Division of Economics and Business
Working Paper Series

Minerals: What Are They and What Makes Them Critical?

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Working Paper 2020-04
http://econbus-papers.mines.edu/working-papers/wp202004.pdf

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July 2020

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Working Paper No. **2020-04**
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ABSTRACT
Minerals and materials are the backbone of industrial productivity and might. With annual sales in the billions, they are key inputs into fulfilling the goal of lifting billions out of poverty and putting us all on a cleaner more sustainable trajectory. This paper provides background information on these crucial markets. I provide some background on the size of markets by tonnage and sales value, market evolution and recurring cycles of scarcity scares for critical minerals. Recent concerns have spawned dozens of government studies to determine which materials are critical in meeting our goals. From reviewing these studies, I consider factors that make materials critical — high economic and/or strategic value coupled with supply insecurity, which might be geological, technical, political, social, and economic. By comparing studies, I come up with a global list of critical materials that make it on the list of many of the existing studies. I summarize what we know about demand and supply elasticities for minerals and use an example of space mining to illustrate their use.

JEL **classifications: L1, L71, L78, M14, Q31, Q33**
Keywords: Demand, Supply, Mineral Industry Structure, Critical Minerals

*I would like to thank Robin Bias for his cheerful and able research assistance. His help is much appreciated.

Introduction and Evolution of Mineral Industries. Non-fuel minerals are critical building blocks to global material well-being. At the millennium it was estimated that global consumption of non-fuel minerals excluding bauxite was on the order of 1.2 billion metric tons amounting to about 200 kilograms per capita increasing to more than 300 kg per capita by 2016 (International Organizing Committee for the World Mining Congresses (2018), Wellmer and Becker-Platen (2007), World Bank (2019)). This consumption is largely satisfied out of production and in some cases from recycled product and stock drawdown. The global distribution across products for this consumption in 1998 is indicated by the production statistics in Figure 1.

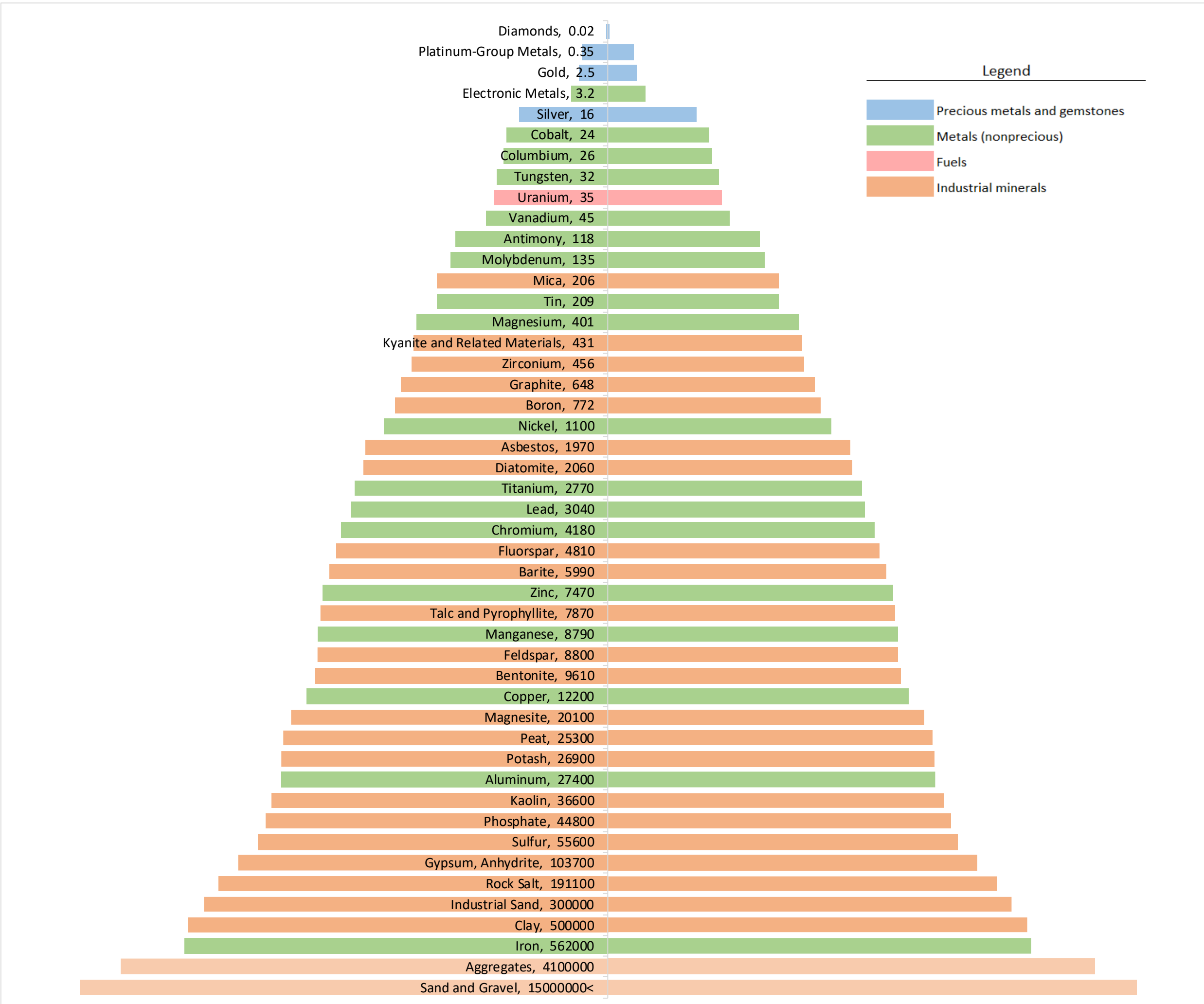


Figure 1: World Primary Production of Mineral Resources (kilotonnes (kt)) 1998.

Notes: In this document tonnes will always refer to metric tons. Ores are given as metal equivalences, diamonds include all precious and semi precious gems, and electronic metals are gallium, indium, and germanium. Graphed in logs except for diamonds and electronic metals. Fossil fuels have been eliminated from original graph.

Source: Wellmer and Becker-Platen (2007)

For the most part, these minerals are non-renewable. Some are quite abundant and do not seem a cause of concern such as those near the bottom of the pyramid: aggregates (stone, sand and gravel), iron (one of the five most abundant elements on earth), and clay. However, as countries develop, their needs for minerals increase in both quantity and diversity. For example, figure 2 shows U.S. consumption of metals and industrial minerals (MIM) from 1900 to 2014. Since 1900, U.S. consumption of non-fuel minerals has averaged a slightly higher growth rate than that of GDP (Center for Sustainable Systems (2018), World Bank (2019)).

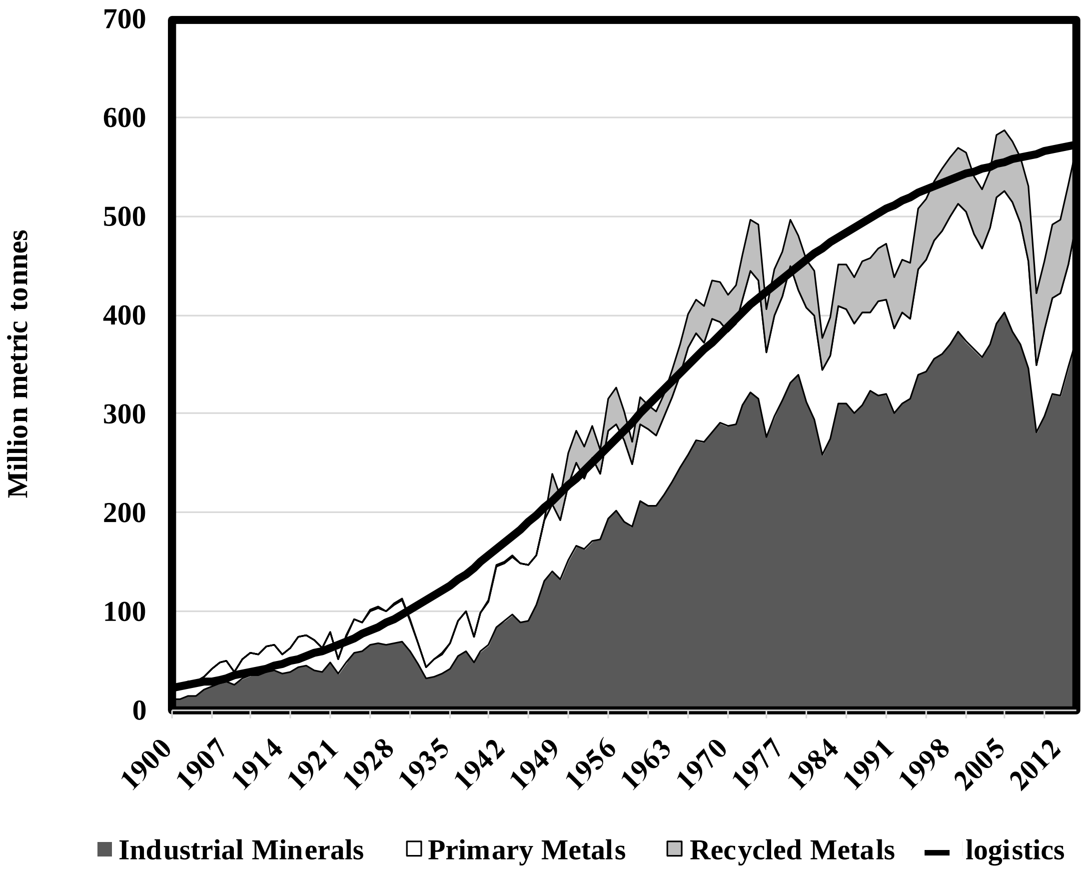


Figure 2: U.S. Use of Industrial Minerals and Metals, 1900-2014
Source: Matos (2017).

There was a run up until the great depression in the 1930's with U. S. MIM use about doubling and annual growth of MIM only slight faster than GDP. This earlier period was followed by an even faster increase from the 1930s to the early 1970s with MIM increasing more than 11 fold at about the same rate of increase as industrial production Federal Reserve Bank of St Louis (2020b)but with GDP increasing less than 7 fold. The increase was considerably less dramatic thereafter. Indeed, MIM use was no higher in 2014 than in 2004. This lifecycle development pattern of a slower growth build-up to a take-off leading to a leveling off with saturation is a common occurrence and is roughly represented by the solid black logistics function in figure 2.

Another lifecycle view of how U.S. MIM use has evolved is seen in figure 3 with per capita use of MIM graphed against real GDP per capita. Per capita use took off between $10,000 - $20,000 (real 2017 dollars) per capita and then became more stable by $30,000. The U.S. reached $10,000 per capita by 1929 and regained it again in 1937 and again in 1939. It reached $20,000 per capita by 1959 and $30,000 by 1976. Industrial mineral use is almost always higher than metal use, and in recent decades has been somewhat below two tonnes per capita, while metal use has hovered below 1.25 tonnes per capita. Whereas the EU28 consumed about 0.6 tonnes of metal ore per capita in 2014 growing to 0.7 tonnes in 2018 (Eurostat (2019)). The metric unit for weight (metric tonne) is used in this paper. For more detail on a number of metals and countries and how metal consumption per dollar changes as per capita income changes, see Crowson (2018).

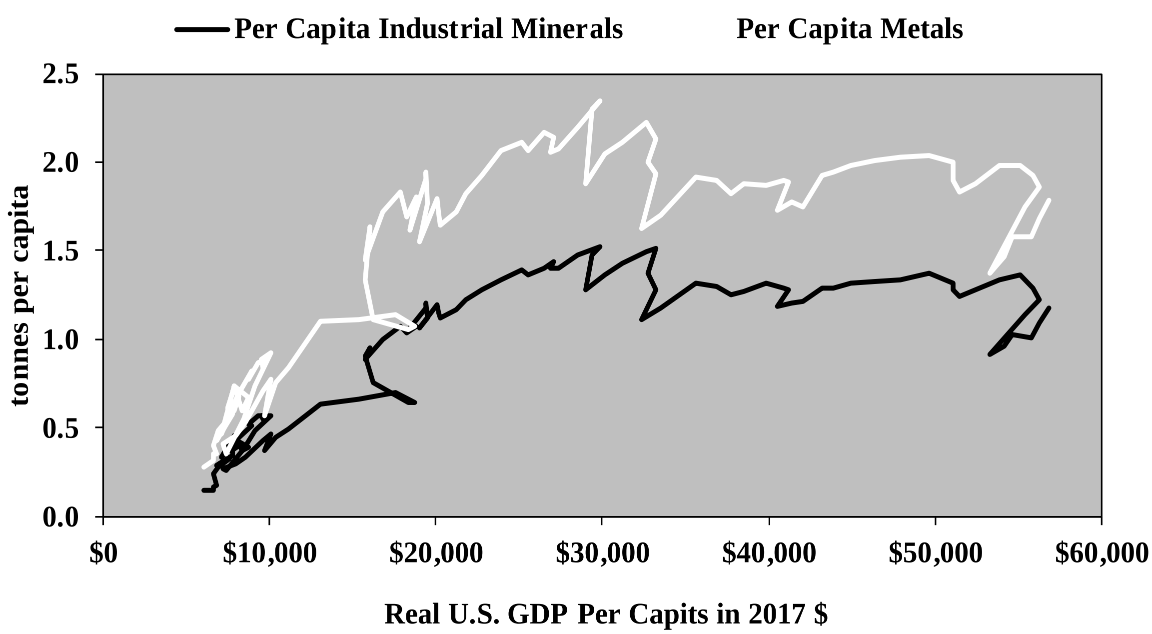


Figure 3: U.S. Per Capita Metal and Industrial Mineral Use and Real Per Capita GDP 1900-2014
Sources: Matos (2017). Executive Office of the President Council of Economic Advisers (2018)

Growth in China is even more impressive. Income in most years has grown faster than for most countries in the last two decades with double digit rates in a significant portion of that period, while its mineral growth has typically exceeded GDP growth (Liu (2013), Humphreys (2015), Humphreys (2018)). Diversity of mineral use has increased as well. Few of us had heard of rare earth elements in 1990. Now we hear of them in many uses including computer chips, mobile phones, and future renewable energy uses.

