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Public policy and future mineral supplies

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A B S T R A C T

A widespread and pessimistic view of the availability of mineral commodities calls for strong government initiatives to ensure adequate future supplies. This article provides a more market oriented and optimistic perspective, one that focuses on production costs and prices rather than physical availability. It sees short-run shortages continuing to plague commodity markets in the future as in the past. Though painful while they last, these shortages are temporary and do not pose a serious long-run threat to human welfare. Moreover, even without government intervention, they self-correct. The sharply higher prices that they evoke create strong incentives that foster supply and curb demand.

Potentially more serious are long-run shortages due to mineral depletion. Such shortages are often thought to be inevitable, a conclusion that flows directly from the physical view of depletion. For various reasons, we reject this view of depletion in favor of an economic view. The latter recognizes that depletion may create long-run shortages, but stresses that this need not be the case if new technology can continue to offset the cost-increasing effects of depletion in the future as it has in the past. The economic view also suggests that a list of mineral commodities most threatened by depletion can best be compiled using cumulative availability curves rather than the more common practice of calculating commodity life expectancies based on estimates of available stocks.

1. Introduction

A recent issue of *Nature* carries an article entitled 'Mineral supply for sustainable development requires resource governance' by Ali et al. (2017). It paints a rather troubling picture of the availability of copper in particular and other metals and mineral commodities in general over the next half century. The challenges that it highlights are numerous and fall into three broad categories—(1) rapid demand growth caused by rising global population as well as the increased material needs for climate change policies and UN sustainable development goals; (2) constraints on supply arising from inadequate investment in exploration and new capacity, growing community resistance to mining, governance problems in many host countries, long gestation periods for new mines, growing government regulations to protect the environment and for other reasons, and declining amounts of identified mineral resources; and (3) the inability of recycling and secondary production to contribute greatly to mineral commodity supply until the middle of the 21st century, given that much of the copper and other materials currently in buildings and other products will not be available for recycling for some time.

To mitigate and avoid future supply crises, the article recommends the adoption of various public policies, including international targets for global mineral production, common standards to ensure maximum efficiency and minimum environmental damage, support for new extraction technologies, harmonization of best practices, and greater public-private cooperation. Their article concludes with the sentence:

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"Ultimately, international legal mechanisms may be needed to anticipate and respond to future mineral availability constraints".

The authors are scientists and engineers with expertise from across a spectrum of fields. In this respect, their paper reflects an interdisciplinary perspective. It also reflects a widely shared, rather pessimistic outlook on the future availability of mineral commodities and hence the need for strong corrective government measures.[1]

There is, however, a different perspective, strongly supported by historical experience, which many geoscientists, economists, policy analysts, mineral industry executives, and others (including all of us) believe provides a more useful and appropriate framework for assessing the future availability of mineral commodities.[2] It is more market focused and less pessimistic—indeed, it is modestly optimistic about the future. It sees an important role for governments and public policy in ensuring adequate future mineral commodity supplies, a role that overlaps with the policy recommendations of the more pessimistic perspective but one that also diverges in a number of important respects.

2. The market-focused and modestly optimistic perspective

Our modestly optimistic perspective concentrates much more on prices and much less on physical availability. What matters for society, this view maintains, is how much we have to give up to obtain an additional barrel of oil or pound of copper. So increasing scarcity and declining availability are defined as either (a) a sharp jump in price over the short run or (b) a persistent increase in real (i.e., inflation-adjusted) price over the long run that slowly but persistently squeezes traditional users out of the market.

This perspective, it is worth noting, does not assume that a peak in production followed by declining output is necessarily an omen of a present or future shortage. Such peaks may simply reflect falling demand.[3] In the early 20th century, for example, the mining of nitrates (saltpeter), used largely in fertilizers and explosives, collapsed thanks to the successful efforts of German chemists to develop synthetic substitutes. Similarly, it was falling demand—largely the result of government regulations motivated by public health concerns—rather than supply constraints, that precipitated the drop in asbestos and mercury production over the past half century.

A case can even be made that the peak in U.S. petroleum production in the early 1970s, so famously predicted by Hubbert (1962), was the result of falling demand for domestic oil as cheaper sources became available from abroad, just as cheaper production from U.S. shale deposits increased the demand for domestic oil and reversed the downward trend during the early 21st century.

The modestly optimistic perspective also makes a clear distinction between short-run or temporary shortages (which rarely last more than a decade and often only a few months or years) and long-run (possibly permanent) shortages. The two are quite different.

