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Our mental models of mineral depletion — and why they matter

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ABSTRACT

Geologists, economists, policy analysts, and others use two different mental models when assessing depletion and the future availability of mineral commodities. The first, the physical view, relies on estimates of the available exploitable stocks of resources and the speed with which society is likely to consume them. The second, the economic view, uses as its measure of availability differences and trends in real (inflation-adjusted) commodity prices.

This paper examines these two approaches, highlighting the very different implications that they suggest for the nature of depletion, its future threat, and the most effective public policies for coping with this threat. After exploring the shortcomings of each, the paper concludes that the economic view is, for several reasons, the more useful and helpful for understanding mineral depletion and its threat.

Keywords: commodity price trends, mineral depletion, mineral policy, mineral resources, mineral shortages.

Nuestros modelos mentales sobre el agotamiento mineral y el por qué esto resulta importante

RESUMEN

Los geólogos, los economistas, los analistas de políticas y otros, utilizan dos modelos mentales diferentes cuando evalúan el agotamiento y la disponibilidad futura de productos minerales. El primero, la visión física, se basa en estimaciones de las existencias de recursos explotables disponibles y de la velocidad con la que es probable que la sociedad los consuma. El segundo, el punto de vista económico, utiliza como medida las diferencias de disponibilidad y las tendencias en los precios reales de los productos (ajustados por la inflación). Este documento examina estos dos enfoques, destacando las muy diferentes implicaciones que sugieren sobre la naturaleza del agotamiento, su amenaza futura y las políticas públicas más efectivas para hacer frente a esta amenaza. Después de explorar las deficiencias de cada uno, el documento concluye que la visión económica es, por varias razones, la más útil para comprender el agotamiento de los minerales y sus amenazas.

Palabras clave: agotamiento de minerales, escasez de minerales, tendencias de los precios de los productos básicos, recursos minerales, política minera.

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

Los geólogos, los economistas, los analistas políticos y otros más, utilizan dos diferentes modelos mentales cuando evalúan la amenaza del agotamiento y la disponibilidad futura de productos minerales. Este artículo comienza con la descripción de ambos. A continuación, examina sus implicaciones para la amenaza planteada por el agotamiento de los minerales y, también, para las políticas públicas necesarias para hacer frente a esta amenaza. Finalmente, después de resaltar sus respectivas deficiencias, concluye que el modelo económico es el más útil para evaluar la amenaza del agotamiento de los minerales.

Paradigmas del desafío

El primero de los modelos mentales, la percepción física del agotamiento, comienza con la observación de que la Tierra es finita. Entonces, la cantidad de cobre o cualquier otro producto mineral contenido en ella también será agotable. Si bien los recursos de los que se extrae el suministro son un stock fijo, el consumo es una variable de flujo. Cada año necesitamos más petróleo, platino y zinc. Eventualmente, como resultado, el consumo agotará nuestras existencias disponibles de estos recursos. Además, dado el desarrollo económico y el aumento de la población, muchos creen que el final llegará más pronto que tarde.

Una pregunta central para quienes ven el agotamiento de minerales a través de la lente de este modelo es la siguiente: ¿Cuánto tiempo durarán nuestros recursos disponibles? ¿Cuáles son sus expectativas de vida? Las respuestas a estas preguntas varían mucho según las suposiciones hechas con respecto al consumo futuro y las existencias disponibles. En el caso del cobre, por ejemplo, a las tasas de producción actuales, las reservas durarían unos 40 años, los recursos un poco más de 300 años y la base de estos recursos unos 84 millones de años.

El segundo modelo mental, la visión económica del agotamiento, ofrece una perspectiva bastante diferente. Se enfoca en lo que la sociedad tiene que ceder para obtener otro barril de petróleo o una tonelada de cobalto. Los precios reales (ajustados a la inflación) de los productos básicos son, con mucho, la medida más utilizada de este sacrificio o coste de oportunidad. Así, por ejemplo, la disminución en el precio real del aluminio desde 1900 indica que el aluminio se ha vuelto más disponible o menos escaso a pesar del rápido crecimiento en su consumo y producción durante este período. Del mismo modo, la diferencia entre el precio del oro y la plata refleja la mayor escasez de oro.