Globally the situation is a bit different. Although I have not found consumption or global use statistics, the International Organizing Committee for the World Mining Congresses (2018) has global production statistics from 1984 for 3 metal categories (iron and ferro-alloy metals, non-ferrous metals, and precious metals) along with industrial minerals not including basic construction materials such as sand and gravel from 1984 to 2017.[2] As global statistics, these should be close to consumption except for the usual statistical errors and stock changes. Putting the mineral categories into perspective, Figure 4 panel a shows the share of all categories of minerals reported in 2017 and

[2] Iron and ferro-alloy metals include "iron, chromium, cobalt, manganese, molybdenum, nickel, niobium, tantalum, titanium, tungsten, vanadium." Non-ferrous metals include "aluminum, antimony, arsenic, bauxite, bismuth, cadmium, copper, gallium, germanium, lead, lithium, mercury, rare earth minerals, rhenium, selenium, tellurium, tin, zinc." Precious metals include "gold, platinum-group metals (palladium, platinum, rhodium), silver." Industrial minerals: asbestos include baryte, bentonite, boron minerals, diamond (gem/industrial), diatomite, feldspar, fluorspar, graphite, gypsum and anhydrite, kaolin (china-clay), magnesite, perlite, phosphates (incl. guano), potash, salt, sulfur, talc (incl. steatite and pyrophyllite), vermiculite, zircon." (International Organizing Committee for the World Mining Congresses (2018)).

the dominance of mineral fuels (fossil fuels and uranium). Figure 4 panel b drops out the fuels and shows the strong dominance of the ferrous metals and the teeny tiny share of precious metals.

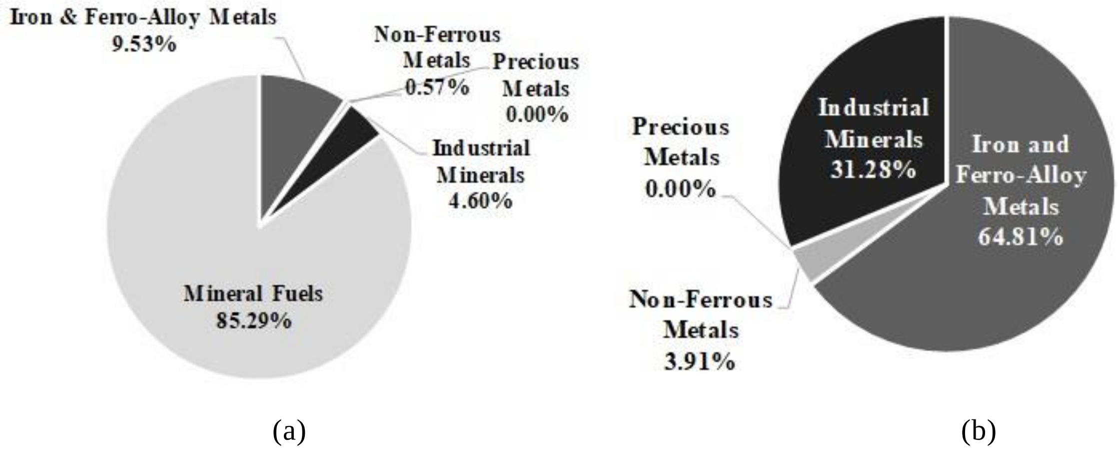


Figure 4 Share of Global Mineral Production by Major Category 2017

Source: Created from data in International Organizing Committee for the World Mining Congresses (2018).

Given the small shares of precious and non ferrous metals, they do not show up well, so in the times series (figure 5), I combine the metal categories. From 1984-2002, growth of global MIM was rather slow averaging about 1.5% per year with most of the growth from metals. Then metals took off, and the growth of MIM jumped to an almost 5% annual average with metal growing almost 2.5 times faster than industrial minerals. The ferrous metal group was particular dynamic with annual average growth of almost 7% per year.

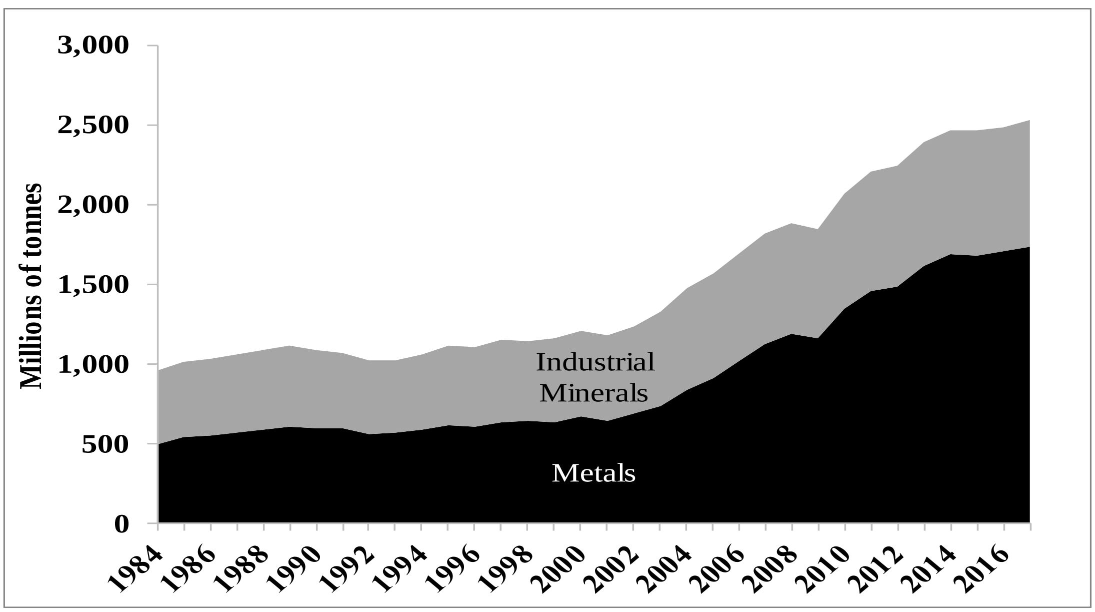


Figure 5: World Production of Industrial Minerals and Metals: 1984-2017

Source: Created from data in International Organizing Committee for the World Mining Congresses (2018).

We can see what happens per capita in figure 6. The horizontal line is GDP measured in purchasing power parity (PPP) dollars available since 1990 (Deaton and Heston (2009)). The vertical axis shows MIM per capita. Interestingly we see the take-off when global per capita GDP is around $10,000.

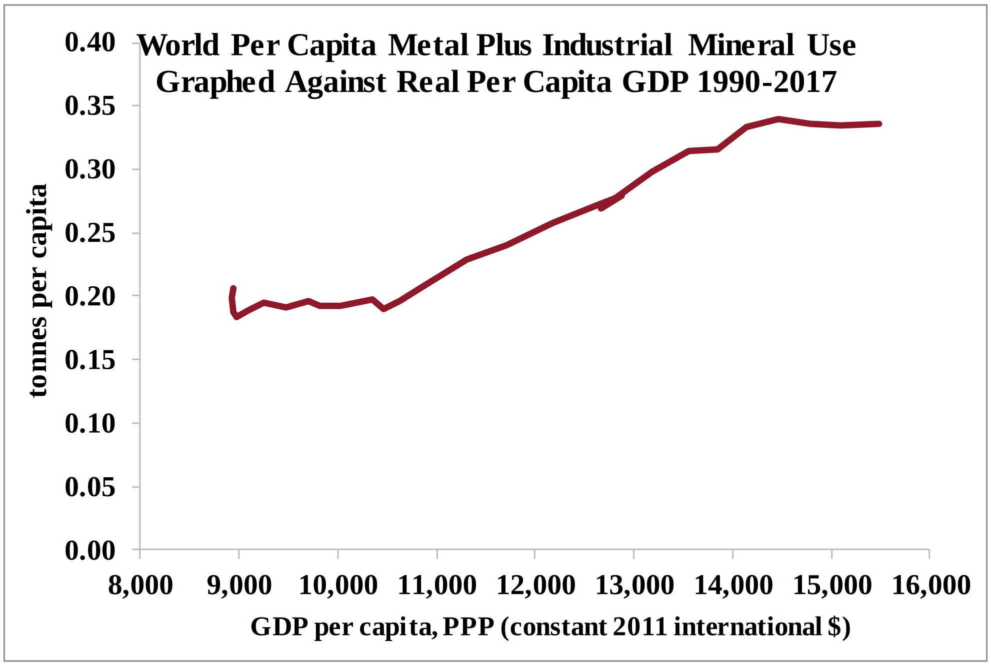


Figure 6: World Per Capita Metal Plus Industrial Mineral and Real Per Capita GDP 1990-2017

Sources: Created from data in International Organizing Committee for the World Mining Congresses (2018) and World Bank (2019).

This rapid increase in mineral consumption has been magnified in some emerging markets, especially China with a more than 5% annual average growth in GDP from 1991-2016 hitting double digits in almost a third of those years (World Bank Development Indicators, growth of GDP in real local currency units). Chinese mineral consumption growth rates have been equally impressive. For example from 2000-2011, Chinese consumption of aluminum and steel grew more than 1.3 times faster than GDP, Chinese dependence on overseas material imports increased from 10% - 30%, and in 2016, China with around 15% of World GDP consumed half or more of global consumption of cement, nickel, copper, and steel (Liu (2013)). This rapid increase in consumption started to put pressure on metal markets and the IMF Metal Commodity Index (figure 7) suggests that global metal prices rose by about 50% from 2005 to 2015 sparking concerns about mineral availability (Federal Reserve Bank of St Louis (2020b)).

Not only does the quantity of mineral use increase with industrial development, so too does the diversity of mineral needs. For example, early portable phones contained around 30 elements, whereas current smart phones contain more than double the number of elements. Computer chips in the 1980s and 1990s included no rare earth elements but included more than a dozen in the 2000s (Eggert, 2018). The 17 rare earth elements with their abbreviations and atomic numbers are scandium (Sc - 21), yttrium Y - 39), and the lanthanides –lanthanum (La - 57), cerium (Ce - 58), praseodymium (Pr - 59), neodymium (Nd - 60), promethium (Pm - 61), samarium (Sm - 62), europium (Eu - 63), gadolinium (Gd - 64), terbium (Tb - 65), dysprosium (Dy - 66), holmium (Ho - 67), erbium (Er - 68), thulium (Tm - 69), ytterbium (Yb - 70) (Tse (2011), Millipore Sigma, 2020).

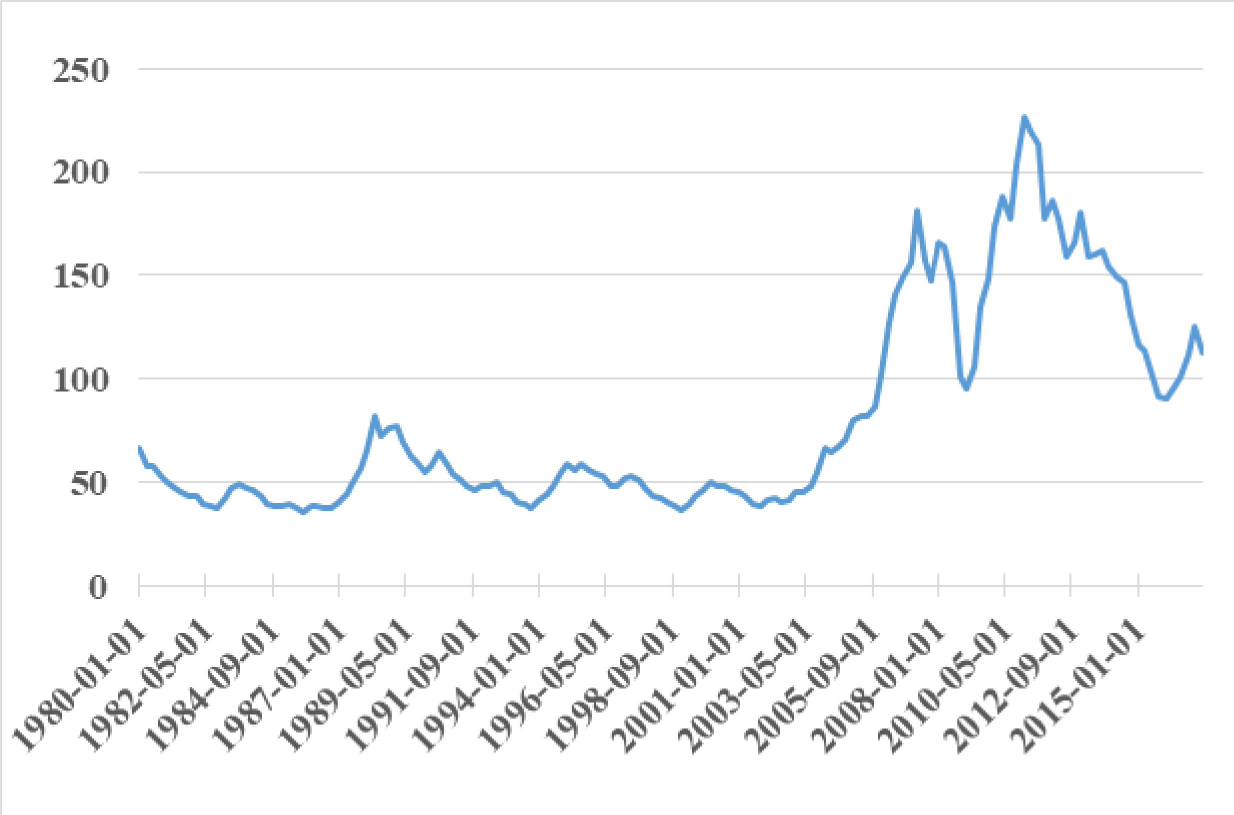


Figure 7: Global metal price index, 2016 = 100, quarterly, not seasonally adjusted, 1980-2019: II
Source: Federal Reserve Bank of St Louis (2020a)

Not all rare earths are rare, but they are hard to process because they frequently occur in small concentrations. With similar properties, they are often found mixed together. Unmixing them requires a number of processing steps with the leftover waste from processing not environmentally friendly (King (2017)). For example, to process the five most important rare earth elements – yttrium, neodymium, europium, terbium, and dysprosium– takes 13 to 330 times as much energy for processing as it does for iron (The Critical Metals Report (2012a), Jordan and Eggert (2018), Nuss and Eckelman (2014)). The light rare earths – lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium and scandium– are abundant. However, the heavy rare earths – terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium – are more rare with 90% of them produced in China (Natural Resources Canada (2017)). These elements are becoming increasingly important with modern uses in defense, mobile phones, disk drives, wind turbines, LED light and screens, super magnets, and batteries. There is special concern with having enough to facilitate the transition out of fossil fuels to cleaner and greener energy sources.