Temporary shortages take place with some frequency and for a variety of reasons. Unexpected surges in global demand, inadequate investment in exploration and new capacity, the control of supply by cartels, wars, interruptions in trade, embargos, government fiats, mine accidents, and strikes can all cause severe short-run increases in mineral commodity prices. Recent illustrations include the surge in global commodity demand in the early years of this century due to the rapid growth of the Chinese economy, the fears over export restrictions on rare-earth minerals imposed in 2010 by the same country, and the Indonesian ban on exports of unprocessed ores of nickel and other mineral commodities since 2014.

Such shortages can be quite painful while they last, but they seldom persist for long thanks to what Wellmer and Dalheimer (2012) call the benevolent *feedback control cycle* of mineral supply. Shortages contain the seeds of their own destruction. In response to sharply higher prices, consumers develop and use alternative materials or simply find ways to produce their products with less material input. Simultaneously, higher prices encourage investors to expand existing sources of primary supply, to find and develop new sources, and to increase recycling and secondary production.

Long-run shortages are in almost all respects quite different. They produce rising trends in real prices over many decades, rather than sharp surges for a few months or years. As a result, they pose, at least potentially, a much more serious threat to the well being of the human race. In the past, they have occurred infrequently; so infrequently that it is difficult to identify any such shortages with certainty. The available studies, and there are many, find both downward and level long-run trends. What they do not find are mineral commodities for which real prices have risen significantly over the past 100 to 150 years.[4]

Fig. 1 shows the average annual real prices from 1900 to 2016 for five important metals—aluminum, copper, lead, nickel, and zinc. The prices for these metals are highly volatile over the short run, rising dramatically during economic booms and falling sharply during recessions, but their long-run trends are either downward (aluminum) or more or less flat (copper, lead, nickel, and zinc).

Why do we not find rising long-run trends in real prices? New technologies, discovered deposits, and other innovations have offset, or more than offset, the cost-increasing effects of more stringent government regulations, rising real wages, and especially mineral depletion. If this favorable situation continues in the future, then some mineral commodities will become more available (or less scarce), while the availability of others will remain more or less the same. Of course, it is possible that the discovery of new deposits and innovation will fail to offset the upward pressure on costs from mineral depletion and other forces. In this case, society will have to pay more for its mineral raw materials.

3. Policy implications for short-run shortages

The modestly optimistic perspective does recognize that government intervention is needed to correct serious market failures. For the mineral sector, a particularly pervasive market failure arises from what economists call externalities. Externalities occur whenever an activity by an individual or firm creates (a) costs to society that the individual or firm does not pay for or (b) benefits that it does not capture.

Examples of the former are air and water pollution and, of particular concern these days, greenhouse gas emissions. Private firms cannot be expected to curtail their pollution to socially optimal levels unless public policy requires their competitors to do the same. So, clearly, sustainable mineral commodity production requires appropriate environmental regulations.

Similarly, public support is needed for education and for R&D, because the expected benefits to society from these activities far exceed those that the firms, institutions, and individuals responsible for these activities can capture. For the mineral sector, this means that governments have an important role to play in supporting educational and innovative activities from exploration through recycling. For the same reason, public policies are needed to support geologic mapping and other early stages of exploration (Herfindahl and Kneese, 1974; Duke,

[1] Elshkaki et al. (2016), Henckens et al. (2016), and Svedrup and Ragnarsdóttir (2014) are other recent examples of this perspective and provide references to other studies in this genre. Earlier studies include U.S. President's Materials Policy Commission (The Paley Commission) (1952), Gordon et al. (1987), Gordon et al. (2006), and Northey et al. (2014).

[2] Arndt et al. (2017) and chapter 9 of Tilton and Guzmán (2016) provide examples of this view of the future availability of mineral commodities as well as references to other studies with a similar perspective.

[3] According to Wellmer and Scholz (2017), most peaks in mineral production are the result of reductions in demand rather than supply constraints.

[4] Chapter 8 in Radetzki and Wårell (2017) discusses long-run trends in the real prices of mineral commodities and provides references to other relevant studies.