Ver el agotamiento a través de la lente del modelo económico no obliga a concluir que el agotamiento es inevitable. Más bien, el futuro depende en gran medida de la competencia entre las reducciones de los costes resultantes de la nueva tecnología (y tal vez nuevos descubrimientos de depósitos minerales) y los aumentos de los costes debidos al agotamiento (y tal vez mayores salarios y otros costes de insumos). Cuando las nuevas tecnologías más que compensasen la presión al alza sobre los costos por agotamiento, como ha sido el caso del aluminio, los precios reales en el largo plazo tenderán a la baja, lo que indica una mayor disponibilidad.

Los estudios que analizan los precios reales de los productos básicos a largo plazo encuentran que la tendencia es a la baja para algunos estos productos, tal como ocurre con el aluminio y el níquel. En la mayoría de los casos, la tendencia es plana, lo que sugiere que las nuevas tecnologías han compensado más o menos los efectos del agotamiento. Lo que los estudios disponibles no encuentran, son los productos minerales cuyas tendencias de precios reales a largo plazo son significativamente al alza, lo que indicaría que su aprovechamiento estaría aumentando su escasez. Si bien esta situación favorable puede continuar en un futuro lejano, este, por supuesto, no tiene que ser el caso.

Implicaciones

Qué modelo mental adoptamos importa mucho. Los dos poseen implicaciones muy diferentes para la naturaleza del agotamiento, así como para las políticas públicas necesarias para hacer frente a su amenaza.

Una diferencia importante ya la hemos apreciado. Con el modelo físico, el agotamiento resulta inevitable. Nuestras existencias fijas disponibles de recursos, finalmente se agotarán. Con el modelo económico, las nuevas tecnologías y otros desarrollos que reducen los costes pueden, en el futuro, tal como lo hicieron en el pasado, compensar la presión alcista que ejerce el agotamiento sobre los costes y precios de los productos de minerales básicos. En este sentido, este modelo ofrece una visión menos pesimista del futuro.

Los dos también anticipan diferentes escenarios en cuanto a cómo es probable que surjan escaseces inducidas por el agotamiento. Con la visión física, la humanidad puede navegar desde una década a la siguiente, sugiriendo tan solo que una crisis está en el horizonte. Una vez que el armario está vacío, se hacen visibles las privaciones que se avecinan. Con la visión económica, si las nuevas tecnologías no compensan los efectos negativos del agotamiento, los costes de producción y los precios de los productos minerales aumentarían, tal vez lenta pero persistentemente, a largo plazo, proporcionando a la humanidad evidencia temprana de una creciente escasez. El aumento de los precios reales también alentaría diversas actividades que fueran capaces de mitigar o al menos reducir algo la escasez: más exploración, tecnologías de producción más eficientes desde la explotación hasta la reutilización, la sustitución por materiales alternativos, más reciclaje y nuevas tecnologías que ahorrasen recursos.

Es muy probable que los dos modelos identifiquen los conjuntos de productos básicos más amenazados por el agotamiento. El modelo físico apunta hacia aquellos con una corta esperanza de vida, tal como el zinc. El modelo económico destaca aquellos cuyos costes de producción y precios futuros podrían aumentar considerablemente. Por ejemplo, muchos metales menores, como el indio, el niobio, el torio, el rodio, el paladio

y las tierras raras, ahora se producen como subproductos o coproductos. Si los nuevos usos hacen que su demanda aumente, esto podría requerir su producción como productos principales a costes mucho más altos.

En cuanto a las políticas públicas, la visión física favorece el reciclaje, la conservación y otras medidas que amplían las expectativas de vida de los productos minerales. La visión económica enfatiza las políticas que promueven las nuevas tecnologías necesarias para compensar los efectos adversos del agotamiento.

Los defensores de la visión económica reconocen que las políticas gubernamentales son necesarias para corregir las imperfecciones del mercado, tal como ocurre con los costes externos asociados con las emisiones de gases de efecto invernadero y otras formas de contaminación. Pero su enfoque consiste en mejorar el funcionamiento de los mercados y luego dejar que ellos mercados tomen las decisiones importantes con respecto a la producción y el uso de productos minerales, en lugar de tener al gobierno directamente involucrado en estas decisiones.