Mineral Industry Use, Resources, and Cycles: The mineral industries have a long economic history. Fulp (2012) notes that nine metals were mined in prehistoric times: iron, copper, zinc, silver, tin, gold, mercury, lead, and bismuth. Being non-renewable, we suspect there have been worries about running out since this dawn of human time. However, Table 1 shows that all 9 of these metals are still being mined and have global sales in the millions if not the billions of dollars.

Table 1: Global Mineral Sales. Wholesale Prices, and Energy Needed for Processing

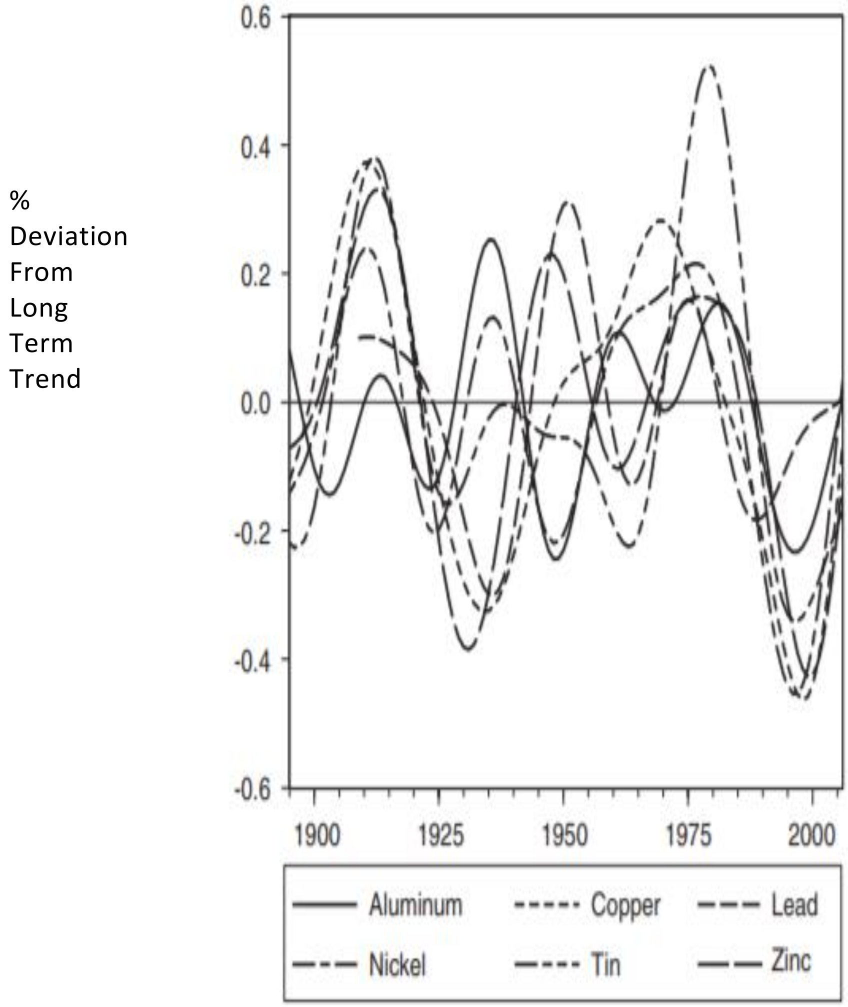
Commodity	2014 sales (million$)	$/tonne 2017	Energy needed (MJ/kg)

Metals			
Aluminum	120,238	1,967.65	131.0
Arsenic	30	1,397.06	5.0
Beryllium	121	819,117.65	1,720.0
Bismuth	213	11,115.38	697.0
Cadmium	43	2,915.38	53.0
Chromium	6,467	$13,250	40.2
Cobalt	3,457	37,347.38	128.0
Copper	129,862	6,169.94	53.7
Gold	116,778	40,431,434.29	208,000.0
Indium	0.542	341,600.00	1,720.0
Iridium	582	22,443,439	169,000.0
Iron ore	325,220	71.76	23.1
Lead	10,352	2,314.67	18.9
Lithium	1,265	13,900.00	125.0
Manganese	36	1,850.00	23.7
Mercury	100	42,061.83	179.0
Molybdenum	7,155	14,750.00	117.0
Nickel	40,471	10,409.64	111.0
Niobium	3,812	41,950.00	172.0
Palladium	5,070	24,138,424.05	72,700.0
Platinum	7,454	55,799,147.39	243,000.0
Rhenium	146	2,843,959.80	9,040.0
Silver	15,969	548,812.45	3,280.0
Strontium	16	5,400.00	48.8
Tantalum	355	128,000.00	4,360.0
Tin	6,395	20,061.17	321.0
Titanium	4,982	4,150.00	115.0
Tungsten	3,637	35,200.00	133.0
Vanadium	1,780	22,600.00	516.0
Zinc	28,881	2,890.87	52.9
Zirconium	1,494	27,205.88	19.9
Non-Metals and Metalloids			
Asbestos	3,089	2,100.00	NA
Barite	1,158	1,920.00	NA
Cement	411,730	62.15	NA
Germanium	314	1,358,000.00	2,890.0
Graphite (natural)	1,480	1,200.00	NA
Gypsum	2,214	$8.20	NA
Helium	688	$3.86/m3	67.5
Industrial diamonds	800	219,420,000.00	NA
Phosphate rock	19,800	231.52	NA

Potash	25,550	231.52	NA
Salt	21,957	99.00	NA
Silicon	26,530	2,490.52	NA
Sulfur	6,878	60.00	NA

Notes: The mineral prices quoted are only indicative as such prices vary by grade, definition, geography, and time period. See Tilton and Guzmán (2016)Table 1.1 for more information on the products included in sales. Energy needed is an estimate for mining, concentration, purification, and refining. For iron ore, energy needed is for iron. Tonne is a metric ton. *Sources*: Sales: Tilton and Guzman (2016), Prices: Pooley and Tupy (2018), Leonland (2018), U. S. Geological Survey (2020), BASF (2020), Northern Graphite (2020) CemWeek (2018), Ashreena (2018), Energy needed: Nuss and Eckelman (2014).

Thus, the earth's crust endowed from the Big Bang and beyond coupled with human ingenuity have not failed us in this regard, yet. When the need has arisen, humans have always managed to search harder, dig deeper, process ever poorer grades of ore, and make do with less. As argued by Adelman (1990) for oil and Tilton (2003), along with others for minerals, their availability is a race between depletion and technology, So far technology has won while only losing a lap now and then. Nevertheless, concerns for availability tend to resurface and mineral industries have had their ebbs and flows. To see these ebbs and flows as measured in prices, Cuddington and Jerrett (2008) used prices from the London Metal Exchange for copper, aluminum, lead, nickel, tin and zinc from the late 1800s and early 1900s to 2006. They deflated the prices with the U.S. consumer price index and used statistical filtering techniques to the separate over-all price trend from super cycles, which they define as having 20-70 years from one price peak or trough to the next (See figure 8). They generally concluded that there were three super cycles for these metals over their sample. The jumble in their figure, here shown as Figure 6, show that the cycles are not always in sync but there is general agreement that the early 1900s was a boom period and 1990 to the early 2000s a trough, which was recovered from by 2006



Source: Cuddington and Jerrett (2008), Figure 3.

Figure 8 Estimates of Metal Super Cycles as Deviation from Trend for Six Metals Traded on the London Metal Exchange

They and others argue that metal and material intensive growth triggered by industrialization and urbanization in the United States, Europe, followed by Japan, and more recently China and other emerging markets have fueled these super cycles. Such periods of structural change require infrastructure that is particularly material and metal intensive. This is demonstrated in Table 2 by data compiled in Humphreys (2015) for China's growth in selected commodities from 1998 to 2008 and China's share in global consumption of these same commodities in 1998, 2008, and 2013. We add some information on Chinese GDP and urban population as well. China had a Purchasing Power Parity (PPP) GDP per capita of around $3000 in 1998 increasing to around 12,000 in 2013. By 2013, China represented around 16% of Global PPP GDP but was consuming between 45-65% of the important listed metals. Smil (2014) sees relative dematerialization but not absolute dematerialization for the industrial countries and many see more economies following the leads of China and India putting continued growth for minerals quite likely.

Table 2 Annual Average Growth Rates and China's Global Share of Selected Commodities, Urban Population, and GDP.

	Average Annual Growth 1998-2013			China as % of Total World		
	China	Rest of World	China/ROW	1998	2008	2013
Aluminum	17.7	2.2	8.0	11	36	48
Copper	13.9	1.0	13.9	11	28	47
Nickel	23.2	0.5	46.4	4	26	51
Zinc	13.9	0.7	19.9	14	36	46
Steel	14.9	3.0	5.0	16	37	46
Iron Ore (Seaborne)	23.9	1.1	21.7	13	52	65
Gold (fabrication)	4.5	-2.8	-2.1	7	13	31
Platinum (fabrication)	7.1	2.9	2.5	12	18	28
Urban Population	3.5	2.2	1.6	16	18	19
GDP Real $	9.3	2.4	3.9	4	8	11
GDP Real PPP	9.3	3.0	3.1	7	12	16

Source: Commodity growth: Humphreys (2015), Table 2.1. Population and GDP growth and share computed from World Bank, World Development Indicators.

Radetzki (2006) takes a more visual and descriptive look at broader classes of producer goods over a shorter time period. He uses the somewhat less dramatic nomenclature of boom rather than super cycle and concludes there were three demand triggered post World War II commodity boom periods (1950-51, 1973-74, and 2004 that was still ongoing at the time of his publication). He measured the price booms using an aggregate commodity price index and four sub-indices: metals and minerals, energy, food, and agricultural raw materials all deflated from nominal to real indices using a price index for manufactured exports of industrialized countries.

Radetzki, Eggert, Lagos, Lima, and Tilton (2008) followed up and noted that the then current commodity boom had gone on longer than the earlier two booms but not because it was a supercycle or because we were depleting these minerals. Rather it resulted from continuing strong demand from China and other emerging markets after a long period of languishing prices and lags in developing reserves as new mines take 5-10 years to develop. However, if you believe the old saying "the best cure for high prices is high prices" and its corollary "the best cure for low prices is low prices" you would expect that the time of reckoning would come. Figure 9 supports that view. It shows the rather precipitous overall drop of the wholesale commodity metal price index from the late 1970s to 2003, then a dramatic increase to 2008, a dip in 2009 with the recession, a two year resumption of the upward spiral. It then fell back to 100 in 2017, below the historical average of 110. The indices after 2017 are forecasts and show the IMF does not expect much rebound above the historical average in the next 5 years.

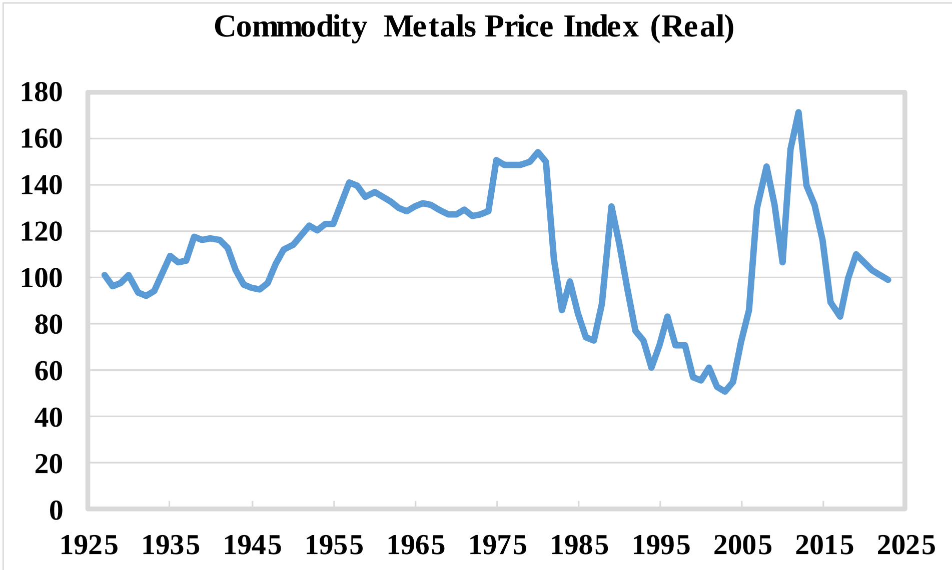


Figure 9: Real Metal Commodity Price Index with 2017 equal to 100.

Source: 1980 – 2017 with forecasts to 2023: IMF Global Price Index of Metals (Federal Reserve Bank of St Louis (2020b)) extrapolated back using averaged monthly data on a U.S. price index for metals and metal products for 1970 -1980 (United States Bureau of Labor Statistics (2019)) and United States Bureau of the Census (1975) for 1926-1970 deflated using U.S. consumer price index for 1926-2017 from McMahon (2019).

During boom times and high prices, worries we are running out of metal regularly surfaced. Pinchot (1910) worried that iron ore, one of five listed critical resources, was being rapidly depleted. However, taconite and technology came to the rescue. The Paley Commission requested by President Truman, believed that rapidly increasing consumption would exceed production raising prices and impairing economic growth (International Materials Policy Commission (1952)). Although figure 8 suggests there was some real price increase in metals from 1952 – 1972, Cooper (1975) notes that U.S. GDP grew faster by a percentage point per year than forecast by the Paley Commission, while with the exception of tin, U.S. consumption of all minerals examined grew slower than that forecast by the Paley Commission. Alternatively, international consumption, which was less carefully studied by the Paley Commission, grew faster than projected.

