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Another look at non-renewable resource exhaustion

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Abstract This paper challenges the widely held hypothesis, considered in some circles as accepted scientific consensus, that modern industrial society is rapidly exhausting non-renewable resources. We argue that this paradigm is amiss and use copper availability as an example to demonstrate the problems with this consensus. In the 80 years for which reasonably reliable estimates of copper reserves and reserve life are available, there is no evidence of resource exhaustion. In addition, an analysis of the economics of resource exploration indicates that mining companies will treat exploration as an inventory control problem and trade off using limited capital resources between expanding inventories of reserves and generating current revenue through production. In the case of the copper industry, it is argued that there is little incentive for major copper producers to explore for more resources. Non-producers, exploration companies do have an incentive for expanding reserves, but this does not change the conclusion that new copper resources are effectively not worth looking for. We also conjecture that, except for in rare and temporary circumstances, this conclusion is applicable to many non-renewable resources. Ultimately, this implies that aggregate reserve-life calculations for all types of non-renewable resources are inherently flawed.

Keywords Mining · Sustainability · Copper

JEL codes Q3 · L7

Introduction: challenging the depletion orthodoxy

This paper examines a widely held belief held by advocates industrial ecology, resource sustainability, and modern day Malthusians that modern industrial society is rapidly depleting natural resources at an unsustainable rate. The focus here is on perhaps the most vulnerable class of resources in this belief system: non-renewable resources and, more specifically, metals.

The "Non-renewable mineral availability" section reviews some of the basic literature on mineral availability and the peak resources hypothesis applied by those concerned about resource sustainability to non-renewable resources. The "Copper as an example" section looks at the peak resources hypothesis applied to copper. We find no evidence of "peak" copper in spite of claims to the contrary. Copper reserve life, i.e., how long society can continue consuming copper from known reserves, is basically unchanged over 80 years that we are able to estimate them in spite of enormous increases in consumption.

The fourth section examines this apparent contradiction by examining the microeconomics of mining companies' decisions to explore for new reserves on which macro reserve data are based. The concluding section argues that these data are generally misconstrued by advocates of the "peak" hypothesis.

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Non-renewable mineral availability

The birth of modern resource economics came in Harold Hotelling's 1931 essay, *The Economics of Exhaustible Resources*. Hotelling motivated his discussion of the subject by noting that standard economic analysis was "plainly inadequate for an industry in which the indefinite maintenance of a steady rate of production is a physical impossibility and which is therefore bound to decline." While renewable assets are governed by the "laws of static theory," a whole new economics was required to deal with the issue of "absolutely irreplaceable assets" Hotelling (1931).

Hotelling's theory assumed a natural resource of fixed and known quantity and calculated the optimal rate of resource extraction over the resource life. This theory is mathematically elegant and has formed the basis for the development of the field of resource economics. His assumptions were mostly unquestioned among economists and conservationists alike. However, over time, these assumptions have been increasingly questioned. The opposition to this mainstream view within the field of resource economics can be broadly viewed as arguing that resource extraction and use should be viewed through the lens of social science. This approach is discussed, and developed in different ways, in Humphreys (2013), Tilton (2003) and perhaps most notably, Simon (1996). Bradley (2006) gives a thorough account of the historical evolution of these ideas, tracing their roots to the institutional economist Erich Zimmermann.

Despite the widespread acceptance of the Hotelling paradigm among economists, many of the empirical predictions of this model have not borne out (Krautkraemer 1998). Predictions of extraction rates decreasing over time, resource prices rising over time, and a link between the change in resource prices and interest rates have simply not come to fruition. Rather than see the predictions of this depletion-based orthodoxy become reality, we see what appears oxymoronic to this paradigm: sustainability of the depletion of non-renewable resources or ever-increasing depletable resources.

