sources

Aluminum: New York Prices and Producers Average Price

1870 - 1957: Potter and Christy (1870-1904: *ABMS Yearbook*, American Bureau of Metal Statistics; 1905-1957: *Metal Statistics*, American Metal Market)

1958 - 1983: *Metal Statistics*, American Metal Market

1984 - 1991: *ABMS Yearbook*, American Bureau of Metal Statistics

1992 - 1997: *Metal Statistics*, American Metal Market

Copper: United States Ingot and Electrolytic Copper at Refinery

1870 - 1957: Potter and Christy (1870-1889: *Aldrich Report - Wholesale Prices, Wages and Transportation*, U.S. Congress, Senate Committee on Finance; 1890-1905: *BLS Wholesale Prices Bulletin*, U.S. Department of Labor, Bureau of Labor Statistics; 1906-1957: *ABMS Yearbook*, American Bureau of Metal Statistics)

1958 - 1973: Manthy (1958-1973: *ABMS Yearbook*, American Bureau of Metal Statistics)

1974 - 1997: *ABMS Yearbook*, American Bureau of Metal Statistics

Pig Iron: United States Average Value

1870 - 1957: Potter and Christy (1870-89: *Statistical Abstracts of the United States - no.1 foundry at Philadelphia*, U.S. Department of Commerce, Bureau of the Census; 1890-1957: *BLS Wholesale Prices Bulletin*, U.S. Department of Labor, Bureau of Labor Statistics)

1958 - 1973: Manthy (1958-1973: *BLS Wholesale Prices and Price Indexes*, U.S. Department of Labor, Bureau of Labor Statistics)

1974 - 1986: *BLS Wholesale Prices and Price Indexes*, U.S. Department of Labor, Bureau of Labor Statistics

Iron Ore: Mesabi, non-Bessemer Iron Ore at Lake Erie Docks

1895 - 1957: Potter and Christy (1895-57: *Metal Statistics*, American Metal Market)

1958 - 1997: *Minerals Yearbook*, U.S. Department of the Interior, Bureau of Mines and United States Geological Survey - Salient Iron Ore Statistics, Average value at mines

Nickel: Average Unit Value Imported for Consumption

1870 - 1957: Potter and Christy (1870-1908: *Mineral Resources of the United States*, U.S. Department of the Interior, Geological Survey; 1909-1957: *Mineral Resources of the United States* and *Minerals Yearbook*, U.S. Department of the Interior, Bureau of Mines)

1958 - 1990: *Nickel Statistical Compendium*, U.S. Department of the Interior, United States Geological Survey

1991 - 1997: *Minerals Yearbook*, U.S. Department of the Interior, United States Geological Survey

Lead: United States Average Price at New York

1870 - 1957: Potter and Christy (1870-1955: *Historical Statistics of the United States, Colonial Times to 1957* and *Statistical Abstracts of the United States*, U.S. Department of Commerce, Bureau of the Census; 1956-1957: *Minerals Yearbook*, U.S. Department of the Interior, Bureau of Mines)

1958 - 1973: Manthy (1958-1973: *Minerals Yearbook*, U.S. Department of the Interior, Bureau of Mines)

1974 - 1987: *ABMS Yearbook*, American Bureau of Metal Statistics - United States Producer Lead Price

1988 - 1997: *ABMS Yearbook*, American Bureau of Metal Statistics - North American Producer Lead Price

Silver: New York Price

1870-1957: *Historical Statistics of the United States, Colonial Times to 1957*, U.S. Department of Commerce, Bureau of the Census;

1958-1997: *Metal Statistics*, American Metal Market

Tin: Straits Tin Prices in New York:

1880-1997: *Metal Statistics*, American Metal Market

Zinc: New York Prices and Prime Western Slab Zinc at New York

1870 - 1957: Potter and Christy (1870-1879: *Aldrich Report - Wholesale Prices, Wages and Transportation*, U.S. Congress, Senate Committee on Finance; 1880-1957: *Metal Statistics*, American Metal Market)

1958 - 1973: Manthy (1958-1973: *Metal Statistics*, American Metal Market)

1974 - 1990: *Metal Statistics*, American Metal Market

1991: Based on average of London Metals Exchange quotes

1992 - 1997: *Metal Statistics*, American Metal Market - Producers U.S. Spot Zinc, Prime Western

Petroleum: United States Average Value

1870 - 1957: Potter and Christy (1870-1914: *Mineral Resources of the United States*, U.S. Department of the Interior, Geological Survey; 1915-1953: *Petroleum Facts and Figures*, American Petroleum Institute)

1958 - 1973: Manthy (1958-1969: *Petroleum Facts and Figures*, American Petroleum Institute; 1970-1973: *Mineral Industry Surveys Petroleum Statement*, U.S. Department of the Interior, Bureau of Mines)

1974 - 1997: *Basic Petroleum Data Book, Petroleum Industry Statistics*, American Petroleum Institute

Natural Gas: United States Average Value, Point of Production

1870 - 1957: Potter and Christy (1919-1921: Barger and Schurr, 1944, *The Mining Industries, 1899-1939: A Study of Output, Employment and Productivity*; 1922-1931: *Mineral Resources of the United States*,

U.S. Department of the Interior, Geological Survey and Bureau of Mines; 1932-1953: *Minerals Yearbook*, U.S. Department of the Interior, Bureau of Mines)

1958 - 1973: Manthy (1958-1973: *Minerals Yearbook*, U.S. Department of the Interior, Bureau of Mines)

1974 - 1997: *Basic Petroleum Data Book, Petroleum Industry Statistics*, American Petroleum Institute

Bituminous Coal: United States Average Value at Mine

1870 - 1957: Potter and Christy (1870: *Census of Mineral Industries*, U.S. Department of Commerce; 1871-1879: *Seward's Coal Trade Journal*; 1880-1896: *Mineral Resources of the United States*, U.S. Department of the Interior, Geological Survey; 1897-1955: *Historical Statistics of the United States, Colonial Times to 1957* and *Statistical Abstracts of the United States*, U.S. Department of Commerce, Bureau of the Census; 1956-1957: *Minerals Yearbook*, U.S. Department of the Interior, Bureau of Mines)

1958 - 1973: Manthy (1958-1973: *Minerals Yearbook*, U.S. Department of the Interior, Bureau of Mines)

1974 - 1997: *Energy Information Administration Annual Energy Review*, Energy Information Administration, U.S. Department of Energy

Producer Price Index: All Commodities

1870 - 1957: Potter and Christy (*Historical Statistics of the United States, 1789-1945*, and *Statistical Abstracts of the United States*, U.S. Department of Commerce, Bureau of the Census)

1958 - 1973: Manthy (*Statistical Abstracts of the United States*, U.S. Department of Commerce, Bureau of the Census)

1974 - 1997: *Statistical Abstracts of the United States*, U.S. Department of Commerce, Bureau of the Census