The next scare came in the 1970s. Meadows, Randers, and Meadows (1972) in their famous *Limits to Growth* book. They used a system dynamic simulation model (World3) to simulate the world economy out to 2100 (A simple public version of the model can be found at Hayes (2012).) They included five variables in their model: population, food production, industrialization, pollution, and consumption of nonrenewable natural resources (including fossil fuels) and simulated these variable from 1900 to 2100. Assuming these variables grew at historical exponential rates, they expected increasing natural resource scarcity (which included fossil fuels) and the world economy to start to collapse around 2015 when global industrial production per capita would peak. Pollution would continue to increase exponentially. However, the metal price indices above suggested mostly a downward trend in prices after 1972 for the next three decades. They updated their model in *Beyond Limits to Growth* in 1992 and again in *Limits to Growth: A 30 Year Update* (Meadows, Meadows, and Ronders (1992), Meadows, Randers, and Meadows (2005). When these later publications simulated from 1900 to 2100 using updated historical growth rates, the dates of industrial collapse, population peak, and pollution profile changed a bit but the natural resource story remained the same. Increasing scarcity of resources would be at the bottom of the collapse. As for industrial collapse in 2015-2020, we still seem to be chugging along. Although this corona virus, hopefully a short-run blip, has slowed the chug.

However, with a strong global economy (except for the subprime crisis in 2009), increasing production costs, and long lead times to increase production, prices generally spiked up from 2004 – 2014. Again, there was worry of global shortages and running out. Popular opinion echoed earlier views of scarcity. For example, if consumption growth continued at the then current rate, Desjardins (2014) has us running out of antimony, lead, indium, zinc, and silver between 2020 and 2030.

Critical Minerals and Insecurity of Supply. This worry of shortage was especially so for strategic minerals leading to studies of minerals to determine which ones were strategic. Strategic typically encompassed high commercial or strategic value coupled with supply vulnerability. Table 1 in Hayes and McCullough (2018) is a rich resource that summarizes the results of 32 such studies published between 2005 and 2018. I restrict my analysis to the 31 studies that considered criticality from the consumer's point of view. They considered a combined total of 55 elements and two element groups, rare earth elements (REE) and the platinum group of metals (PGM). All but three (sulfur, chlorine, and sodium) were found to be critical in at least one study. All elements in these studies are included in the appendix in Table A1.

Most of the studies were conducted by government organization. In comparing results, I pick a representative study for each country or region. The study is typically the most recent and/or the most extensive. Six studies considered critical minerals for the U.S. with the latest and most extensive, Fortier et al. (2018), finding 34 minerals to be critical out of 52 non-fuel minerals studied. Six studies consider critical minerals for the European Union (E.U.). Again the latest study, European Commission (2017), is the most extensive and it finds 24 out of 43 minerals critical. There were 4 studies for the United Kingdom (U.K.). The latest (British Geological Survey (BGS) (2015)) found 25 out of 40 minerals studied to be critical. Around 2/3 of the minerals studied for the U.K. overlapped with those studied for the whole E.U and around half of the rankings of critical or noncritical were the same.

There are 5 studies for critical minerals in Japan. The most extensive (Ministry of Economy Trade and Industry (METI) (2014)) studied 27 minerals and found all 27 to be critical. All the minerals studied by the Japanese were included in the most representative studies for the U.S., U.K., and E.U. but only about half of Japan's critical minerals were designated as critical in these other three areas. While three of Japan's critical minerals (nickel, iron, and zinc) were all found to be non-critical in the other three areas.

There are three other studies that consider critical minerals in one country each. Bastein and Reitveld (2015) finds 10 minerals to be critical for the Netherlands out of the 37 studied. Thirty four of those studied overlapped with those studied in the E.U., but only six of the Netherland's critical minerals (gallium, germanium, indium, antimony, platinum metal group, and rare earth elements) were found to be critical compared to European Commission (2017) which found 24 out of 43 studied critical. Bae (2010) found 11 minerals critical for Korea out of 11 studied. All overlapped with minerals found critical in Japan (Ministry of Economy Trade and Industry (METI) (2014)). Bortnikov et al. (2016) found 18 minerals critical for Russia out of the 18 studied. All but thallium were also studied for the U.S. in Fortier, Nassar, Lederer, Brainard, Gambogi, and McCullough (2018). Of the 17 overlapping mineral groups studied, all but three (selenium, yttrium and cadmium) were found to be critical in both countries. The correlation between criticality was a bit lower between Russia and the E.U.

Of the 57 elements or groups considered in the 31 studies, there were 22 most studied (included in 19 or more studies). Of those, there were 14 that were more often critical (found critical in 11 or more studies). Results for these critical minerals, reported in Table 3, are extracted from the representative studies by geographical area discussed above and another six studies that consider global criticality.

Table 3 Selected Critical Minerals from Selected Studies

Atomic #	3	4	23	27	31	32	41	49	51	73	74	75	44-46, 76-78	21,39, 57-71			
	Mineral or Mineral Group																
Study	**Li**	**Be**	**V**	**Co**	**Ga**	**Ge**	**Nb**	**In**	**Sb**	**Ta**	**W**	**Re**	**PGM**	**REE**	**Stud.**	**Crit.**	**Place or Sector**
Buchert et al. (2009)	1			1	1	1		1		1			1	1	**8**	**8**	sustainability and recycle potential
Bae (2010)	1				1			1			1		1	1	**6**	**6**	Korea
Willis & Chapman (2012)	1	1	0	1	1	1	1	1	1	1	1	1	1	1	**14**	**13**	by-products
METI (2014)	1		1	1	1		1	1	1	1	1		1	1	**11**	**11**	Japan
Zepf et al. (2014)	1		1	1	1	1	1	1			1	1	1	1	**11**	**11**	critical to energy
BGS (2015)	1	1	1	1	1	1	0	1	1	1	1	1	1	1	**14**	**13**	United Kingdom
Bastein et al. (2015)	0	0	0	0	1	1	0	1	1	0	0	0	1	1	**14**	**6**	Netherlands
Graedel et al. (2015)	0	0	0	0	0	0	0	1	1	0	0	1	1	0	**14**	**4**	criticality of metal and metaloids
Bortnikov et al. (2016)	1	1		1	1	1	1	1		1		1		1	**10**	**10**	Russia
NSTC (2016)	0	0	1	1	0	1	0	0	1	0	1	0	1	1	**14**	**7**	methodology of metal determination
EC (2017)	0	1	1	1	1	1	1	1	1	1	1	0	1	1	**14**	**12**	European Union
Fortier et al. (2018)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**14**	**14**	United States
Stud	**12**	**8**	**9**	**11**	**12**	**10**	**10**	**12**	**8**	**10**	**10**	**9**	**11**	**12**			
Crit	**8**	**5**	**6**	**9**	**10**	**9**	**6**	**11**	**8**	**7**	**8**	**6**	**11**	**11**			

Source: Selected minerals and studies extracted from Hayes and McCullough (2018), Table 1.

Notes: 1= found critical, 0 = included but not found critical. Stud in the next to last row = number of studies that considered an element, while Stud in the third to last column is number selected minerals or groups included in the study. Crit in the last row = the number of studies that found a selected element or group critical, while Crit in the next to the last column = the number of selected minerals or mineral groups included in a study. Minerals are designated by their standard abbreviation: Li=Lithium, Be=Beryllium, V=Vanadium, Co=Cobalt, Ga=Gallium, Ge=Germanium, Nb=Niobium, In=Indium, Sb=Antimony, Ta=Tantalum, W=Tungsten, Re=Rhenium, PGM=platinum metal group, which includes Ru=Ruthenium, Rd=Rhodium, Pd=Palladium, Os=Osmium, Ir=Iridium, and Pt=Platinum, and REE=rare earth elements, Sc=Scandium, Y=Yttrium, and the 15 lanthanides – Ce=cerium, Dy=Dysprosium, Er=Erbium, Eu=europium, Gd=Gadolinium, Ho=holmium, La=Lanthanum, Lu=Lutetium, Nd=Neodymium, Pr=Praseodymium, Pm=promethium, Sm=Samarium, Tb=Terbium, Tm=Thulium, and Yb=Ytterbium (Yb). For other minerals included in these and other studies, see Table 1 in Hayes and McCullough (2018).

These elements or groups deemed as critical have supply insecurity, which can take a variety of forms. As non-renewable resources, they are finite, suggesting we could conceivable run out. Although we don't know exactly how much of these resources exist, the estimates of parts per million (ppm) in the earth's crust shown in Table A1, give us some indication of relative scarcity. The earth's crust is typically 30-40 km thick on land and thinner under the oceans. Because many of the earth's crustal minerals come as oxides, oxygen is the most abundant element in the earth's crust approaching half of the earth's crustal mass, with around another quarter (277,000 parts per million) being silicon followed by aluminum at about 8%. Iron, which accounts for about 90% of global annual metal production, is the fourth most abundant element in the earth's crust. The mass of the continental earth's crust is thought to be around 2.2 times 10^{19} tonnes if the crust thickness averages about 25 km (Peterson and Depaolo (2007)). If we multiply parts per million in table A1 times this mass estimate, we get some very impressive numbers. The largest for silicon and aluminum are in the quintillions of tonnes with the smallest for iridium still in the millions of tonnes. We can see the relative scarcity by also considering production rates, which are available for 4 dozen or so elements or groups in Table A1. If we consider how long these estimated resources (R) would last at current production rates (R/P), all are in the millions of years or longer and about a third would run out after the sun will have blinked out in around 5 billion years. However, there are some problems with these values. Production is unlikely to stay constant. Were production to grow exponentially at 3% a year (an estimate a bit more than the global average over the last 3 decades (International Organizing Committee for the World Mining Congresses (2018)), the resources would last from 400-800 years. Although mineral consumption may grow faster than 3% in the near term, it seems unlikely to continue as emerging markets catch up and population stabilizes (e.g. U.S. MIM growth averaged less than half a percent a year from 1973-2014).

There is yet another problem. These estimates are for the whole earth's continental crust. The deepest underground mine is the Mponeng Gold Mine in S. Africa, which operates at depths of 2.4 to around 4 km (Mining Technology (2019)). The deepest open pit mine in the world (Bingham Canyon Mine in Utah), which produces copper with gold, silver, and molybdenum as by products is 1.2 km deep (Mining Technology (2013)). If we took these depths as rough limits and the average earth crust at 25 km, only about 4% of these resources might be available. If 4% of the crustal resources are available at an annual growth rates of 1%, the estimated resources would last 3 to 4 decades and in some cases a bit longer.

However, even if the metal is close enough to the surface, many concentrations may be too low to be metal ore with concentrations economically extracted at current prices. We show some sample ore concentrations that we have found along with their approximate year in Table 4. Current concentrations are likely lower than the older ones in the sample as technology continues to improve making lower concentrations of metals increasingly economically attractive as time passes.

As the best resources are depleted, mining companies need to dig deeper and move to less concentrated deposits on land and face rising costs. Technology typically offsets some of the increases and the discovery of new resources is another. As cost mount, at some point the shift to a once higher cost frontier area will commence. Figure 10 shows the beginning of this transition. Suppose S_c represents the conventional terrestrial supply of minerals with P_f the lowest price at which some frontier area resources can compete. Add the frontier area supply curve (S_f) to the conventional supply to get the total supply.

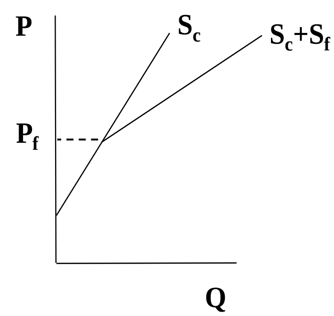


Figure 10 Total Mineral Supply From Conventional and Frontier Area

As the price rises the frontier share increases. With depletion, the conventional supply curve will decrease, while with technical improvement it will increase. The same changes can also happen to the frontier supply curve. These constitute the primary supply. The total supply would also include the supply of scrap comprised of new scrap left over during goods manufacture and old scrap from goods that have no useful life left.

An earthly frontier source, the ocean, is thought to contain large deposits of minerals. Land minerals have been eroded into the seas and sea water is estimated to contain about 3 % salt (sodium chloride (NaCL)) and 0.5% other solids. We already derive some products from the sea in shallow areas – a small amount of seawater is desalinated for use in desert regions. Salt is derived by evaporating sea water on land, although considerably more salt comes from beds on land deposited by ancient seas. Other minerals we have already derived from the seas include K, Mg, sand, gravel, limestone, gypsum, and diamonds (Craig (2009)). Seabed mining was prominently on the radar in the 1980s and Dick (1985) provides are fairly extensive though now rather dated cost comparison of seabed versus land based mining.

Table 4 Sample Metal Concentrations in the Earth's Crust and Ore Grade

Substance	Average Crustal Abundance (ppm)	Ore grade ppm	Year of ore grade	Sources
Al (Aluminum)	82,000.00	280,000.0	2012	Nelson (2012)
Fe (Iron)	41,000.00	377,000.0	2012	Nelson (2012)
Mg Magnesium)	23,000.00	280,000.0	1972	Phillips and Edwards (1976)
Ti (Titanium)	5,600.00	537,500.0	2012	Nelson (2012)
Mn (Manganese)	950.00	300,000.0	1972	Phillips and Edwards, p 168
Cr (Chromium)	100.00	432,000.0	2012	Nelson (2012)
Ni (Nickel)	80.00	25,000.0	2008	British Geological Survey (2008)
Zn (Zinc)	75.00	24,600.0	2012	Nelson (2012)
Ag (Silver)	70.00	80.0	2012	Nelson (2012)
Cu (Copper)	50.00	8,700.0	2012	Nelson (2012)
Hg (Mercury)	50.00	3,200.0	1972	Phillips and Edwards, p 168
Co (Cobalt)	20.00	1,000.0	2012	Cobalt Institute (2020)
Nb(Niobium)	20.00	3,600.0	1972	Phillips and Edwards, p 168
Pb (Zinc)	14.00	59,000.0	1972	Phillips and Edwards, p 168
U (Uranium)	2.40	1,200.0	2012	Nelson (2012)
Sn (Tin)	2.20	8,600.0	1972	Phillips and Edwards, p 168
Mo (Molybdenum)	1.50	2,100.0	1972	Phillips and Edwards, p 168
Au (Gold)	1.10	9.0	2012	Nelson (2012)
Au (open pit)	1.10	2.5	2019	Lioudis (2020)
Pt (Platinum)	1.00	3.0	2012	Nelson (2012)
W (Tungsten)	1.00	3,100.0	1972	Phillips and Edwards, p 168
Sb (Antimony)	0.20	68,000.0	1972	Phillips and Edwards, p 168
Cd (Cadmium)	0.11	150.0	1972	Phillips and Edwards, p 168
PGM	0.005	10.0	2017	Zientek, Loferski, Parks, Schulte, and Seal (2017)
REE	146	1150	2017	Van Gosen, Verplanck, Seal, Long, and Gambogi (2017)

Notes: Ore grades vary considerably across deposits. The above examples are not necessarily representative of all ore grade values. Where ranges were given I have taken the average.