How can the depletion of a non-renewable resource be sustainable? This seeming paradox can be easily resolved by understanding that the definition of a "resource" is economic as opposed to physical. The mass of the earth is, indeed, finite, so the physical quantity of any given element such as copper, iron, zinc, gold, etc.,[1] must therefore also be finite and can be approximated by multiplying the mass of the earth by the crustal abundance of the element measured in terms of kilograms per tonne. The fact that there exists a finite number of copper atoms on our planet is not, however, economically relevant to determining how much of this resource exists. The portion of this physical quantity that is a "resource" is limited to the portion that has been both located and determined to be recoverable at an economic profit (which, in modern financial usage is referred to as a mineral "reserve"). Hence, a reasonable hypothesis is that a very small proportion of the physical quantity of these elements in existence on earth is actually a resource or reserve—new deposits of these minerals are discovered all the time, and humans have hardly even begun to explore the two thirds of the earth's surface that is underwater. The fact that these elements are non-renewable is thus not a binding constraint on our ability to deplete these resources at a sustainable rate for the foreseeable future.

The nature of resources is illustrated by the McKelvey diagram below, a graphical representation of mineral resources with respect to economic and geologic certainty relative to the physical quantity of an element contained in the earth's crust. When resource sustainability is discussed, the subject mineral is confined to the upper left hand corner of the diagram—"reserves" which are resources that have been "demonstrated" and "economic," which means that we know where they are and that they can be produced at a profit. Historically, reserves have been a small fraction of potential resources (United States Bureau of Mines 1980).

Mineral availability is a critical issue for the human race, arguably more important than climate change, for example, because we will need minerals to provide the earth's population with the materials to improve their quality of life—regardless of the earth's temperature. Growing affluence in developing nations will require more minerals for more cars, home appliances, industrial facilities, etc. In a 2001 speech for Resources for the Future, noted mineral economist B.J. Skinner predicted that in the twenty-first century, we will need to produce three to four times the quantity of minerals produced in the entire human history to meet this demand. In the same speech he said that we have sufficient mineral resources available to meet this demand (Skinner 2001).

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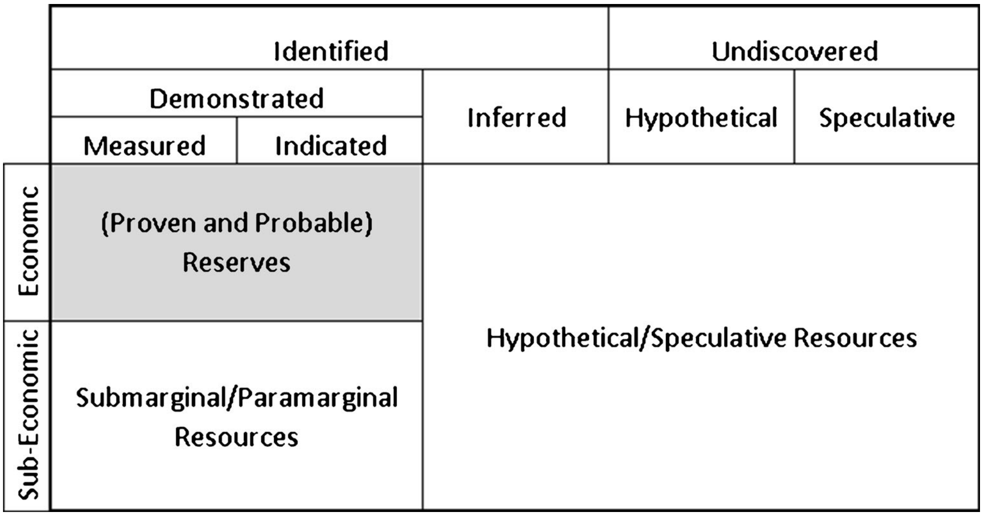
[1] For simplicity, we limit the discussion to metalliferous minerals although the analysis can possibly be extended to carbon-based minerals such as coal, oil, and natural gas.



<table>
<tr><th></th><th colspan="3">Identified</th><th colspan="2">Undiscovered</th></tr>
<tr><th></th><th colspan="2">Demonstrated</th><th rowspan="2">Inferred</th><th rowspan="2">Hypothetical</th><th rowspan="2">Speculative</th></tr>
<tr><th></th><th>Measured</th><th>Indicated</th></tr>
<tr><td>Economc</td><td colspan="2">(Proven and Probable) Reserves</td><td colspan="3" rowspan="2">Hypothetical/Speculative Resources</td></tr>
<tr><td>Sub-Economic</td><td colspan="2">Submarginal/Paramarginal Resources</td></tr>
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The key to understanding this seeming paradox is to understand that the definition of a "resource" is elastic. It depends upon commodity prices, representing the value of a material, the costs of extraction, opportunities for substitution of other materials (or technologies, like substituting the electromagnetic spectrum for copper through the use of mobile phones instead of land lines), and other factors.