Deficiencias

Después de revisar las principales deficiencias de los modelos económicos y físicos, esta sección concluye que la primera proporciona los conocimientos más útiles y válidos necesarios para comprender el agotamiento y su amenaza. Identifica varias limitaciones del modelo económico, pero encuentra las siguientes deficiencias serias del modelo físico:

1. *Muchos productos minerales, incluidos todos los metales, no se destruyen cuando se usan. El consumo puede degradar estos productos básicos, lo que los hace demasiado costosos para reciclar, pero esto es una cuestión de costes, no de disponibilidad física.*
2. *En la mayoría de los usos finales, los productos minerales compiten con los sustitutos de la cuota de mercado. Si el petróleo (que se destruye cuando se usa) se vuelve escaso, la sociedad puede cambiar a otras fuentes de energía: gas natural, viento y energía solar. Si el cobre escasea, la sociedad puede sustituirlo en diversas aplicaciones por el aluminio, los plásticos, la fibra óptica y otros materiales.*
3. *La corteza terrestre contiene enormes cantidades de todos los productos minerales. La disponibilidad física no es la restricción relevante. Mucho antes de que el último barril de petróleo, la última tonelada de carbón o la última onza de plata se extrajera de la Tierra, los costos de extracción aumentarían, ahogando la demanda para cada uso final, uno tras otro. Si el agotamiento de minerales se convirtiese en un problema, lo hará empujando los costes hacia arriba y extinguiendo la demanda, no consumiendo las últimas moléculas de petróleo o átomos de plata que queden de la Tierra.*
4. *Además, incluso si pudiéramos estimar de manera confiable solo aquellos recursos que ahora o en algún momento en el futuro serán rentables de explotar, esta información podría arrojar conclusiones engañosas con respecto a la futura amenaza de agotamiento. Como muestra la siguiente cita, atribuida tanto a Don Hubert de Royal Dutch Shell, como al ex ministro de petróleo saudita Sheikh Ahmed Zaki Yamani, indica: "La Edad de Piedra no terminó porque el mundo se quedó sin piedras, y la Era del Petróleo no terminará porque no tengamos petróleo". Si la caída de la demanda de petróleo debido a nuevas y más baratas fuentes alternativas de energía pone fin a la era del petróleo, la disminución resultante de sus reservas explotables no representará una amenaza para el futuro bienestar de la sociedad.*

Conclusiones

Como lo es para el petróleo, también lo es para otros productos minerales: los precios y el sacrificio que la sociedad tiene que hacer para obtener otro barril de petróleo o una tonelada de aluminio proporcionan una buena medida de la escasez futura que las cantidades físicas de las existencias explotables restantes. Por estas razones, es el modelo económico, no el modelo físico, el que resulta más útil para evaluar el agotamiento y diseñar políticas públicas a fin de hacer frente a la amenaza que representa para el bienestar futuro de la humanidad.

Introduction

Shortages of mineral commodities can arise for numerous reasons—mineral depletion, inadequate investment in new mines and processing facilities, unanticipated surges in demand, cartels, embargoes, wars, mine accidents, and even prolonged strikes. It is useful, however, to separate mineral commodity shortages into two distinct groups. The first includes shortages due to mineral depletion; the second, shortages owing to all the other causes. The two types of shortages differ in almost all respects.

Shortages caused by depletion are extremely rare. Indeed, it is hard to identify any in the past. Of course, this does not preclude such shortages in the future. Should they occur, they are likely to last for a long time and possibly forever. As a result, at least potentially, they pose a serious threat to human welfare.

In contrast, shortages arising for other reasons are quite common. During World War II, both the Allies and Axis powers suffered from numerous shortages as traditional supply sources were curtailed or cut off. In 1973, the major oil-exporting countries cut their production and imposed an embargo on shipments to the United States and the Netherlands, causing a global shortage of this important commodity. During the early years of this century, the dramatic economic boom in China caused global demand and prices for many commodities to surge. While they last, these shortages can be quite painful, but rarely do they persist for more than a few years. The sharply higher prices that they unleash provide strong incentives to find new sources of supply, to substitute alternative materials, and to undertake other self-correcting actions. As a result, they do not pose a major threat to the long-run welfare of humanity.

This article focuses on mineral depletion, the first and potentially more serious source of shortages. It begins by describing the two dominant mental models that geologists, resource economists, and others including the general public use when assessing the threat of mineral depletion. It then examines the implications that flow from each for the future availability of mineral commodities and for the public policies needed to address the threat of mineral depletion. Finally, it compares the usefulness of these models by highlighting their limitations and shortcomings.