Hein, Mizell, Koschinsky, and Conrad (2013) consider those minerals that are needed for new technologies and suggest that ferro-manganese crust and ferro-manganese nodules in the Pacific Ocean may be very rich in critical mineral resources including Co, Te, Mo, Bi, Pt, W, Zr, Nb, Y, REE's, Ni, Cu, and Li, and they develop some reserve estimates for them. We have found no cases of commercial ocean mining operations for these deposits yet started but there have been some excavations with robotic vehicles and 29 mining claims have been recognized by the International Seabed Authority as of 2018 (Letman (2018)).

Space mining to supply the Earth with minerals is another possibility that has been getting a fair amount of press recently, but is likely not ready for prime time yet (I provide some support documentation for their computations in this paper. Further support on aspects of space mining can be found in Dahl (2020b).

Geopolitical and Market Structure Risk. In addition to the geologic supply risks, which don't yet seem so binding, there are geopolitical risks when major supplying countries are unstable, not particularly bound to the rule of law, or are inclined to withhold supplies for economic or political reasons. These may create short term problems that can persist for some time as it may take 2-8 years to prospect and explore for new deposits and 4-12 years to develop them (Super Fund Research Program (2017)).

Figure 11 is a map showing world governance index rankings by country. These rankings indicate the quality of a countries government or its ability to govern. The index is based on six criteria: "Voice and Accountability, Political Stability and Absence of Violence, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption. As country colors move from yellows to orange to red, they are getting progressively riskier with poorer governance, while greens going from light to dark are considered progressively safer with better governance. You can see the latest world governance indices at World Bank (2020).

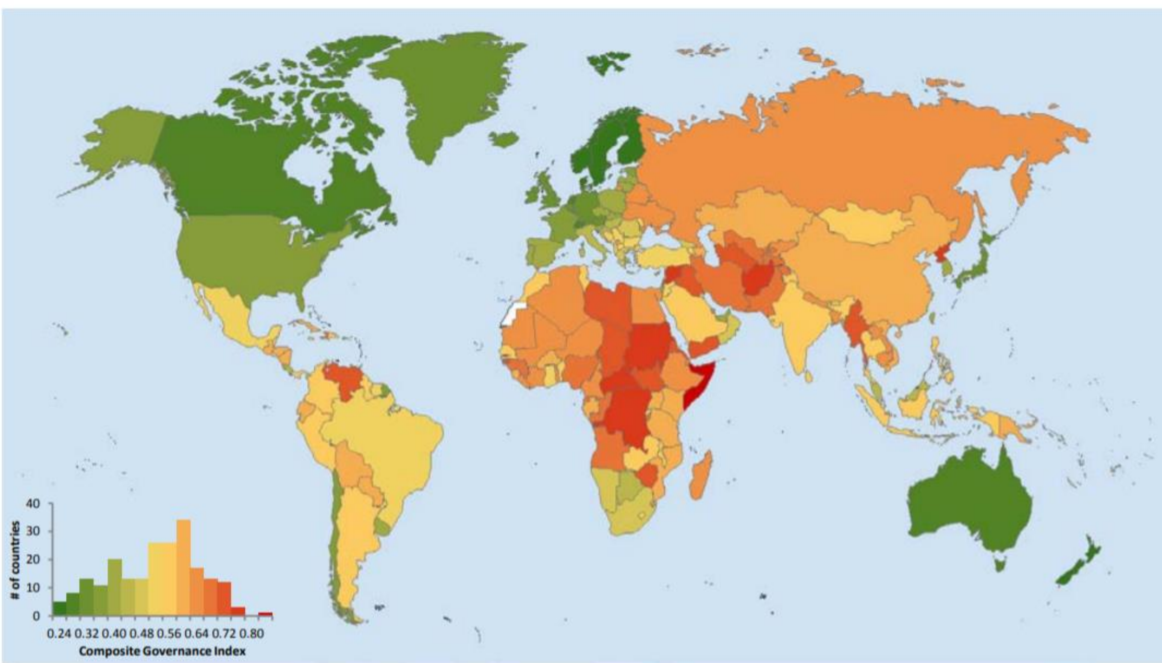


Figure 11. Governance Indices by Country with Darkest Green Indicating the Best Governed and Red Indicating the Worst Governed
Source: National Science and Technology Council (NSTC) (2016), p 9.

Figure 12 from the British Geological Survey shows what a powerhouse the Chinese have become in international mineral markets. It shows the number of elements on their 2015 list of studied minerals (British Geological Survey (BGS) (2015)) for which the indicated country is the largest producer. Of the 41 minerals studied, China is the number one producer of 23 of them. Australia and

S. Africa trail with 3 and 2 each. China is also the number 1 producer of 7 of the 14 critical minerals or groups we have identified in Table 3 (REE, Sb, Ge, V, Ga, W, In). (You can see the number 2 and 3 producer as well as the top 3 reserve holders and a measure of supply risk for the elements in Royal Society of Chemistry (2019) by clicking on the element and the topic supply risk.) The importance of China as a global producer coupled with the perception of shakier governance contributes to these element's membership on the critical list. (China's composite governance index is 0.57 on a scale of 0-1 with 0 the best and 1 the worst (National Science and Technology Council (NSTC) (2016), p 31). You can see the rankings of China's six components of governance at World Bank Group (2017).

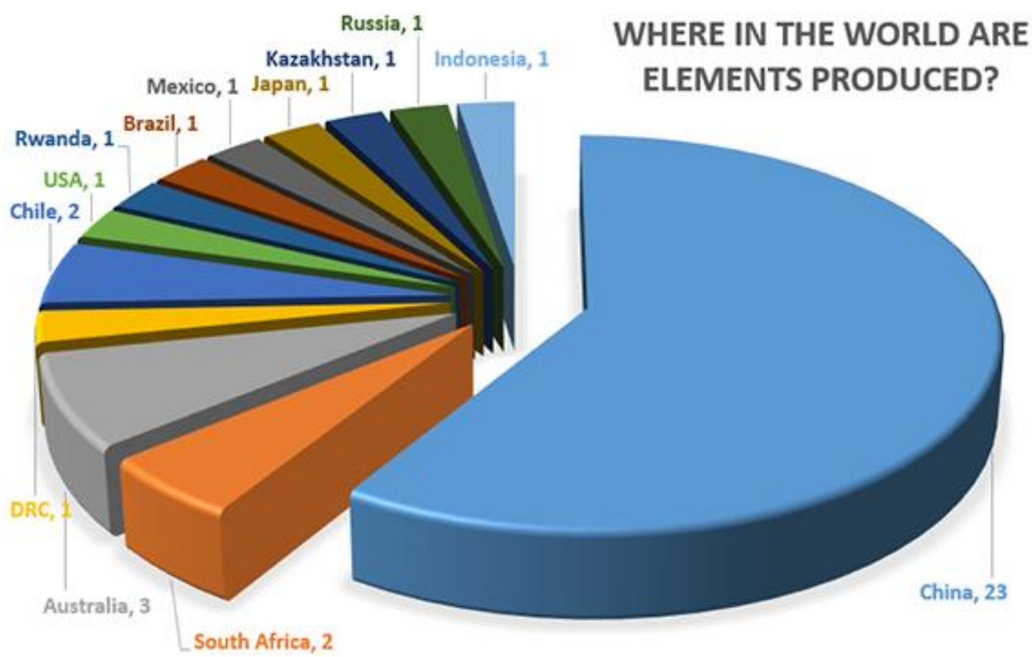


Figure 12 Number of Times a Country Is Largest Producer of an Economically Valuable Element or Group for the U.K.
Source: British Geological Survey (BGS) (2015), Figure 1.

Besides the 7 elements with China as top producer, all the other elements in Table 3 are also included in the BGS ranking. The number 1 producer by element, country and governance rank for the other 7 elements or groups in Table 3 are: (Co, Democratic Republic of Congo, 0.72), (PGM, Ta, Li, South Africa, 0.47), (Re, Chile, 0.33), (Ni, Brazil, 0.5), and (Be, U.S, 0.32).

If the number one supplier is insecure, but the market is well diversified with the largest only a small share, supply may still be relatively safe. A way of measuring how diversified a market is Herfindahl–Hirschman Index of concentration (HHI):

$$HHI = \sum_{i=1}^{n} \alpha^2$$

where α_i is the ith players' percent of the market.

If one player produced all the mineral, its market share is 100% with HHI = 100^2 = 10,000. If n identical players each produced the same amount of the mineral, the market share is 100(1/n) with HHI=n*$(100/n)^2$= 10000/n. This HHI can be market share by country or by company. If measured by country it is often considered a measure of political vulnerability if the HHI is high and concentrated in politically unstable or poorly governed countries.

Figure 13 shows the HHI by country for the mining of 29 non-fuel minerals. Most of the 14 elements or groups in Table 3 have country HHI>3300 (more concentrated than three countries each producing 1/3 of the total supply). All of the platinum group but Os are listed separately. The rare earth group comes in at about 7000, while the one rare earth listed separately (Y mostly produced by China) comes in at more than 9500).

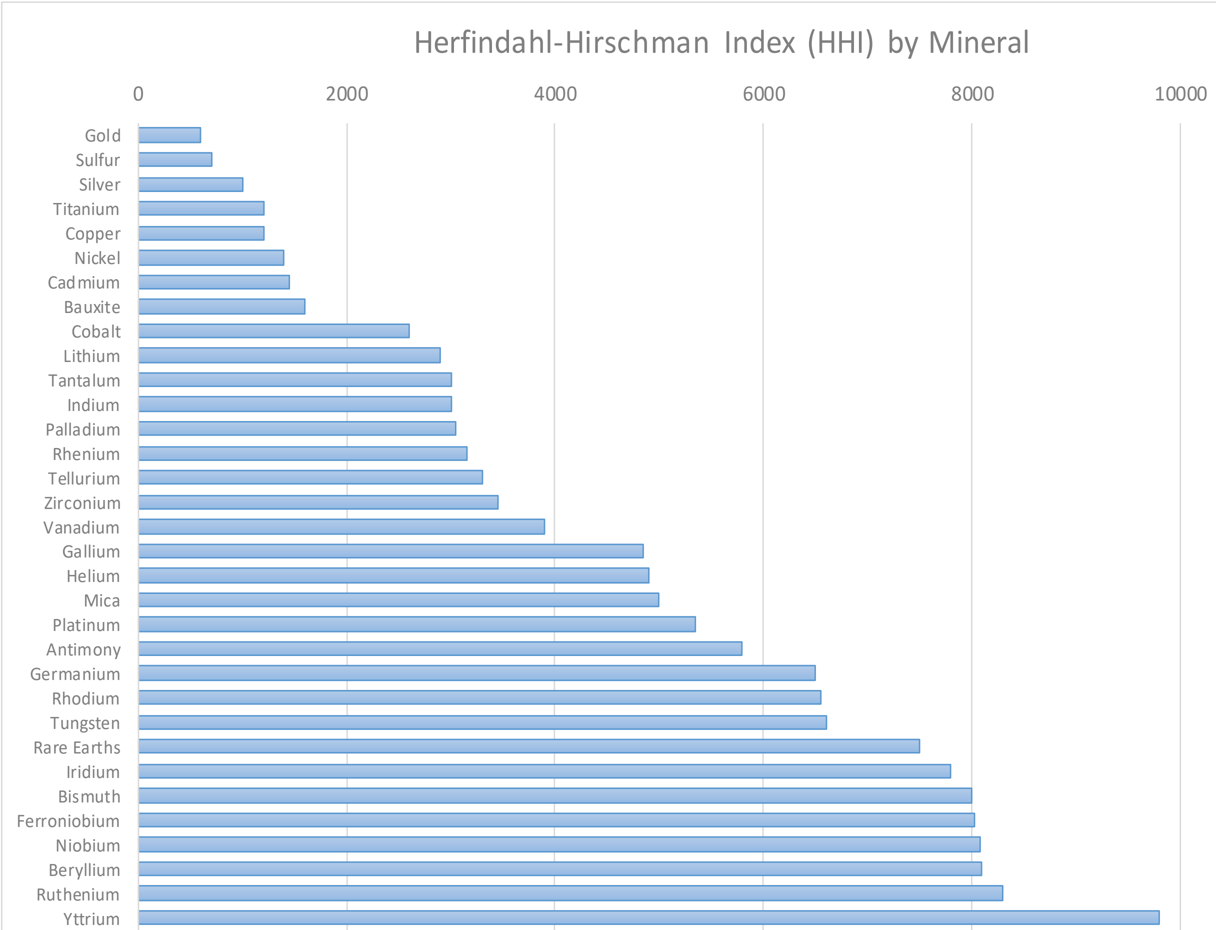


Figure 13 Country Level HHI for Mining of 29 Non-fuel Minerals
Source: National Science and Technology Council (NSTC) (2016), figure 3, with additional information for 4 minerals from U. S. Geological Survey (2015) for Indium, U. S. Geological Survey (2016b) for Vandium, U. S. Geological Survey (2016a) for Lithium, U. S. Geological Survey (2018) for Tungsten.

Although a country may dominate the market, if there are multiple firms in the country and the country is stable, the market may still be relatively competitive and secure. Alternatively, large multinational firms that operate in multiple countries may develop market dominance. With such market power they can restrict supplies to raise world prices. Tilton and Guzmán (2016)have computed 4 firm concentration ratios (C4=the percent of global production by the 4 largest firms) for 24 mineral elements with C4s that range from 15.7% to 91.4%. Almost all of these minerals were considered in at least one of the studies summarized by Hayes and McCullough (2018) and six are included in our critical mineral list in Table 4. Three are in PGM –Pd: C4=69.1%, Pt: C4=91.4%, and Rh: C4=88.1%. The other three are Co: C4=38.2%, Li: C4=87%, and Ni: C4=98.9%. Investopedia suggests a five firm concentration ratio greater than 60% signifies an oligopoly (or a few firms with some market power) (Kenton (2019)). We truncate this rule for our C4 indices to flag as suspicious industries with C4 > 50%. For our critical minerals that overlap from Table 4, we find that all but cobalt exceed this 50% by a large margin. However, the majority of the minerals (14 out of the 25 minerals or groups) have C4<50%.