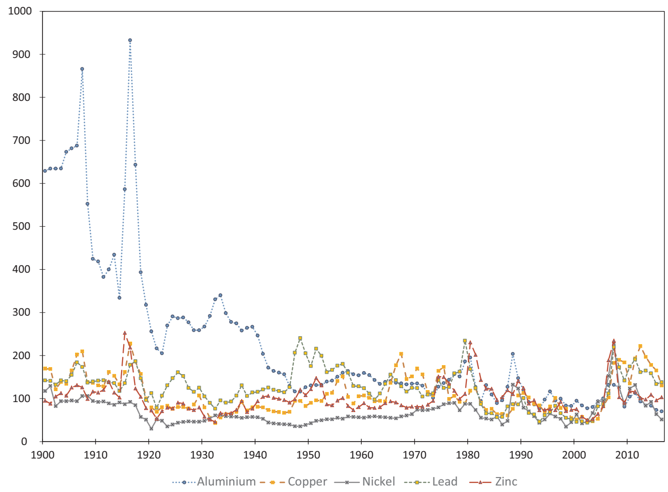

Fig. 1. Index of real prices for aluminum, copper, lead, nickel, and zinc, 1900–2016 (100 = Average of 2000–2009 prices). Notes and Sources: All prices are given in US dollars per metric ton. The source for copper prices from 1960 and aluminum, lead, nickel and zinc prices from 1980 is the London Metal Exchange (annual average cash settlement prices of the prevailing shapes and grades in each year). Prices of copper and lead until July 1993, and of zinc until September 1988, were quoted in sterling. They have been converted to US dollars at the exchange rates ruling at the time. The basis of the zinc price moved from standard high grade in September 1980 and to special high grade in January 1990. The copper quotation moved from electrolytic wirebars to copper higher grade in December 1981 and to Copper Grade A on June 30, 1986. Prices for the remaining years for each metal are United States' quotations and are from Schmitz (1979). Nominal prices are converted to real prices using the US implicit GDP price deflator for the years 1929–2016. For earlier years the deflator is the US wholesale price index from *Historical Statistics of the United States*.

2010), as well as the collection and public dissemination of mineral industry data important to the national economy and national security.[5]

Other than to address such significant market failures, however, proponents of the modestly optimistic perspective are inclined to rely on markets to ensure future mineral commodity supplies. They are reluctant to have governments set output goals, require particular production methods, encourage recycling beyond what is economically justified, promote the use of renewable over non-renewable resources, and in other ways substitute public for private decision making.

As noted earlier, the modestly optimistic perspective makes a clear distinction between temporary and long-run, possibly permanent, shortages. Temporary shortages have plagued the mineral industries since at least the Industrial Revolution and are due to the inherent nature of short-run mineral supply and demand. Once full capacity is reached, supply is more or less unresponsive to increases in price. The same is often true for demand as well. This is in part because the cost of a mineral commodity often accounts for a small percentage of the price of the final products in which it is embodied, and in part because the opportunities to substitute one material for another are, for various reasons, limited in the short run (Tilton and Guzmán, 2016, ch. 2). This means that both the short-run supply and demand curves are very steep. So a shift in either causes the market-clearing price to change greatly.

Mergers, cartels, producer-consumer agreements, and other efforts, both by private firms and governmental bodies, to cope with this volatility date back centuries, possibly even millennia. The formation of U.S. Steel in the early 19th century, often described as a merger of mergers and at the time the largest corporation in the United States, was in part motivated by the desire to eliminate or at least dampen the violent cyclical swings in steel prices that plagued the second half of the 19th century. More recent examples include OPEC (the Organization of the Petroleum Exporting Countries), CIPEC (the Intergovernmental Council of Copper Exporting Countries), IBA (the International Bauxite Association), APEF (the Association of Iron Ore Exporting Countries), and the six International Tin Agreements. Such efforts have seldom succeeded for more than a few years, and very rarely for more than a decade.

More effective measures for coping with this inherent volatility are stockpiling in anticipation of shortages and shifting the risk of price changes via hedging and other financial derivatives to those more able and willing to accept it. On occasions, public stockpiles make sense, particularly when national strategic interests are at stake. Often, though, decisions to stockpile or hedge are best made by those private interests that shortages are most likely to affect. There is little to suggest that public officials are any better at anticipating unexpected shifts in demand or supply than the private entities that produce and consume mineral commodities.

4. Policy implications for long-run shortages

Particularly interesting and important differences emerge between our modestly optimistic perspective and the more pessimistic perspective with regard to long-run shortages and the threat of depletion.