Dueling Paradigms

The first of the mental models—known in the resource economics literature as the *fixed stock paradigm* and which for brevity we will refer to as the *physical* view or model of depletion—is the most popular, presumably because of its simple and persuasive logic. It starts with the observation that the Earth is finite. So the amount of copper or any other mineral commodity contained in the Earth is also finite. While the resources from which supply is extracted are a fixed stock, demand is a flow variable (Brooks, 1976). Every year we need more oil, platinum, and zinc. Eventually, as a result, demand will exhaust our available stocks of resources. Moreover, given economic development and rising population, many believe the end will come sooner rather than later.

A central question for those who view mineral depletion through the lens of this mental model is: How long will our available resources last? What are their life expectancies? To answer this question requires data on (a) the available stock of resources and (b) the current and future consumption for the commodity.

While information on current consumption is readily available, future consumption has to be estimated. This is often done by simply assuming that consumption in future years will be the same as current consumption or by assuming that consumption will increase in the future at some given percentage rate (often the same or similar rate at which the commodity's consumption has increased over some recent historical period).

There are many, quite different measures used for the available stock. Some studies, such as the widely read and influential book *Limits to Growth* by Meadows *et al.* (1972), use reserves—defined as the amount of a mineral commodity found in known deposits that are profitable to exploit given current prices and other conditions—or some multiple of reserves to allow for new discoveries and other developments increasing reserves over time.

Other studies, such as Gordon, Bertram, and Graedel (2006) use resources, which by definition include current reserves as well as other identified and undiscovered resources that could become reserves in the future (which they call "potentially feasible reserves").

Still other studies, for example, Mudd and Weng (2012) use what they call remaining ultimately recoverable resources or URRs. This approach identifies all known deposits, estimates the total amount of the mineral commodity these deposits contained before any mining, and then calculates the quantity of the commodity remaining to be mined. Despite the use of the word resources, URRs are defined in a much more restrictive manner than the resources defined as current and potentially feasible reserves.

Finally, a few studies, including Tilton (2006), use "resource base" to measure fixed stocks. The resource base includes all of a mineral commodity found in the Earth's crust.

Life expectancies vary greatly depending on the assumptions made regarding future consumption and the available stock. In the case of copper, for example, at current production rates, reserves would last about 40 years, resources a little over 300 years, and the resource base some 84 million years (Tilton and Guzmán, 2016). The latter figure might suggest we have more pressing problems to address. However, if we assume future production grows at just 2 percent a year, rather than remaining at its current level, the 84 million figure drops to just 723 years, a nice illustration of the tyranny of exponential growth and just how sensitive estimates of life expectancies can be to the assumptions made regarding growth in consumption.

The second mental model—known in the professional literature as the *opportunity cost paradigm* and which again for brevity we will refer to as the *economic* view or model of depletion—offers a quite different perspective on mineral depletion and the threat it poses. It focuses on what society has to give up to obtain another barrel of oil or ton of cobalt. Real (inflation-adjusted) commodity prices are by far the most widely used measure of this sacrifice or opportunity cost, as reliable price data are readily available for many mineral commodities over extended periods of time. According to the economic model of depletion, for example, the decline in the real price of aluminum since 1900 indicates that this commodity has actually become more available or less scarce despite the rapid growth in its consumption and production over this period. Similarly, the difference between the price of gold and silver reflects the greater scarcity of gold.

Of course, prices reflect not just depletion, but all the forces shaping mineral commodity availability and scarcity, including wars, unexpected surges in demand, inadequate investment in new mines and processing facility, embargoes, and the other causes of shortages. So, when assessing mineral depletion it is important to focus on long-run trends in real prices, for as noted earlier depletion affects availability over the long run while the other causes of shortages typically persist only over the short run.

Viewing depletion through the lens of the economic model does not force one to conclude that depletion must at some point cause shortages. Rather, the future hinges largely on the competition between cost reductions resulting from new technology (and perhaps new deposit discoveries) and cost increases owing to depletion (and perhaps higher wages and other input costs). When new technology more than offsets the upward pressure on costs from depletion, as has been the case for aluminum, real prices over the long run trend downward, indicating increasing availability.