We can also consider HHI measured by companies. Such HHIs are also indicative of how much market power companies might exert. U.S. Department of Justice and the Federal Trade Commission (2010) guidelines suggest that markets with HHI < 1500 (roughly equivalent to 7 equal sized firms are relative unconcentrated. They would consider 19 of the minerals categories in Table 5 as unconcentrated. Their intermediate level of concentrations is for HHI between 1500 and 2500 (roughly equivalent to 5 to 7 equal sized firms). Lithium, palladium, and the PGM fall in this category. At HHI>2500 (equivalent to 4 or less equal sized firms), the market is considered to be concentrated for only platinum, rhodium, and nickel.

Table 5 Four-firm Concentration Indices (C4), HHI, and Largest Producing Country for 25 Mineral Industries, 2013

Bauxite (Australia)	**Market share (%), C4, HHI**	**Lead (China)**	**Market share (%), C4, HHI**
Alcoa	18.1	Glencore Xstrata	5.5
Rio Tinto (Alcan)	16.7	BHP Billiton	4.2
US Rusal	8.6	Doe Run Company	3.5
BHP Billiton	7.4	Volcan Compania Minera	2.6
C4	50.9	C4	15.7
HHI	750	HHI	100
Copper (Chile)		**Manganese (China)**	
Freeport-McMoRan	10.2	BHP Billiton	20.0
Codeleco	9.8	Eramet	8.7
Glencore Xstrata	8.2	Consmin	8.1
BHP Billiton	6.3	Yale	5.6
C4	34.5	C4	42.4
HHI	350	HHI	600
Gold (China)		**Molybdenum (China)**	
Barrick	7.5	Freeport-McMoRan	17.4
Newmont	5.7	Codelco	8.5
Anglo American	4.3	Grupo Mexico	7.4
Gold corp	2.8	China Molybdenum	5.7
C4	20.2	C4	39.0
HHI	200	HHI	500
Paladium (S. Africa)		**Tin (China)**	
Norilsk Nickel	36.0	Yunnan Tin Group	
Anglo American	18.6	Glencore Xstrata	
Impala Platinum	11.5	PTTimah	7.2
StilwaterPalladium	3.0	Minsur	7.0
C4	69.1	C4	44.3
HHI	1800	HHI	700
Iron Ore (China)		**Nickel (Indonesia)**	
Vale	22.8	Norilsk Nickel	12.8
Rio Tinto	16.8	Vale	12.0

BHP Billiton	10.7	Glencore Xstrata	10.2
Fortescue Metals Group	5.1	BHP Billiton	6.9
C4	55.5	C4	41.9
HHI	995	HHI	550
Platinum (S. Africa)		**Titanium (Canada)**	
Anglo American	40.4	Rio Tinto	25.7
Impala Platinum	27.6	Tronox	12.0
Lon min	12.1	Sierra Rutile	3.2
Norilsk Nickel	11.3	Iluka Resources	2.9
C4	91.4	C4	43.8
HHI	2650	HHI	800
Rhodium (S. Africa)		**Uranium (Kazakhstan)**	
Anglo American	41.6	KazAtomProm	15.8
Impala Platinum	24.9	Cameco	15.4
Lonmin	11.5	Areva	14.8
Norilsk Nickel	10.2	ARMZ- Uranium one	13.7
C4	88.1	C4	59.8
HHI	2600	HHI	1100
Silver (Mexico)		**Zinc (China)**	
Peiloles	5.7	Glencore Xstrata	10.4
KGHM	4.5	Vedanta Resources	6.3
Glencore Xstrata	4.3	Teck Cominco	4.6
BHP Billiton	4.1	Minmetals	4.3
C4	18.5	C4	26
HHI	150	HHI	250
Cobalt (Democratic Republic of Congo)		**Zirconium (Australia)**	
Glencore Xstrata	20.8	Iluka Resources	26.0
Freeport-McMoRan	9.4	Rio Tinto	19.0
Gecamines	5.0	Tronox	14.0
Vale	2.9	Cristal	6.0
C4	38.2	C4	65.0
HHI	550	HHI	1300
Iodine (Chile)		**Chrome (S. Africa)**	
SQM	31.5	State of Kazakhstan	17.3
Cosayach	11.9	Tata Iron & Steel	7.7
ACF Minera	7.9	Glencore Xstrata	4.8
Bullmine	5.1	International Minerals Resources	2.7
C4	56.4	C4	32.5
HHI	1250	HHI	400
Diamonds (2012) (Russia)		**Lithium (Australia)**	
Alrosa	26.9	Talison	36.0
Anglo American(De Beers)	22.0	SQM	26.0
Rio Tin to	10.0	Rockwood Lithium	15.0

BHP Billiton	1.0	FMC Lithium	10.0
C4	59.9	C4	87.0
HHI	1300	HHI	2300
Potash (Canada)		**Niobium (2012) (Brazil)**	
Potash Corp.	19.0	CBMM	80.0
Uralkali	18.0	Anglo American	6.7
Mosaic	16.0	lamgold	6.4
Belaruskali	14.0	Grupo Parana-Panema	5.7
C4	67.0	C4	98.9
HHI	1350	HHI	6500
Platinum Group Metals (2015) (S. Africa)			
Anglo Platinum	31.0		
Norilsk Nickel	26.0		
Impala Platinum	16.0		
Lonmin	9.0		
C4	67.0		
HHI	2039		

Source: Tilton and Guzman (2016), Table 7.1 and HHI estimated from Figure 7.3, # from Ndlovu (2015), largest producing country from Royal Society of Chemistry (2019).

Notes: C4 is share of the largest 4 firms. HHI is the Herfindahl-Hirschman Index

Since many metals come packaged together by nature, some are produced as by-products. For example, silver, gold, tellurium, selenium, and cobalt may be byproducts of much larger copper production Graedel (2016). By product production may then be more dependent on economic drivers in the copper market than in their own market and can add to the criticality of the metal. Nassar, Graedel, and Harper (2015) study metals and measure the degree to which they are produced as companion metals as shown in figure 14. For which metals are companions, see also their figure 2.

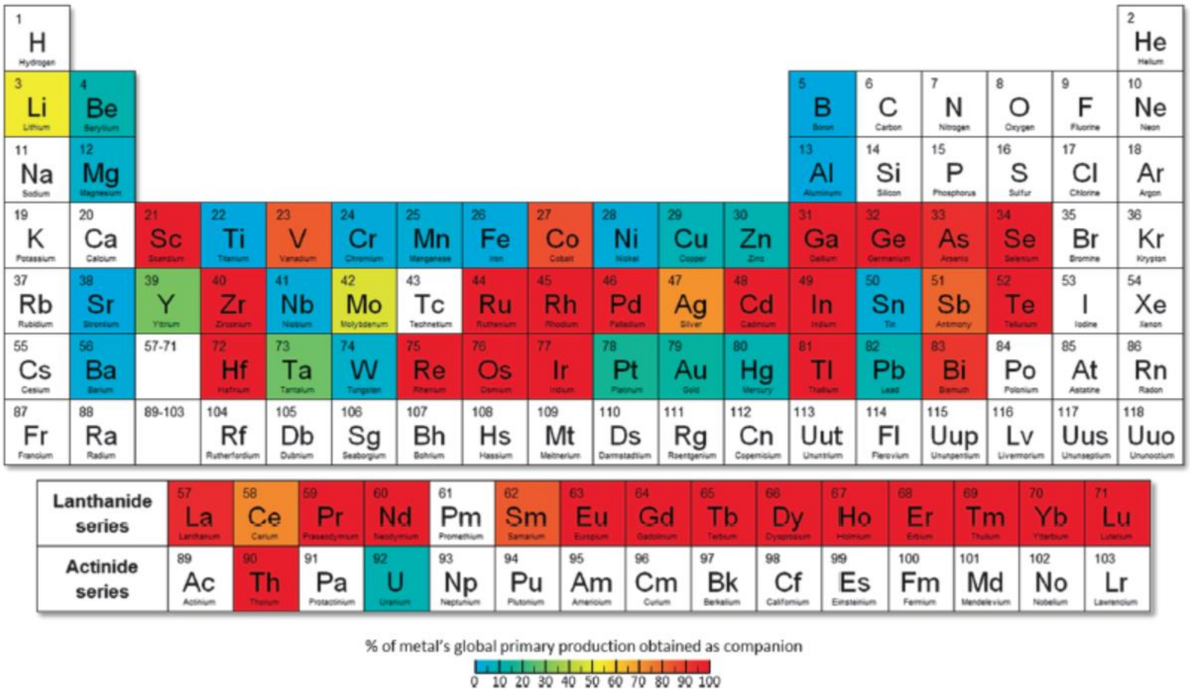


Figure 14 Percent of metal produced as a byproduct

Source: Nassar, Graedel, and Harper (2015), figure 1.

If a metal is a by-product of producing another more economically important mineral, its market may be unstable as its production may respond more to the economic conditions in the dominant market. For example, high prices in a tight byproduct market couple with low prices in the dominant market may not elicit the desired increased byproduct output.

Resource pressures can be reduced by the recycling of metals. The scrap from recycling end of life products is called old scrap, whereas scrap that is produced and recycled during the production process is called new scrap. The accuracy of scrap statistics is somewhat questionable, especially for new scrap. Also the definitions of rates may vary depending on whether old and new scrap are included and whether it is the rate for production or consumption of the metal. With these caveats, we present the results of our literature search in table 6. I have found sample rates for 25 metals or metal groups for the U.S. and/or the World so far. Twelve were not found critical but I include them for comparison purposes. For my critical minerals, I have not yet found any sample recycle rates for the U.S. or the World for indium (In), antimony (Sb), and rhenium (Re). For the seven cases where I have found estimates for both the U.S. and the World, the U.S. rate is most often higher and on average is about twice as high. Not unexpectedly, the average recycling rate is about a third higher for critical than non-critical minerals for the U.S., but is surprisingly similar for the World. Lithium and rare earth metals, that are much in the news relating to new energy technologies, have very low rates of recycling. Hopefully that will change as the stock of end of life scrap gets larger and their recycling technologies improve.

Table 6: Estimates of recycle rates by metal or metal groups

	U.S. metal production from recycled		Global metal production from recycled		
Metals	Year	%	Year	%	Source:
Aluminum	2016	50	2015	21	Bureau of International Recycling (2019)
Beryllium	2016	20			U.S. Geological Survey (2018)
Chromium	2016	34			U.S. Geological Survey (2019b)
Cobalt	2018	29			U.S. Geological Survey (2019c)
Copper	2016	33	2015	40	Bureau of International Recycling (2019)
Gallium	2018	low			U.S. Geological Survey (2019d)
Germanium			2018	30	U.S. Geological Survey (2019e)
Gold	2018	66			U.S. Geological Survey (2019f)
Iron and steel	2016	52			U.S. Geological Survey (2019g)
Lead	2016	67	~2015	50	Bureau of International Recycling (2019)
Lithium			2018	3	Nikolewski (2018)
Magnesium	2016	54	2017	7	Recycling Today Staff (2017)
Molybdenum	2018	30			U.S. Geological Survey (2019h)
Nickel	2018	52			U.S. Geological Survey (2019i)
Niobium	2018	20			U.S. Geological Survey (2019j)
Palladium			2018	30	Cowley (2018)
Platinum			2018	26	Cowley (2018)
REE			2018	1	Jowitt, Werner, Weng, and Mudd (2018)
Rhodium			2018	32	Cowley (2018)
Tin	2016	27	2015	14.3	Bureau of International Recycling (2018)
Tantalum	2018	10			U.S. Geological Survey (2019k)
Steel	2016	69	2016	36	U.S. Geological Survey (2019a)
Tungsten			2018	28	Asian Metal (2020)
Vanadium in catalysts	2018	40			U.S. Geological Survey (2019l)
Zinc	2018	17	2015	30	U.S. Geological Survey (2019m)

Social License: Increasingly, resource producers are expected to produce profits but are also being held to higher operating standards sometimes referred to as the triple bottom line: profits, environmental stewardship, and social acceptability Slaper and Hall (2011). Given the cyclical nature of mineral industries, they tend to be risky. We expect this will require a higher rate of return to attract capital into these industries. This tendency is suggested in U.S. BEA data. The average of gross surplus divided by sales for 1997 to 2017 is 0.21 for all U.S. industry but is 0.36 for mining and 0.31 for mining without oil and gas U.S. Bureau of Economic Analysis (2020) Another indicator of industry riskiness comes from the CAPM model. In this model, the required return on an asset (r_r) is based on the risk free rate (r_f) on a secure asset such as a ten year government bond plus a risk premium that is higher the riskier the asset. The risk premium in the whole market is the return for the whole market minus the risk free rate (r_m-r_f). The risk premium for an individual asset is assumed to be related to the market premium by $\beta(r_m-r_f)$. If β is greater than 1, the asset is more volatile and risky than the overall market and if it is less than one it is less so. The required rate of return for an asset can be written as

$$r_r=r_f+\beta(r_m-r_f).$$

β can be estimated at particular point in time but a more accurate longer term measure of the required premium is often sought by fitting the above function to historical data. McClure (2019). Damodaran (2020) has a database with βs for a number of industries. In his estimates, he uses the S&P500 returns for his market returns in the U.S. Recent βs for the U.S. industry groups related to raw materials have βs exceeding 1. They are metals and mining with β =1.31, precious metals with β = 1.44, and steel with β =1.61. These do suggest that risk premiums for basic materials are higher than for the S&P500. Going to his new home page, you will find links if you want to check his archives for U.S. historical β's going back to the late 1990s to see how they have changed over time. He also has links to more recent data for other regions including Europe, Japan, and emerging markets.

Next, mining and mineral processing present a host of environmental issues that are often not fully reflected in the pricing, production and consumption of minerals. For example, mineral wastes leaching into our water, failing tailing dams, disruption of surface land, loss of biodiversity, and wind borne mineral dust can leave a legacy of damage (Jain, Cui, and Domen (2016)). Of the more than 1300 Superfund Sites on the National Priority List U. S. Environmental Protection Agency (2020c) more than 100 are hard rock mines and processing facilities that have been abandoned. U. S. Environmental Protection Agency (2020a). Of the 17 sites put on a list for special attention, about a third are related to hard rock mining or ore processing U. S. Environmental Protection Agency (2020b). This may not contribute to short term criticality but may have significant longer term effects, as we may be reducing both stocks of the minerals as well as supporting environmental capital (Diamond (2005)).