Nonetheless, the scientific consensus in many fields, most notably industrial ecology and those focused on sustainability, holds that we are running out of non-renewable resources. The Hubbert "peak oil" curve has been popularized and spread to the extent that if one puts "peak oil" (or alternately peak copper, peak gold, etc.) into an internet search engine, one finds extrapolations of mineral availability that look like Fig. 1 (US Energy Information Administration, Crude Oil Production. http://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm) (Hubbert 1956, also see Leherrere 2010 for an example of the peak copper hypothesis). Hubbert's observations were directed at the productive life of a given oil field or region with a more or less fixed technology.

While many following in the Malthusian tradition have extrapolated Hubbert's observation to virtually all non-renewable resources to conclude that we are running out of non-renewable resources, the extension of the "peak oil" hypothesis to other minerals has been questioned by a number of authors. Crowson (2011), for example, notes numerous differences between non-fuel minerals and oil such as recyclability and the lack of a clear boundary between ore and waste. Humphreys (2013) examines factors such as discoveries, technological advances, and economies of scale and suggests that other resources such as land, clean water, and food supply may well be more binding constraints on mining activity than mineral availability. May et al. (2012), on the other hand, sees some potential applicability of the "peak" hypothesis to non-fuel minerals but concludes that this applicability is limited. These authors raise good points from a "macro" view of mineral availability. Below, we suggest reasons why a "micro" view, i.e., an analysis of mineral reserve data based on the behavior of mining companies, makes using aggregated company reserve data to evaluate the peak hypothesis suspect.

Copper as an example

Copper is a non-renewable commodity that is essential for modern life. The infrastructure for powering lights, appliances, telecommunications, etc. requires copper. The average person in North America consumes 9.5 kg of copper per year compared to a world average of 2.0 kg (Skinner 2001). This is certainly in line with Skinner's prediction that we will need to