Many studies have examined the long-run trends in real commodity prices (Krautkraemer, 1998; Tilton, 2003). In some instances, including aluminum and nickel, the trend is downward. In most instances, the trend is not significant, suggesting the new technology has more or less just offset the effects of depletion. What the available studies do not find are mineral commodities whose long-run real price trends are significantly upward, indicating that depletion is causing increasing scarcity. While this favourable situation may continue into the distant future, this of course need not be the case.

Implications

Does it matter which of the mental models of depletion we adopt? Indeed, it matters greatly. The two models have very different implications for the nature of depletion as well as for the public policies needed to cope with the threat that it poses.

One of the important differences we have already noted. With the physical model, depletion is inevitable. The resources from which we can extract mineral commodities are fixed stocks. Because consumption is a flow variable that continues year after year, eventually it will deplete the available stocks. The critical question is simply how long do we have before we run out?

With the economic model, depletion-induced shortages are possible but not inevitable. This is because it uses differences and trends in real prices, rather than physical quantities, to assess availability. So new technologies and other cost-reducing developments may in the future, as they have in the past, offset the upward pressure that depletion exerts on mineral commodity costs and prices. In this respect, the economic model of depletion offers a less pessimistic view of the future.

The two mental models also predict different scenarios as to how depletion-induced shortages are likely to emerge. With the physical view, humanity can cruise from one decade to the next with little to suggest that a crisis is looming on the horizon. Only when the cupboard is bare, when the available stocks are gone, does the pending transition to a much more difficult future become clear. With the economic view, should new technology fail to offset the negative effects of depletion, the production costs and prices of mineral commodities would rise, perhaps slowly but persistently over the long run, providing humanity with early evidence of increasing scarcity. Moreover, as noted earlier, rising real prices would encourage a number of activities that mitigate or alleviate scarcity—more exploration, better production technologies from exploration through reuse, the substitution of alternative materials, more recycling, and resource-saving new technologies.

The two mental models also offer quite different approaches for identifying those commodities most threatened by depletion. With the physical model one employs estimates of the fixed stock and future consumption to calculate life expectancies. Those commodities with short life expectancies, such as zinc, are presumed most vulnerable and hence most in need of our attention.

With the economic model, the focus is instead on commodities whose future production costs and prices could rise greatly. These are commodities currently produced from low-cost but limited sources, which if exhausted would require production from much higher cost sources. For example, many minor metals, such as indium, niobium, thorium, rhodium, palladium, and the rare earths, are now produced as by-products or co-products with other metals. Major new uses in electric cars, renewable energy facilities, or other high tech products could cause their demand to surge requiring their production as main products at much higher costs (Lokanc *et al.,* 2015; Jordan *et al.,* 2015; Jasiński *et al.*, 2017). Even major metals could conceivably experience sharply higher production costs and prices in the future if the low-cost sources of supply from which they are currently extracted become exhausted. Skinner (1976) has suggested this could happen to copper if at some point society depletes its traditional sulphide ores and has to extract this metal from silicate minerals instead.

On the other hand, some mineral commodities have large unexploited sources of supply whose production costs do not greatly exceed current prices. For example, lithium can be extracted from seawater, an almost infinite source of supply, at costs that are higher but not greatly higher than lithium's current price (Yaksic and Tilton, 2009). Such commodities are not likely to experience sharply higher costs and prices and hence depletion-induced shortages, even if their current sources of supply are depleted.

Turning to public policies, advocates of the physical view of depletion advocate measures that extend the life expectancies of mineral commodities. These include conservation, recycling, and, where possible, the substitution of renewable resources for non-renewable mineral commodities. They contend that current market prices are not good indicators of future scarcity (a concern discussed in the next section) and hence the true value of postponing the use of limited mineral resources. As a result, these measures are worth pursuing beyond what the market indicates is profitable. Government subsidies, regulations, and other measures are needed to tilt private incentives toward a more benevolent—that is, restrictive—use of remaining mineral resources. For this and other reasons, advocates of the physical view of depletion often believe that strong and comprehensive government actions are desirable to ensure the optimal use of mineral resources over time.