4.1. Competing paradigms

The more pessimistic perspective typically relies on a physical view of depletion, what mineral economists call the *fixed-stock paradigm* of depletion (Tilton and Lagos, 2007). Since the earth is finite, it follows logically that the supply of any mineral commodity is limited, as it is produced from a resource of given and limited quantity. Different measures are used to estimate this quantity, among them resources, reserves,[6] and remaining ultimately recoverable resources (URR).[7] For example, the Ali et al. (2017) study, cited at the beginning of this article, uses a model designed to reflect the peak in copper production during the 2020s that Northey et al. (2014) anticipate. The latter derives this peak using estimates of the available copper stock based on data for the remaining URR.

While the resources extracted to create supply are a fixed stock, production and consumption are flow variables. They continue year after year, possibly accelerating over time, particularly if population and per capita consumption are growing. Given these assumptions, long-run shortages are inevitable. Eventually the available stocks will be consumed. One can calculate the life expectancies of mineral commodities using estimates of their available stocks and future consumption. For copper, for example, at current rates of primary production, reported reserves and resources would last about 40 and 300 years, respectively.[8]

To postpone the day of reckoning, many proponents of the more pessimistic perspective favor public policies that encourage recycling, conservation, and the substitution of renewables for mineral resources. With some justification, they are skeptical that current prices provide a reliable indicator of future scarcity. Rather, they flag mineral commodities with relatively short life expectancies as those most vulnerable to shortages and most in need of immediate attention.

Advocates of the modestly optimistic perspective advocate a

[5] Chapter 5 of U.S. National Research Council, Committee on Critical Mineral Impacts on the U.S. Economy (2008) provides a strong rationale for government support in gathering and disseminating mineral information and data.

[6] The U.S. Geological Survey (annual) provides data on reserves (the quantity of a mineral commodity contained in discovered deposits that are currently profitable to exploit) and limited information on resources (the quantity of a mineral commodity found in deposits, both identified and undiscovered, whose economic extraction is currently or potentially feasible).

[7] Mudd and Weng (2012) describes a more recent method to measure the availability of copper, referred to as remaining ultimately recoverable resources. This approach identifies all known copper deposits, estimates the total copper these deposits contained prior to any mining, and finally calculates the quantity of copper remaining in these deposits.

[8] U.S. Geological Survey (annual) provides the data on production, reserves, and resources used to calculate these life expectancies.

different view of depletion. They acknowledge the logic of the physical view—clearly, since the earth is finite, the amount of any material found in the earth has to be finite as well—but for several reasons believe as a guide to public policy the physical view is seriously flawed.

First, many mineral commodities are not destroyed when used. The earth contains as much copper today as it ever has with the possible exception of the miniscule quantities shot into space. And, even these amounts have presumably been more than replaced by the copper in the roughly 40 thousand tons of interstellar dust penetrating the Earth's atmosphere every year (Taylor et al., 1996).

Second, most mineral commodities have substitutes in many end uses. If petroleum, which is destroyed when used as a fuel, becomes scarce causing its price to rise over time, society will at some point switch to other sources of energy—solar power, for example, whose availability for all practical purposes is unlimited.

Third, the physical quantities of various mineral commodities contained in the earth are huge. The copper in the earth's crust, for example, would last 84 million years at current production rates. For aluminum, the figure is 7.7 billion years.[9] If physical existence were the relevant constraint on future production, we would have more pressing problems to address.

However, long before society extracted the last ton of copper in the earth's crust, the costs of extraction would rise, extinguishing demand in one end use after another until at some point production ceased. So physical existence is not the relevant constraint. For this reason, proponents of the modestly optimistic perspective prefer an economic view of depletion, what mineral economists call the *opportunity cost paradigm* of depletion, over the physical view.

The economic view focuses on what society has to give up or sacrifice to obtain another barrel of oil or ton of copper. Typically, this opportunity cost is measured by differences and trends in real prices. The difference between the price of copper and gold today reflects the fact that copper is less scarce than gold. The decline in the real price of aluminum over the past century indicates that this material has actually become more available (less scarce) despite the extraction of many tons of low-cost reserves.

With the economic view, shortages due to mineral depletion are no longer inevitable. The future depends largely on the balance between the cost-increasing effects of depletion and the cost-reducing effects of new technology. In the past, as noted, new technology has offset or more than offset the negative effects of depletion. This could continue to be the case in the future, though of course this is not a certainty.