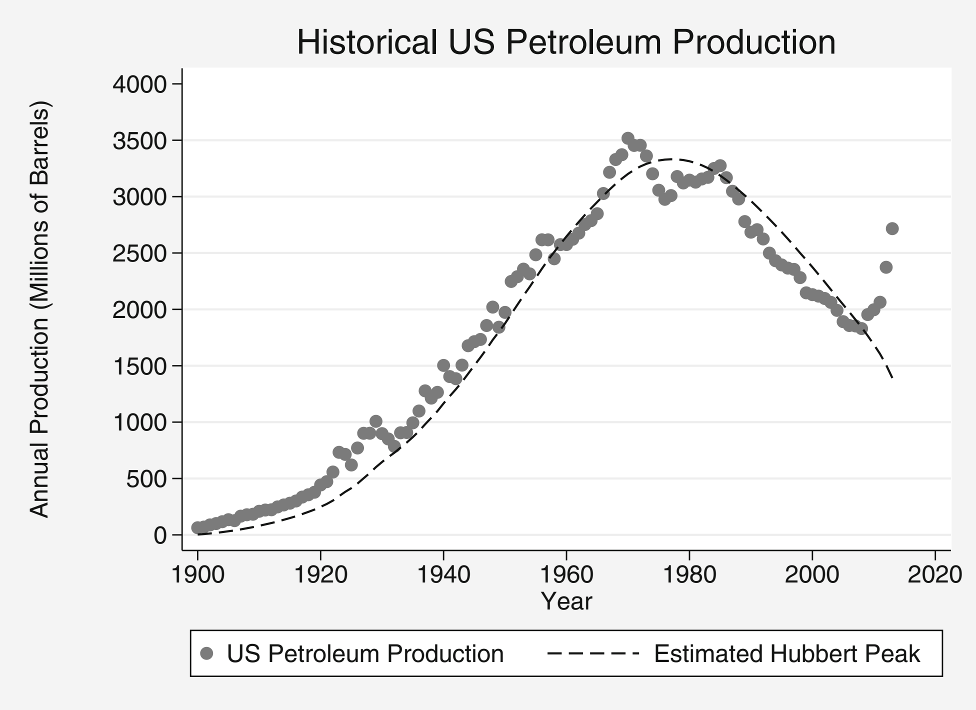

Fig. 1 US crude oil production versus Hubbert curve

produce three to four times the quantity of metallic elements ever produced to accommodate the rising aspirations of citizens of developing nations who want to enjoy the same standard of living as those in the developed world represents a daunting task. Growth in world copper reserves—resources that we know where they are located and can extract them at a profit—are shown on Fig. 2.[2] These reserves are what are represented by the upper left hand box in the McKelvey diagram for copper.

There are several obvious features of the world reserves that deserve mention. First, the data shown are the only years that information is provided by the United States Geological Survey (USGS), in our opinion the best authority on world copper reserves.[3] However, numerous discussions of peak copper show reserves going back to 1900 (Leherrere 2010, e.g., shows reserves back to 1900). These representations may be reasonable extrapolations and, to be completely frank, the USGS data are admittedly just estimates as well. But at least the USGS does not have a cause to promote, especially back in the 1930's.

Second, the actual reserve curve on Fig. 2 may show the early phase of the classic Hubbert logistic curve depicted in Fig. 1, but it clearly does not show a decline in the rate of growth in known reserves in spite of the rapid (from a historical perspective) rate of resource depletion during this period. Annual world copper production, as illustrated by Fig. 3, is currently eight times production in 1930 and orders of magnitude greater than production in all prior human history. Yet, in spite of rapid growth in production and consumption during this period, reserves have continued to increase. One could argue that the reserve curve will eventually resemble Hubbert's logistic curve at some point in the future. Many others, like economist Julian Simon[4] have argued against this view, however, and have shown that real, inflation-adjusted resource prices have fallen over time because of relative abundance and will continue to do so (contrary to Hotelling's hypothesis).

A third point to notice about Fig. 2 is that during the 1980s, world copper reserves actually decreased slightly. This decline coincides with a worldwide economic recession and a collapse in copper prices. Put simply, the fall in reserves is actually an economic, not a geologic, phenomenon. When the price fell, producers decided that copper was no longer worth looking for, reducing exploration and consequently decreasing the rate at which new reserves were added. Moreover, with lower prices in the 1980s, some materials considered "reserves" during the 1970s when prices were higher were no longer considered reserves because they could not be mined at a

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[2] USGS, personal communication with Daniel Edelman, USGS Copper Specialist.

[3] So note, for example, that there are no estimates for the period during WWII, and estimates are not available on an even five-year basis. Also, the definition of "reserves" was broadened slightly in the 1980s to "reserve base" which can include some sub-economic materials.

[4] Julian Simon was an early proponent of this view. See, for example, *The Resourceful Earth: A Response to "Global 2000"* (1984), Julian Simon & Herman Kahn, eds.