The advocates of the economic view favour public policies that promote the new technologies needed to offset the adverse effects of depletion. Ultimately, as noted earlier, whether or not depletion becomes a serious threat depends on the ability of new technology to keep the cost-increasing effects of depletion from pushing commodity prices higher. Recycling, conservation, and the substitution of renewable for non-renewable resources can slow down the negative effects of depletion and increase commodity life expectancies. However, new cost-reducing technologies offer the possibility of keeping depletion indefinitely in check.

The economic view of depletion also tends to favour more reliance on markets and less on government controls for allocating mineral resources. This is, in part, because it sees depletion-induced shortages, if they do occur, emerging slowly over the long run in the form of persistent increases in real prices. Assuming that governments do not impose price controls or other counterproductive measures, higher prices as already noted encourage the market to undertake self-correcting actions that mitigate shortages. The economic view recognizes that government policies are necessary to correct market imperfections, such as the external costs associated with greenhouse gas emissions and other forms of pollution. But its approach is to improve the functioning of markets and then let markets make the important decisions regarding the production and use of mineral commodities, rather than have governments directly involved in these decisions (Tilton *et al.,* 2018).

Shortcomings

The preceding sections describe the important differences between the physical and economic models and highlight their very different implications for the nature of depletion and for public policies. They show that which of these models we adopt does matter. This section explores the weaknesses of each model. It argues that, despite the widespread acceptance of the physical model and despite its simple and persuasive logic, the economic model provides the more useful and valid insights needed to understand depletion and its threat.

Before examining the shortcomings of the physical model, however, it is important to acknowledge several limitations of the economic model.

Firstly, trends in real prices take into account only those costs that are internalized or paid for by producing firms. Because they may not reflect all pollution and other external costs, they are not necessarily a good measure of the opportunity cost to society and hence the scarcity of mineral commodities. More specifically, if the share of the total costs to society that firms pay over time is declining, trends in real prices will overestimate the increasing trend in availability when real prices are falling and underestimate the increasing trend in scarcity when real prices are rising. This is because prices track just the costs incurred by producing firms. Of course, just the opposite is the case if the costs that producing firms pay account for a rising share of the total costs to society over time.

So we would like to know whether the share of the total costs that firms pay has been rising or falling. Unfortunately, the answer is uncertain. Over time, society has placed a higher value on the environmental amenities that pollution undermines, increasing external costs. At the same time, however, governments around the world have forced firms to reduce and pay for much more of the damage that their operations do to the environment. If these two opposing developments roughly offset each other, reported price data provide a reasonably accurate reflection of the trends in the full costs to society of mineral products.

Secondly, price trends reflect all the causes of scarcity, not just depletion. The others, as noted earlier are particularly important in the short run and much less important over the long run. So when using prices to assess the impact of depletion, it is important to focus on the long-run trends in real prices and to ignore the often volatile swings in prices over the short run.

Thirdly, as also noted earlier, there is no guarantee that past trends in real prices will continue into the future. For this and other reasons, future trends in commodity prices are uncertain and difficult to reliably estimate.

If markets operated perfectly, current prices would reflect future shortages. This is because investors would accumulate stocks today, raising the current price, in order to sell them in the future, when prices were higher as a result of increased scarcity. In this case, current prices would reflect both current and future scarcity. But markets are not perfect. They suffer from uncertainty about future demand and supply as well as other imperfections. Therefore current commodity prices are not a reliable indication of future availability.

Without some idea of how costs and prices are likely to evolve in the future, the economic model cannot shed helpful insights into where and when mineral commodity shortages are likely to arise. As the previous section pointed out, however, information on the availability of sub-economic sources of supply for mineral commodities can provide a way around this shortcoming. In particular, depletion is not likely to pose much of a threat for those commodities that can be extracted from abundant resources at costs only slightly higher than current production costs.

We need to be aware of these shortcomings of the economic view of depletion. They are not trivial and can complicate the assessment of mineral depletion. Still, they are far less serious than the following shortcomings, which plague the physical view of depletion.

1. Many mineral commodities, including all the metals, are not destroyed when used. The world contains as much iron or platinum today as it did a hundred or a thousand years ago, aside from the small amounts that have been shot into space and the larger though still minute amounts in the meteors and other debris from space. Consumption may degrade a commodity, making it too expensive to recycle profitably, but this is an issue of costs, not of physical availability.