Social acceptability refers to a good relationship between a company, its stakeholders, the surrounding community, and the public in general. It has the connotation of being a good neighbor and has come to be called social license to operate (SOL). In the mining industry, it reflects society's willing acceptance of mining companies to extract and process mineral resources. Gehman, Lefsrud, and Fast (2017) define and track the evolution and measurement of the concept and demonstrate its recent increase in importance.

Typically SOL involves more than just complying with regulatory requirements and minimizing operational impacts but requires building trust through means that can include direct two way communication and engagement with stakeholders, adherence to social norm, ethical and fair behavior, and contributing to social capital and infrastructure (Boutilier, Black, and Thomson (2012)). Although modern mining is not so labor intensive, including local content whenever possible has the potential to contribute to more and better stakeholder engagement and in some cases may be a legal requirement of a company's operating license (Korinek and Ramdoo (2017)).

Modeling Supply with Curves or Costs. For economic decision making in mineral markets including forecasting, project evaluation, and policy analysis knowing supplier behavior is essential. In perfectly competitive markets, a top-down approach is to represent this behavior by supply curves, which show how production responds to price changes, economic activity and other variables. These simplifications of reality estimated from historical data can be quite helpful in modeling responsiveness and over the years some studies have used historical data to estimate such curves. The response from such curves are often summarized by the elasticities. For example, the price elasticity of supply is the percentage change in quantity demanded divided by the percentage change in price as show below.

$$\varepsilon_s = \frac{\Delta Q_s}{Q_s} \bigg/ \frac{\Delta P_s}{P_s} = \frac{\Delta Q_s}{\Delta P_s}\frac{P_s}{Q_s}$$

If metals are byproducts of the production of another more important metal, this elasticity may be quite small or could even be zero. A small response to own price can increase the criticality of metals. Nassar, Graedel, and Harper (2015) show such dependence reproduced in Figure 15. The basic source metals are in the center with the joint products further out.

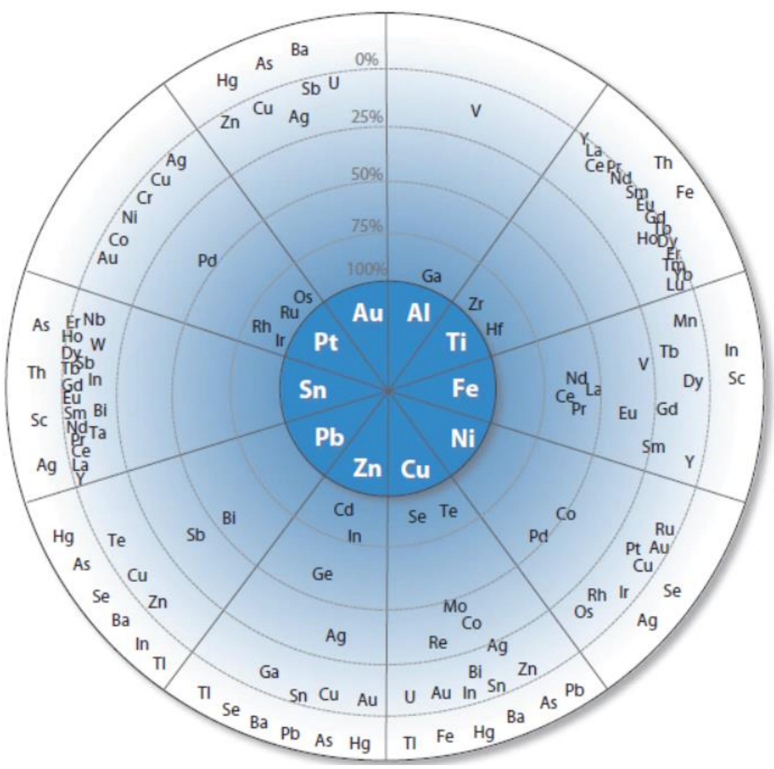
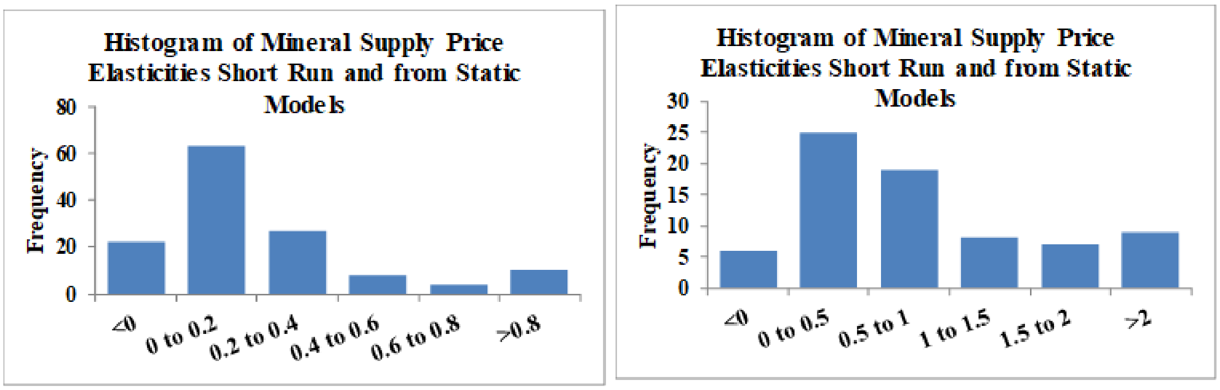


Figure 15 Host metals and their likely by-products.

Source: Nassar, Graedel, and Harper (2015), p. 3.

To get the supply elasticity with respect to any economic variable replace the price and price change in the above equation by the variable and its change. Such elasticities can be computed from estimates of the supply equation or can be used to create such equations around recent data. In an ongoing effort, has identified 36 studies published from 1970 and 2014 and collected 163 separate sets of estimates for supply elasticities. Most of the estimates come from econometrically estimated equations relating to sixteen metals–Uranium, Aluminum, Cobalt, Copper, Gold, Indium, Iron Ore, Lead, Magnesium, Manganese Ore, Mercury, Nickel, Platinum, Tellurium, Tin, Tungsten, and Zinc. The price elasticities from these studies are summarized in figure 15. Elasticities from models with short-run estimates or those from static models have been combined in figure 15, panel a, while long-run elasticities are summarized in figure 15, panel b.



(a) (b)

Figure 15: Mineral Supply Price Elasticities
Source: Dahl (2020a)

Dahl (2020a) provides summaries of all these studies by metal but has not yet ranked and presented the most credible. These summaries are reproduced here in Table 7.

Table 7 Summary of Supply Elasticities by Material from Dahl Mineral Elasticity of Demand and Supply Database

		P sr	**Pstat**	**P lr**	**Y sr**	**Ystat**	**Y lr**	**Qt-1**
aluminum	**average**	**0.359**	**0.403**	**0.962**	**0.835**	**0.910**	**1.529**	**0.479**
studies	median	0.235	0.170	0.580	0.869	0.910	1.348	0.516
#=6	stdev	0.417	0.449	1.061	0.195	–	0.954	0.299
oldest: 1975	minimum	0.050	0.117	0.073	0.570	0.910	0.570	0.005
newest: 2000	maximum	1.190	0.921	3.290	1.030	0.910	2.850	0.806
	count	6	3	8	4	1	4	6
cobalt	**average**	**0.230**	–	**0.395**	–	–	–	**0.560**
studies	median	0.230	–	0.395	–	–	–	0.430
#=2	stdev	0.028	–	0.064	–	–	–	0.279
oldest: 1980	minimum	0.210	–	0.350	–	–	–	0.370
newest: 1985	maximum	0.250	–	0.440	–	–	–	0.880
	count	2	–	3	–	–	–	3
copper	**average**	**0.247**	**0.134**	**1.048**	–	**0.970**	–	**0.754**
studies	median	0.188	0.100	0.719	–	0.930	–	0.795
#=9	stdev	0.241	0.080	0.955	–	0.115	–	0.246
oldest: 1970	minimum	0.007	0.050	0.052	–	0.870	–	0.210

newest: 1990	maximum	1.200	0.254	3.800	–	1.150	–	1.070
	count	25	9	18	–	8	–	21
gold	**average**	**-0.355**	**-0.425**	**0.617**				**0.989**
studies	median	-0.422	-0.400	0.738				0.980
#=3	stdev	0.143	0.222	0.377				0.023
oldest: 1983	minimum	-0.522	-0.700	0.090				0.960
newest: 1999	maximum	-0.140	-0.200	1.049				1.020
	count	11	4	8				9
indium	**average**	**0.066**	**-0.003**	**0.122**	**0.006**	**0.010**	**0.041**	**0.462**
studies	median	0.066	-0.003	0.122	0.006	0.006	0.041	0.462
#=1	stdev	0.014	0.123	0.025		0.018		0.004
oldest: 2014	minimum	0.056	-0.090	0.104	0.006	-0.006	0.041	0.459
newest: 2014	maximum	0.076	0.084	0.140	0.006	0.029	0.041	0.464
	count	2	2	2	1	3	1	2
iron	**average**	**0.203**	**0.382**	**0.539**	**0.746**	**1.140**	**1.446**	**0.481**
studies	median	0.160	0.318	0.422	0.700	1.045	1.298	0.470
#=3	stdev	0.153	0.309	0.455	0.361	0.587	0.613	0.200
oldest: 1979	minimum	0.040	0.040	0.060	0.210	0.180	0.774	0.120
newest: 2011	maximum	0.550	0.885	1.625	1.560	2.190	2.943	0.920
Includes bauxite	count	14	10	13	14	10	14	20
lead	**average**	**0.160**	**0.187**	**0.928**	–	–	–	**0.514**
studies	median	0.169	0.187	0.700	–	–	–	0.752
#=3	stdev	0.054	0.058	0.624	–	–	–	0.521
oldest: 1975	minimum	0.086	0.109	0.470	–	–	–	-0.264
newest: 1995	maximum	0.217	0.271	1.840	–	–	–	0.817
	count	4	5	4	–	–	–	4
manganese ore	**average**	**0.104**	**0.558**	**0.316**	–	–	–	**0.690**
studies	median	0.104	0.558	0.316	–	–	–	0.672
#=6	stdev	–	–	–	–	–	–	0.118
oldest: 1985	minimum	0.104	0.558	0.316	–	–	–	0.582
newest: 1985	maximum	0.104	0.558	0.316	–	–	–	0.817
	count	1	1	1	–	–	–	3
mercury	**average**	**1.000**	–	**3.000**	–	–	–	–
studies	median	1.000	–	3.000	–	–	–	–
#=1	stdev		–		–	–	–	–
oldest: 1974	minimum	1.000	–	3.000	–	–	–	–
newest: 1974	maximum	1.000	–	3.000	–	–	–	–
	count	1	–	1	–	–	–	–
nickel	**average**	**0.718**	–	**2.922**	–	–	–	**0.676**
studies	median	0.750	–	2.015	–	–	–	0.766

#=3	stdev	0.434	–	2.027	–	–	–	0.324
oldest: 1975	minimum	0.133	–	1.200	–	–	–	0.247
newest: 1990	maximum	1.280	–	5.500	–	–	–	0.990
	count	6	–	6	–	–	–	6
tellurium	**average**	**0.016**	–	**0.034**	–	–	–	**0.533**
studies	median	0.016	–	0.034	–	–	–	0.533
#=1	stdev	0.026	–	0.057	–	–	–	0.016
oldest: 2014	minimum	-0.003	–	-0.006	–	–	–	0.521
newest: 2014	maximum	0.034	–	0.075	–	–	–	0.544
	count	2	–	2	–	–	–	2
tin	**average**	**0.400**	–	**1.024**	–	–	–	**0.472**
studies	median	0.300	–	0.910	–	–	–	0.465
#=3	stdev	0.356	–	0.609	–	–	–	0.155
oldest: 1990	minimum	0.032	–	0.180	–	–	–	0.230
newest: 1990	maximum	1.110	–	2.090	–	–	–	0.710
	count	7	–	7	–	–	–	6
tungsten	**average**	**0.122**	–	**0.614**	–	–	–	
studies	median	0.110	–	0.500	–	–	–	
#=2	stdev	0.024	–	0.296	–	–	–	
oldest: 1974	minimum	0.107	–	0.393	–	–	–	
newest: 1977	maximum	0.150	–	0.950	–	–	–	
left out China	count	3	–	3	–	–	–	
uranium	**average**	**0.102**	**0.363**	**2.473**	–	–	–	**0.383**
studies	median	0.102	0.630	0.160	–	–	–	0.304
#=7	stdev	0.034	0.488	4.993	–	–	–	0.297
oldest: 1975	minimum	0.060	-0.200	0.128	–	–	–	0.110
newest: 2011	maximum	0.142	0.660	11.400	–	–	–	0.848
	count	6	3	5	–	–	–	6
zinc	**average**	**0.257**	**0.110**	**0.595**				**0.451**
studies	median	0.181	0.110	0.509				0.408
#=3	stdev	0.191		0.535				0.159
oldest: 1975	minimum	0.085	0.110	0.000				0.248
newest: 1990	maximum	0.642	0.110	1.750				0.744
	count	7	1	8				7
all	**average**	**0.189**	**0.185**	**0.934**	**0.725**	**0.898**	**1.389**	**0.603**
studies	median	0.151	0.129	0.628	0.700	0.920	1.313	0.601
#=36	stdev	0.349	0.329	1.456	0.363	0.521	0.729	0.278
oldest: 1970	minimum	-0.522	-0.700	-0.800	0.006	-0.006	0.041	-0.264
newest: 2014	maximum	1.280	0.921	11.400	1.560	2.190	2.943	1.070
	count	97	41	90	19	24	19	99

Source: Dahl (2020a), Table 1

Notes: # under studies shows the number of studies for the material, while oldest and newest indicate the dates of the oldest and newest studies. Stdev= standard deviation for the elasticities for each material and each elasticity category. Psr indicates short-run price elasticity, Pstat indicates price elasticities from static models, and Plr indicates long-run price elasticities from dynamic models. Ysr, Ystat, and Ylr are similar elasticities for income or activity elasticities. Qt-1 is the coefficient on a lagged endogenous model for those models that estimate dynamics in a model using one lagged endogenous model. Count is the number of elasticity estimates for each material and elasticity category.