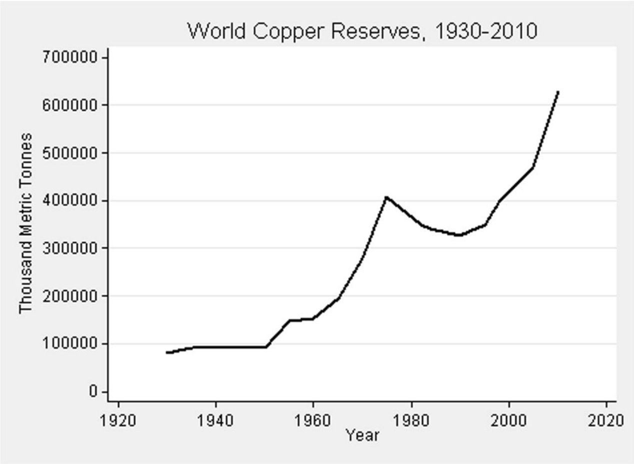

Fig. 2 World copper reserves, 1930–2010

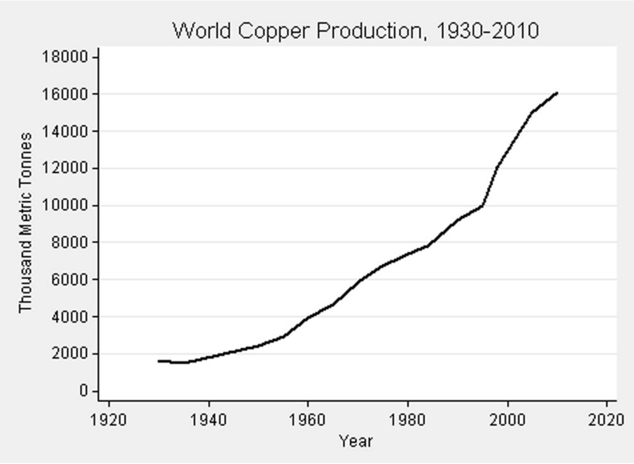

Fig. 4 World copper production, 1930–2010

profit. When the price increased in the 2000s, these materials were re-classified as "reserves", and exploration increased. Figure 3 illustrates the link between world copper reserves and copper prices; world copper reserves and copper prices are correlated at ρ=.86. Again, going back to the basic definition of reserves and resources, the definition is fundamentally economic in nature and elastic with respect variables such as price and technology.

Turning to copper production, Fig. 4 shows the production for the period comparable to Fig. 2 for reserves. It is important to compare the vertical scales on Figs. 2 and 4. The reserve scale on Fig. 2 goes up to 700,000,000 metric tonnes, while production on Fig. 4 only goes up to 18,000,000 tonnes. If the series from Figs. 2 and 4 were plotted on the same graph, production would be a line hugging the horizontal axis.

As indicated by Fig. 4, however, copper production has increased eight-fold during this period and could form the start of a Hubbert-like logistic curve. However, there is little evidence that we are running out of copper in spite of the fact that we produced more copper during this period than in the entire prior history of human existence. There was a decline in the rate of production growth during the 1980s for the reasons noted above; but otherwise, there is no indication of an imminent decline. This enormous gap between reserves and production leads us to a look at reserve life on Fig. 5.

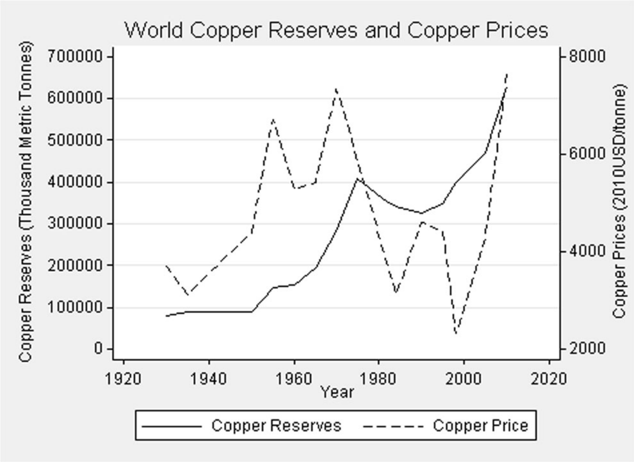

Fig. 3 World copper reserves and copper prices

If we divide reserves by annual production, we get world reserve life measured in years that we can maintain current levels of production. Figure 5 illustrates the results. It shows that over the 80-year period between 1930 and 2010, the reserve life of world copper mines has remained relatively stable. There was a relatively large increase in reserve life in the 1970s because of some significant discoveries and the application of new extraction and metallurgical techniques and a decline in the 1980s because of the low prices discussed above. With higher prices in the first decade of the twenty-first century, reserve life has increased as would be predicted by conventional economic models provided by McKelvey and Hotelling.[5] But, 2010 reserve life of approximately 39 years is virtually indistinguishable from the average for the period of 43 years. In other words, we are not running out of copper resources and reserves. The size of the upper left hand box in the McKelvey diagram has basically remained the same size for the last 80 years.

A theory of reserve life

If the peak copper hypothesis were correct, the reserve life curve on Fig. 5 would be a downward sloping curve. However, the decline is slight and is readily explained by changes in the external economic environment. Moreover, if we look at the economics of extractive industries, specifically the economics of mineral exploration (for simplicity, we will

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[5] Hotelling's model for non-renewable resources predicts long-run rising prices of commodities to allow continued production from lower-grade materials. As Julian Simon's famous bet with Paul Ehrlich demonstrated, the opposite has occurred—inflation-adjusted prices of non-renewable resources have declined over time.