The preceding suggests that the best weapon society has in its arsenal for coping with the threat of depletion is research and development—aimed at enhancing and increasing primary production from lower quality resources with less environmental damage, increasing manufacturing efficiency and recycling, and developing substitutes. In other words, innovation to produce more, waste less, and use less of a material. It is new technology that has kept depletion at bay in the past and has the potential to do so in the future. Other measures, such as slowing primary production by promoting conservation, recycling, and the substitution of renewable for non-renewable resources beyond what is economic, can delay the day of reckoning but offer no hope of eliminating it.

It is important to note that public policies designed to alter market behavior, such as sponsoring R&D or promoting recycling beyond what the market would undertake by itself, require valuable public resources. These resources come with a cost, since they could otherwise be used to promote other social goals, such as education and public health.

[9] Tilton and Guzmán (2016, ch. 9) provides life expectancies of reserves and resources for a number of mineral commodities based on data from the U.S. Geological Survey.

4.2. Assessing the threat

The economic view of depletion also suggests a quite different methodology for identifying those mineral commodities that depletion most threatens. As noted earlier, the physical view relies on life expectancies based on estimates of future consumption and the available stocks. This approach falters because the estimates used for the available stock, such as reserves and even resources, are not truly fixed stocks. Reserves, as is well known, often increase over time thanks to exploration and discoveries at both greenfield and brownfield sites.[10] New technologies that permit the profitable exploitation of previously uneconomic deposits are also an important source of new reserves.

Resources are defined as the quantity of a mineral commodity contained in deposits, both identified and undiscovered, whose economic extraction is currently or potentially feasible. Yet, they too change over time, largely in response to technological developments that make economic extraction appear potentially feasible where previously this was not the case. For example, seabed mining of copper and other mineral commodities is now considered a future probability. For such reasons, the U.S. Geological Survey estimates of copper resources have risen from 2.3 billion tons in 2000 to 5.6 billion tons today (U.S. Geological Survey, annual), more than doubling within 20 years. This figure climbs to 6.4 billion tons if one includes new estimates of undiscovered porphyry and sediment-hosted copper deposits along with the other kinds of undiscovered copper-bearing deposits (Singer, 2017).

While the quantity of copper contained in the earth's crust is more or less fixed, as noted previously, using this quantity as the available stock to estimate copper's life expectancy—some 84 million years at current rates of extraction—is clearly unhelpful, as most of this copper with high certainty will remain forever uneconomic to mine.

So, in place of life expectancies, the economic view of depletion argues for focusing on mineral commodities whose real production costs and in turn prices are likely to rise significantly over the coming decades and centuries. This, as noted, depends largely on the balance over time between the cost-increasing effects of depletion and the cost-reducing effects of technology. Since the future course of technological change is unknown and presumably unknowable, one might conclude that it simply is not possible to identify the mineral commodities most vulnerable to shortages over the long run. It turns out, however, that the situation is not quite as hopeless as it may at first appear.

4.3. The cumulative availability curve

The cumulative availability curve shows the total quantities of a mineral commodity, such as copper, that can be produced economically at various prices with today's technology and other conditions (such as wage rates and other input prices).[11,12] Fig. 2a illustrates such a curve. As price rises, the number of economic deposits increases and, along with it, the amount of copper in these deposits classified as economic.

As drawn in Fig. 2a, this curve indicates that the copper available not only increases with price but increases at an increasing rate. This need not be the case. When the demand for a commodity now produced as a byproduct, such as germanium or gallium, rises sufficiently to require its extraction as a main product, costs may jump dramatically.

In the case of copper, Skinner (1976) has argued that, once the sulfide and oxide minerals from which we now produce copper are depleted, we may have to extract copper from silicate minerals. This

[10] For an interesting discussion of how copper reserves at one particular mine, the El Teniente Mine in Chile, have changed over the past century, see Radetzki (2009).

[11] Tilton and Skinner (1987) provides an early discussion of the cumulative availability curve. This and other early references to the cumulative availability curve use the term the cumulative supply curve.

[12] Babitzke et al. (1982) describes the Minerals Availability System, a major and early effort to estimate cumulative availability curves for a large number of mineral commodities undertaken by the U.S. Bureau of Mines during the 1970s and 1980s.