2. In most end uses, mineral commodities compete with substitutes for market share. Should petroleum, a mineral commodity that is destroyed when used, become scarce, society could switch to other sources of energy—natural gas, wind, and solar power (whose supply for all practicable purposes is unlimited). Should copper become scarce, society could substitute aluminum, plastics, fiber optics, and other materials in various end uses.

3. The Earth's crust contains huge amounts of all mineral commodities. Physical availability is not the relevant constraint. Long before the last barrel of oil, the last ton of coal, or the last ounce of silver were pulled from the Earth, the costs of extraction would rise, choking off demand in one end use after another until no demand remained. If mineral depletion threatens the future availability of mineral commodities, it will do so by pushing costs up and extinguishing demand, not by extracting the last remaining molecules of oil or atoms of silver from the Earth.

In the words of one prominent mineral economist (Humphreys, 2018),

"... there is a tendency to talk about depletion as if the notion is self-evident and that it is all about the quantity of mineral resources and ore grades. And yet depletion is also about quality, about the size and depth of deposits, the complexity of mineralogy, the hardness of the rock, the presence of deleterious constituents, etc. This is not just an omission in the analysis it is also a further argument in favour of the 'economic' perspective since this perspective can manage such complications much more readily than can a fixed paradigm model focused almost exclusively on the quantitative."

The advocates of the physical view of depletion contend that physical availability is nevertheless relevant. What is important is to define properly the appropriate fixed stock: namely, the amount of a mineral commodity that ultimately can be recovered profitably from the available resources. They acknowledge that reserves provide estimates that are too low. This is, in part, because mining companies estimate reserves to obtain a working inventory of their economically extractable supplies and so reserve data reflect corporate philosophy on how much effort should be expended to gather geologic information on a mineral property. In addition, new discoveries and new technologies are constantly creating new reserves (U.S. Geological Survey, annual; Schulz *et al.,* 2017, p. A4-A5).

On the other hand, the resource base clearly provides estimates of the fixed stock that are way too large, since most of the resource base will never be economic to exploit. Somewhere in between, however, there is a figure that accurately reflects the fixed stock. Perhaps it is a multiple of current reserves; perhaps it is current estimates of resources; perhaps it is some other figure.

But, is it possible to identify the fixed stock of resources that will be economic to exploit from now far into the future? In theory, the data that the U.S. Geological Survey and other organizations provide for resources should provide this information, because resources include both current and future reserves. We know, however, that the estimates of resources, like those for reserves, change over time as new technologies and other developments change our view of the sub-economic identified resources and undiscovered resources that could be reserves in the future. The U.S. Geological Survey (annual), for example, has more than doubled its estimate of copper resources over just the past two decades, from 2.3 billion tons in 2000 to 5.6 billion tons today.

The difficulty of getting the fixed stock right arises because we are shooting at a moving target, whose trajectory is governed in large part by unknown and unknowable future technological developments. Will we one day be able to mine seawater profitably for the multitude of mineral commodities it contains? Will the extraction of cobalt, manganese, copper, and nickel from deep-sea nodules become economic? Will we eventually mine gold at depths 50 or 100 percent below any of our current operations? We simply do not know and have no reliable way of obtaining the information needed to know.

4. Moreover, even if we could reliably estimate the fixed stocks of resources that now or at some point in the future will be profitable to exploit, this information may provide misleading insights into the future threat of depletion. The world all but ran out of the renewable resource (sperm whales) from which it obtained whale oil for lighting in the mid-19th century. However, at that time society was shifting to alternative and cheaper sources of light (Nordhaus, 1997). And, in a quote variously attributed to Royal Dutch Shell's Don Hubert and former Saudi oil minister Sheikh Ahmed Zaki Yamani, "The Stone Age did not end because the world ran out of stones, and the Oil Age will not end because we run out of oil." (Quote Investigator, 2018). If it is falling demand for oil due to new and cheaper alternative energy sources that brings the Oil Age to an end, the resulting decline in exploitable petroleum stocks will pose no threat to the future welfare of society.

As it is for oil, so it is for other mineral commodities: Prices and the sacrifices that society has to make to obtain another barrel of oil or ton of aluminum provide the most useful insights into the future and the threat that we face from depletion, rather than the physical quantities of our remaining exploitable resource stocks.

For these reasons, it is the economic model, not the physical model, which is the most helpful and useful when assessing depletion and designing public policies for coping with the threat that it poses to the future welfare of humanity.

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