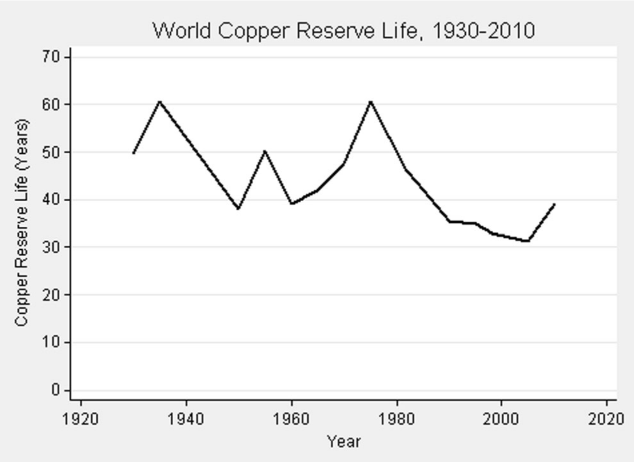

Fig. 5 World copper reserve life, 1930–2010

continue using copper mining as our example, although the point is likely more generally applicable), it is easy to understand why.

The existence of reserves comes about as a result of decisions by mining and exploration companies to invest in exploration efforts. From the perspective of addressing the concerns of the peak resources hypothesis, this is an important point. A government (or people concerned with the peak resources hypothesis) may want to find every tonne of copper, ounce of gold, barrel of oil, etc., in the world or within its borders, but mining companies are the ones who are looking for reserves, and mining companies are not concerned with global supply. Exploration companies also look for reserves, and we will address them below, but reserves are only worth something to exploration companies if they can sell them to mining companies.

From an economic perspective, reserves can be viewed as inventory; as in any other business, mining companies want to hold inventories of reserves in order to conduct ordinary planned business. And, also just like any other business, a mining company does not want excess inventories because the cost of acquiring them takes resources from current operations. It also does not want to run out of inventories which would interrupt current operations.

In its simplest form, from the perspective of a mining company, exploration effort can be represented as a present value calculation. The firm must allocate its capital between current mining activities which produce income today and exploration activities that may produce income in the future. Hence, expanding the reserve base or reserve life of a mine of a mining company comes at the expense of current income, cash reserves, and the firm's capital value as measured by the price of the company's stock. Since the company management's current and future compensation is based on these factors, they are also considering their current versus future compensation in allocating financial capital. Consequently, management will consider today's cost of finding more reserves that can be mined in the future. They will also consider the future price of the commodity, the cost of extracting the commodity in the future, and how long it will take to be able to mine the marginal unit of reserves.

Consider a simple two-period model in which a profit maximizing mining company is choosing whether to allocate its scarce resources to either mining *(m)* or exploration (*e*). For simplicity, let

$$e + m = 1 \tag{1}$$

In period 1, the firm incurs a cost of *C* from its mining operations and sells its output at a price of *P*, so net revenue is *m*(*P*-*C*). In addition, the firm incurs eE exploration costs, where E is simply the cost of exploration. The amount of discovered reserves is given by *R*(*e*), where *R*'>0 and *R*"<0. These reserves are mined and sold in period 2, and the sales are discounted at rate *r*. For simplicity, assume *r* to be an amalgam of both the interest rate and the amount of time until the reserves can be mined (i.e., it reflects development time, capacity constraints, etc.). The mining company's profit function is therefore:

$$\Pi = m(P - C) - eE + R(e)\left(\frac{P - C}{1 + r}\right) \tag{2}$$

As a first approximation of the exploration calculation, we will assume that there is no risk involved to simplify the analysis. This means that the company is completely certain to find new reserves of known quality if they explore and that the price that they can sell their future production is guaranteed as are their production costs at their current levels. On the margin, then, the firm maximizes profit by choosing *e* and *m* such that:

$$(P - C) - E = R'\frac{P - C}{1 - r} \tag{3}$$

Intuitively, the left side of Eq. (3) is the marginal cost of exploration—a little more exploration results in less production, hence a loss in net revenue of amount *(P-C)* as well as an increase in exploration costs *E*. The right side of (3) provides the marginal benefit of exploration—a marginal increase in exploration yields *R*' more reserves, which are mined and sold in period 2 for marginal net revenue *(P-C)* that is discounted at rate *r*. Comparative statics of this result yield the unsurprising results that exploration is decreasing in both *E* and *r*. The comparative statics for *P* and *C* are slightly more nuanced and depend on the marginal effectiveness of exploration, *R'*. An increase in the cost of mining leads to more exploration if exploration is relatively ineffective and less exploration if exploration is relatively effective. Conversely, an increase in the price received for mining output leads to more exploration if exploration is relatively effective but less exploration if exploration is relatively ineffective.

Also note that the NPV analysis suggested above is different than the standard life of mine financial feasibility analysis in a number of ways. First, it is a short run analysis that ignores fixed costs. It assumes fixed assets are in place so they are treated as sunk costs that have no relevance in the short run. As such, it is an analysis based solely on cash flow considerations. Second, it ignores reasons other than cash flow that would lead an ongoing operator to conduct exploration. For example, expanding reserves makes it easier to raise private capital and can enhance share prices.

Since the simple model discounts future production at current prices and costs, the outcome of the exploration decision is obvious: the marginal cost of exploration will nearly always exceed the marginal benefit of exploration because the discount rate is, in most cases, likely to be quite large as it combines both the interest rate and the amount of time before any actual mining might occur. New reserves are not really worth looking for, and producers have no interest in finding these reserves just to prove they are there unless there are some extenuating circumstances such as trying to raise capital from investors by proving they have long-lived assets. For example, a mining company may already have enough ore to continue for many years before the new ore would be accessible with current equipment or may face extensive regulations requiring the obtaining of operating permits to mine the new ore or may require capital development and construction prior to beginning operations. For example, a recent Behre Dolbear (2013) report found that the permitting process in the USA typically results in a 7- to 10-year waiting period before mine development can begin.“ The Resolution Copper Mine in Arizona provides a useful example. The vein was initially discovered between 1992 and 1997 (Manske and Paul 2002), and Resolution began exploration near Superior, AZ in 2001. As of year-end 2013, Resolution has yet to be able to even acquire the required land, and the timetable in their Mine Plan of Operations submitted to the US Forest Service in November 2013 indicated that they hoped to begin mining in 2024.

As noted, there are some important factors involved in exploration decisions that are not included in this simple example. There are political risks, price risks, cost risks (e.g., mining is an energy-intensive activity so energy costs and availability are important), and geological risks (low-grade orebodies are more likely to become uneconomic if prices fall). Allowing for risk that reserves will not be found will only reduce the expected return from exploration. This risk could be reflected in the model a number of ways—we could increase the cost of finding the reserves (E) to reflect the cost of unsuccessful exploration efforts, make more restrictive assumptions about the $R(e)$ function, or create a geological risk variable, ρ ($0<\rho<1$), to represent the probability of finding reserves. Either way of reflecting geologic risk will reduce the net present value of reserves and reduce the incentive to explore.

On the other hand, as the comparative statics analysis suggests, mines with relative short operating lives, i.e., where r is small, there is more incentive to explore for reserves because the difference between the value of current and future production shrinks. But for mines that account for the vast majority of reserves and production (Humphreys 2013), this is generally not the case.

The observation that mining companies have little incentive to expand reserves also comports with what we observe in the mining industry. In the copper industry, we observe a number of very large long-lived properties like the Anaconda mine in Butte, Montana, Bingham Canyon in Utah, Southern Peru’s operations, Chilean, and Indonesian copper mines, etc. Some of these have been producing for over a century, and they have still significant reserve lives left.

The same is true when it comes to other metals. Mining districts like the Witwatersrand basin in South Africa, Eastern Russia, the Carlin and Cortez Trends in Nevada, the Val d’Or in Ontario, Canada, are areas that have produced gold for over a century in some cases and still have significant reserves and reserve lives—even with much higher rates of production that we have seen in the last century.