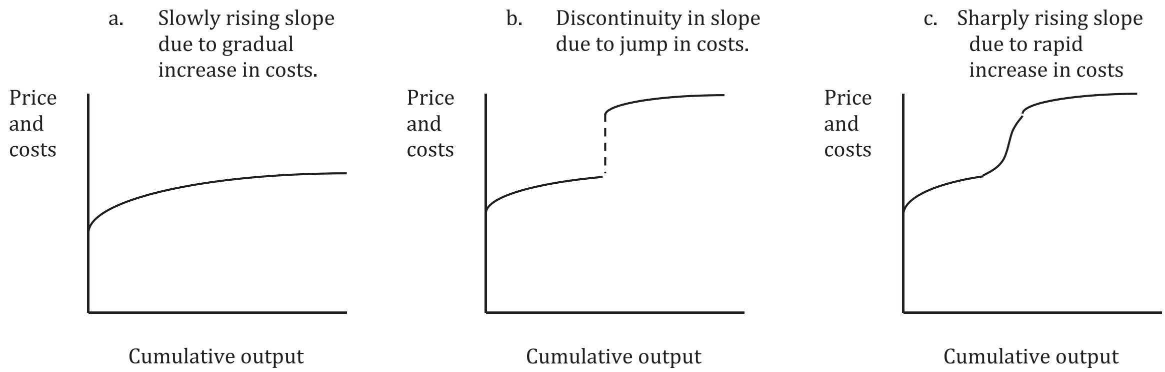

Fig. 2. Illustrative cumulative supply curves.

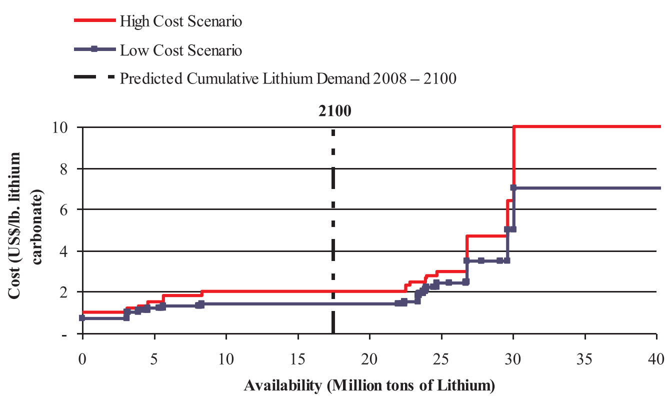

Fig. 3. Cumulative availability curves for lithium under high and low cost scenarios with predicted cumulative demand from 2008 to 2100[a]. Note: [a]Costs are in 2007 U.S. dollars.

could cause costs to surge for two reasons. Ore grades are likely to drop requiring the mining of many more tons of material per ton of copper recovered; and the technologies available to process silicate ores will probably require much more energy input per ton of output. Sharply higher costs would produce a discrete jump or an upward surge in the cumulative availability curve, as illustrated in Fig. 2b and c.

The cumulative availability curve is a useful expository device. It allows one to place all the factors influencing the long-run future course of any mineral commodity's real price into three categories. First, there are the geologic and environmental considerations—the number, nature, quality, byproducts, and accessibility of the identified resources from which the commodity can be produced, as well as (at least in principle) an estimate of the external costs associated with production of a mineral resource. These determine the shape of the curve. Second, there are all the forces that govern how rapidly society moves up the curve. Here we find the change in demand for a mineral commodity (which depends on changes in global population, per capita income, consumer preferences, and the technologies used to produce consumer goods and services) as well as trends in recycling and secondary production. Finally, there are the forces that cause the curve to shift over time, such as new technology and changes in input costs. Since new technology is adopted only if it reduces production costs (including negative externalities, such as environmental pollution), the cumulative availability curve is likely to shift downward over the long run. For a time, though, a surge in input costs or more stringent government regulations could push it upward.

We know that the future course of real mineral commodity prices will reflect all three of these considerations—the shape of the cumulative availability curve, the speed with which society moves up the curve, and the extent to which the curve shifts. We also know that these two last considerations—the speed society moves up the curve and shifts in the curve—depend on future developments that are for the most part not only unknown but unknowable.

This is not the case, however, for the first consideration—the shape of the curve. It depends as noted on the nature and incidence of existing resources created by geologic processes in the distant past. For many mineral commodities, the information needed to construct their cumulative availability curves is not now known, but it is knowable. So with some effort we can estimate the shape of cumulative availability curves. Indeed, a few such studies have recently become available—for lithium (Yaksic and Tilton, 2009; Jasiński et al., 2017), petroleum (Aguilera et al., 2009), PGMs (Jasiński et al., 2017), iron ore (Pustov et al., 2013), thorium (Jordan et al., 2015), tellurium (Redlinger et al., 2013), and indium (Lokanc et al., 2015).