Under current geologic circumstances, many reserves are found by accident. Producers will conduct “condemnation drilling” to locate ground to construct facilities for processing ore, roads, worker housing, etc. If they find ore in the condemnation drilling, they look for another site for the facilities but also add to their reserves without intending to discover more ore. In numerous cases, producers have just given up and constructed facilities on top of orebodies and accepted the fact that they will have to be moved in the future.

Another factor at work in these examples of long-lived orebodies and the incentives or lack thereof to explore is the “lumpiness” of mineral discoveries and the magnitude of capital investments required to develop them; when ore bodies are found, they tend to be very large relative to an operator’s capacity to extract the mineral over time. That is why many mining districts like those named above have been mined for over a century. The lumpiness of capital investment required to explore for, find, acquire government permits, finance, develop, and construct a mine also serves as an impediment to expanding the reserve base. Per unit of ultimate output, these fixed costs are much higher for smaller ore bodies providing another reason that these reserves are currently not worth looking for.

The case of exploration companies

It should be noted, however, that the exploration calculation above is quite different for the many smaller non-producing exploration companies in the industry. They do not have the high opportunity cost of capital of producers, which are the profits from mining. They frequently—at least they would claim—lack capital and face a short time frame for exploration work, but we do see significant exploration effort from this sector. Hence, it is not surprising that these smaller exploration companies are responsible for many major discoveries that are not next to existing mines which they turn around and sell to the larger producing companies.

Large producers face pressure from investors to replace their annual production with reserves. Bullis (2001) has suggested that this is a problem for large gold producers, and it is a problem for a company (note that Bullis refers to the sustainability of gold *producers*, not gold *production*). But large producers have historically had a poor record at finding reserves, and the analysis above suggests why. It is generally less expensive to buy reserves from companies specializing in exploration that it is to look for them themselves. However, in any event, this is a problem for an individual company.

A final point on reserve life is also worth adding. Considering reserve life on a mine by mine or company basis is quite a different matter than world resources. Many mines and potential mines are relatively short-lived for geologic, economic, political, or other reasons. The fundamental problem with what has been done with the Hubbert curve is that logically, it represents is a fallacy of composition. That is, it assumes that what is true about isolated events and circumstances is true in general.

Conclusion

Certainly, non-renewable resources are finite from a physical perspective on a planet with finite mass. But, there is no indication that we cannot produce increasing quantities of these resources for the foreseeable future. Yes, these resources will eventually become depleted, but it is unlikely to happen in the lifetime of anyone currently living or even in the lifetimes of their great great grandchildren.

One might claim that our argument simply pushes back the point in time that we will hit peak copper (or any other peak resource). This misses our larger point about the sustainable use of non-renewable resources, however, which is that the development of resources adds to the wealth, well-being, and the human and physical capital available to society. If the depletion of physical non-renewable resources is matched by investments in renewable capital, such as human capital, technology, etc., it will be possible to indefinitely sustain the development of non-renewable natural resources such as copper (Arrow et al. 2004). Such investments have proven historically, and will tend in the future, to be in a sense substitutes for natural resources. For example, technological advances in wireless telephony have allowed society to substitute electromagnetic spectrum for copper.

We would note that while we see no significant constraint on the physical quantity of strategically important materials like copper available in the foreseeable future, the main constraints on supply are political. We also believe that we could conduct the same analysis on any strategically important non-renewable mineral and get similar results. Supply disruptions caused by dysfunctional governments in various corners of the world to more reasonable discussions about environmental, cultural, and social impacts of mining are much more important than the crustal abundance of mineral elements.

Another factor that proponents of the “peak minerals” hypothesis fail to recognize is the nature of the minerals producing industry itself. This industry consists of profit-seeking firms that have no interest in discovering all of the copper, gold, or whatever mineral that exists on the planet. Their only interest is in discovering enough reserves to sustain their businesses for the foreseeable future. Therefore, known reserves certainly do not reflect all minerals available and significantly understate inferred and unknown resources.

Moreover, as we have seen, current mineral producers generally have little incentive to expand proven reserves beyond those that can be mined within a relatively short period of time. Hence, the reserve estimates that proponents of the “peak minerals” hypothesis are using to make their point are, by their nature, incapable of making their case.

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