Just knowing the shape of cumulative availability curve can provide useful insights into the likely future threat of mineral depletion. When the curve possesses the benign shape shown in Fig. 2a, production costs and hence prices are not likely to rise substantially even if consumption increases rapidly and technology fails to shift the cumulative availability curve downward.

According to Yaksic and Tilton (2009), this is the case with lithium. Fig. 3 shows the cumulative availability curve that they estimate for this mineral commodity under high-cost and low-cost scenarios. The vertical broken line indicates cumulative lithium consumption over the period 2008–2100 for the world as a whole under very optimistic projections for the use of lithium in hybrid and all electric vehicles. At somewhere between 7.50 and 10.00 (2007) dollars a pound for lithium carbonate, they find that the extraction of lithium from seawater becomes economic. For all practical purposes, seawater is an infinite source of supply. So, at these costs, their curves become horizontal and extend to the right far beyond the cumulative quantities shown in the figure.

This means that, should the demand for lithium increase at unprecedented rates over the next several decades as some are predicting, the price of lithium could increase perhaps by 50 percent from its present level but no more. This, according to Yaksic and Tilton, would not significantly increase the costs of vehicles powered by lithium batteries, nor greatly curtail the demand for lithium.

Of course, for other mineral commodities, the shape of the cumulative availability curve may not be so benign. Curves constructed for the PGMs, for example, rise much more rapidly with cumulative output (Janiński et al., 2017). So mineral depletion could pose a more serious threat to their long-run availability.

As noted earlier, this may also be the case for many commodities now produced as byproducts. Gallium, for example, is extracted as a byproduct of bauxite and zinc ores. Should the demand for gallium increase beyond what is available from these sources, prices might have to rise sharply to cover the higher costs of main product output. Here again, the shape of the cumulative availability curve could tell us much about the potential threat of depletion.

There is, however, an important asymmetry between mineral commodities with and without benign (i.e., quite flat) cumulative availability curves. For the former, we can with confidence conclude that mineral depletion does not pose a significant threat. Even if demand increases rapidly and new technology fails to shift the curve downward, future production costs should not rise greatly above current levels. For commodities whose cumulative availability curves rise appreciably with output, though, we cannot conclude that mineral depletion will necessarily create future shortages. This will be the case only if new technology is unable to offset the negative effects of depletion.

5. Conclusions

We believe the modestly optimistic perspective described above is more useful than the more pessimistic perspective in assessing the future availability of mineral commodities. It focuses on prices and costs rather than physical supply. It distinguishes between temporary or short-run shortages (which are quite common and occur for numerous reasons) and long-run shortages (which are due to mineral depletion and have been so rare historically that we have found no examples to cite).

Short-run shortages are largely due to the inherent nature of short-run mineral commodity supply and demand. Once output approaches full capacity, neither is very responsive to changes in price. So a shock to either causes large changes in the market-clearing price. Public policies to avoid and mitigate such shortages have not been very successful. The sharp price increases shortages provoke are probably the best antidote, as they encourage new supply and curtail demand in numerous ways. They also provide strong incentives for firms and others to reduce their risks by maintaining stockpiles, resorting to financial derivatives such as hedging, and undertaking R&D as an insurance policy against future market shocks.

Under the modestly optimistic perspective, long-run shortages due to mineral depletion are not inevitable. New technology has in the past offset the adverse effects of mineral depletion, and may continue to do so in the future. Moreover, if long-run shortages do occur, they should manifest themselves by persistent increases in real costs over decades, slowly choking off demand in one end use after another. So society is not likely to be caught by surprise, but instead should have some time to respond once long-run shortages become apparent.

For these reasons, the search for public policies at this time to cope with possible but uncertain long-term shortages should focus on those policies justified by externalities and other market failures. In particular, the modestly optimistic perspective would favor policies that foster innovation and new technologies that have the potential to increase and enhance the efficiency of primary production, to improve manufacturing efficiency and recycling, and develop substitutes. These innovations alone offer the possibility of keeping mineral depletion at bay indefinitely.

This perspective also suggests that a better understanding of cumulative availability curves provides a more reliable approach to identifying those mineral commodities most threatened by mineral depletion than does estimating commodity life expectancies based on reserves, resources, remaining URRs, or other estimates of the available or existing fixed stock.

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