A second way of representing supply is to look at mining and processing costs and what they imply about decision making. This bottom up approach requires cost information, which is often proprietary and varies considerably depending on ore grade, infrastructure, distance from market and a host of local conditions. Thus, such data is often hard for an outsider to come by.

Table 8 shows some representative earthly costs for an open pit mine for the mining and processing of ore. These costs can be adjusted to metal costs based on the concentration of metals in the ore by dividing these costs by the percent of metal in the mined ore. Fortunately, I have a colleague more intimately involved in mineral industries with experience in project evaluation, who was able to provide some representative costs (Davis (2019)). These costs are extrapolated and used in the space mining example in Dahl, Gilbert, and Lange (2019). The un-italicized numbers show the actual representative costs for a representative mine, while I computed the italicized values.

I discuss first the cost computations from his actual cost numbers and then my extrapolations for other sized mines. At the top of the table are sample mining costs with actual numbers for averages of 500, 1000, and 2000 tonnes per day or varying from 182,500 tonnes/year (t/y) to 730,000 t/y. The given costs show strong economies of scale. Operating costs fall from \$13 to \$8 per tonne as we quadruple ore processing, while capital costs only double. Levelized costs (LC) are computed assuming that the mine takes 3 years to develop with capital cost (K) spread over the three years of construction in the following shares (0.15, 0.25, 0.6) and the mine produces (X) per year for 20 years and the discount rate is 10% using the following formula:

$$LC = \frac{0.15K + \frac{0.25K}{(1+0.1)} + \frac{0.65K}{(1+0.1)^2}}{\sum_{i=3}^{22} \frac{X}{(1+0.1)^i}}$$

The levelized cost per tonne of ore falls from \$2.72 per ton at 500 t of ore per day(t/d) to \$1.36 at 2000 t/d. To extrapolate the operating and capital costs to other mine sizes, I measure the economies of scale (S_{ij}) in going from production Q_i to Q_j with cost changing from cost C_i to C_j as:

$$S_{ij} = \frac{\ln(C_i / C_j)}{\ln(Q_i / Q_j)}$$

This yields the S_{ij} using for the three actual cost values for operating and capital costs shown in table 7.

Table 7 Economies of scale in mining costs

=S_{ij}=ln(C_i/C_j)/ln(Q_i/Q_j)		
Mining	**i =500 to j = 1000**	**i=2000 to j=1000**
Opex Mining	-0.38	-1.32
Capex Mining	0.61	0.19

Besides the three mine sizes with cost information, I picked one larger size at a million t/y. I also picked two smaller sizes for simulation of asteroid mining in Dahl, Gilbert, and Lange (2019). Given the huge costs of moving things into space these operations might start out quite small. Since I have some starting S_{ij}, C_j, Q_j, and Q_j, I solve for alternate unknown C_i as follows with resulting costs shown in Table 8.

$$S_{ij} = \frac{\ln(C_i / C_j)}{\ln(Q_i / Q_j)} \rightarrow S_{ij} \ln(Q_i / Q_j) = \ln(C_i / C_j) \rightarrow \ln((Q_i / Q_j)^{S_{ij}}) = \ln(C_i / C_j)$$

$$\rightarrow \exp(\ln((Q_i / Q_j)^{S_{ij}})) = \exp(\ln(C_i / C_j)) \rightarrow (Q_i / Q_j)^{S_{ij}}) = C_i / C_j \text{ and } (Q_i / Q_j)^{S_{ij}})C_j = C_i$$

To compute for a Q_h nearest in size to Q_i

$$(Q_h / Q_i)^{S_{ij}})C_i = C_h$$

Table 8 Sample Costs of Mining and Processing on Earth

Mining	**ore**	**ore**	**ore**	**ore**	**ore**	**ore**
t/day ore	*3*	*12*	500	1,000	2,000	*2,740*
t/per year ore	*1,000*	*4,500*	182,500	365,000	730,000	*1,000,000*
OPEX/t (ore)	*$93.29*	*$52.80*	$13.00	$10.00	$4.00	*$2.64*
CAPEX × $$10^6$	*$0.17*	*$0.42*	$4.00	$7.00	$8.00	*$8.50*
CAPEX LC/t ore	*$20.72*	*$11.53*	*$2.72*	*$2.38*	*$1.36*	*$1.05*
Processing	**ore**	**ore**	**o[illegible]**	**o[illegible]**	**o[illegible]**	**ore**
t/day (ore)	*3*	*12*	20	50	100	*2,740*
t/year	*1,000*	*4,500*	7,300	18,250	36,500	*1,000,000*
1 metal						
OPEX/t (ore)	*$619.29*	*$248.24*	$185.00	$106.00	$75.00	*$14.37*
CAPEX × $$10^6$	*$3.37*	*$4.54*	$5.00	$6.00	$10.00	*$114.69*
CAPEX LC/t ore	*$417.78*	*$125.23*	*$85.00*	*$40.80*	*$34.00*	*$14.23*
2 metals						
OPEX/t (ore)	*$685.68*	*$271.97*	$202.00	$115.00	$80.00	*$14.14*
CAPEX × $$10^6$	*$2.49*	*$4.84*	$6.00	$9.00	$13.00	*$75.28*
CAPEX LC/t ore	*$308.95*	*$133.57*	*$102.00*	*$61.20*	*$44.20*	*$9.34*
3 metals						
OPEX/t (ore)	*$819.44*	*$302.98*	$220.00	$120.00	$85.00	*$16.37*
CAPEX × $$10^6$	*$4.01*	*$6.76*	$8.00	$11.00	$16.00	*$95.79*
CAPEX LC/t ore	*$497.51*	*$186.47*	*$136.00*	*$74.80*	*$54.40*	*$11.89*
4 metals						
OPEX/t (ore)	*$872.73*	*$322.68*	*$234.31*	*$127.80*	*$90.53*	*$26.96*
CAPEX × $$10^6$	*$5.06*	*$8.53*	*$10.10*	*$13.88*	*$20.19*	*$136.76*
CAPEX LC/t ore	*$627.91*	*$235.35*	*$171.64*	*$94.40*	*$68.66*	*$16.97*
5 metals						
OPEX/t (ore)	*$929.49*	*$343.67*	*$249.54*	*$136.11*	*$96.41*	*$44.39*
CAPEX × $$10^6$	*$6.39*	*$10.77*	*$12.74*	*$17.52*	*$25.49*	*$195.27*
CAPEX LC/t ore	*$792.49*	*$297.03*	*$216.63*	*$119.15*	*$86.65*	*$24.23*
6 metals						
OPEX/t (ore)	*$989.93*	*$366.01*	*$265.77*	*$144.97*	*$102.68*	*$47.28*
CAPEX × $$10^6$	*$6.80*	*$11.47*	*$13.57*	*$18.66*	*$27.14*	*$207.97*
CAPEX LC/t ore	*$844.03*	*$316.35*	*$230.72*	*$126.89*	*$92.29*	*$25.81*
8 metals						
OPEX/t (ore)	*$1,122.86*	*$415.16*	*$301.46*	*$164.43*	*$116.47*	*$53.63*
CAPEX × $$10^6$	*$10.83*	*$18.27*	*$21.62*	*$29.73*	*$43.24*	*$331.28*
CAPEX LC/t ore	*$1,344.47*	*$503.92*	*$367.51*	*$202.13*	*$147.01*	*$41.11*
10 metals						
OPEX/t (ore)	*$1,273.65*	*$470.92*	*$341.94*	*$186.51*	*$132.11*	*$60.83*
CAPEX × $$10^6$	*$17.26*	*$29.11*	*$34.44*	*$47.35*	*$68.87*	*$527.70*
CAPEX LC/t ore	*$ 2,141.63*	*802.7005527*	*$585.42*	*$321.98*	*$234.17*	*$65.49*

Source: Non-italicized font, Davis (2019). Italicized font author's extrapolations.

Notes: Levelized costs (LC) are computed assuming the mine and processing plant are built in 3 years with spending percent distributed to now, at the end of one year, and at the end of two years:15%, 25%, and 60% at a discount rate of 10%. Operations last 20 years. To get cost per tonne of metal divide costs by metal per tonne of ore.

Next, consider the cost of milling the ore. Mills tend to operate at smaller scale than mines, have higher tonnage costs, but also have large economies of scale. For actual operating cost and processing for one metal scaling up from 20 to 100 tonnes per day, operating costs fall from $185 per tonne of ore to $75, while levelized capital costs fall from $85 to $34 per tonne. I use the same procedure as for mining to compute the levelized milling cost and to extrapolate the costs to other sized operations. Unit costs fall considerably as I scale up but increase for each additional metal separated out. Using the sample milling cost and economies of scale elasticities for up to three metals, I compute possible milling costs. Going from extracting 2 to extracting 3 metals raised operating costs by 7% and capital costs by 26% in the sample data. I used these percentages per metal added to increase the costs and add metals up to 10 metals, I show some of these costs below mining costs in Table 8. If all ten metals are separated out in a mill processing 20 t/d, the operating and levelized cost per unit of ore for milling is about $341.94 + $585.42 per tonne. With these costs falling to less than half these amounts for a 100 tonne a day mill. Once the ore has been milled to concentrate the metal, the final process to get almost pure metal is smelting. According to Davis (2019) smelters typically charge 10% of the sales revenue for the purified metal.

Mineral Demand Elasticities. In addition to supply side determinants in the market, buyer responsiveness is also highly important to mineral criticality and the evolution of its use. As with supply, we can measure such responsiveness of metal purchases to economic variable as elasticities. For example, the price elasticity of demand is percentage change in quantity demanded divided by percentage change in price as show below.

$$\varepsilon_d = \frac{\Delta Q_d}{Q_d} \Big/ \frac{\Delta P_d}{P_d} \rightarrow \frac{\Delta P_d}{P_d} = \varepsilon_d \frac{\Delta Q_d}{Q_d}$$

We can use this elasticity to compute what happens to purchases from a change in the mineral price or we can use the rearranged form above to see what happens to price for a change in quantity put into or taken out of the market. Substituting $\frac{\Delta Y}{Y}$ for $\frac{\Delta P_d}{P_d}$ (with Y equal to income or some economic activity) and rearranging indicates how mineral consumption will evolve as economic activity changes across time.

The more substitutes for a metal, the more flexible or more price elastic demand is likely to be. Demand is also likely to be influenced by the price of the substitute (P_s).

Graedel, Harper, Nassar, and Reck (2015) provide information on substitutability for 62 metals in figure 16 below. The shaded boxes in their periodical table are metals that have been studied with substitutability scaled from 0 to 100, with 0 having the best substitutes and 100 having no suitable substitutes.

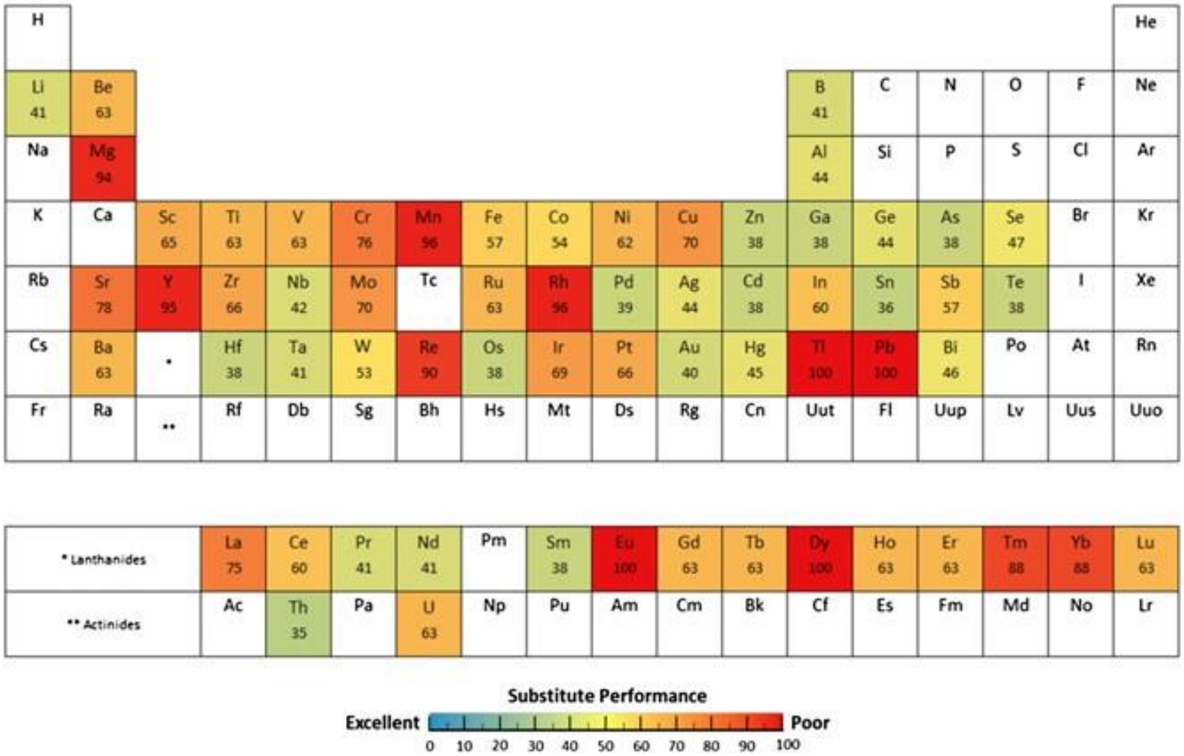


Figure 16 Measures of metal substitutability
Source: Graedel, Harper, Nassar, and Reck (2015), figure 5.

Notes: 0 indicates best substitutability and 100 indicates no substitutability.

The slower demand growth and the more responsive demand is to price the less likely a mineral is to be critical. These characteristics are reflected in price, activity, and cross price elasticities. Again we can represent this substitutability by substituting the percentage change in the substitute price for the mineral's own price $\left(\frac{\Delta P_{sub}}{P_{sub}} \text{ for } \frac{\Delta P_d}{P_d}\right)$.

In Dahl (2020a), I have identified fifty six studies and catalogued more than 1300 sets of demand elasticities for 29 categories of metals or materials– aluminum, chromium, cobalt, copper, gold, heavy rare earth elements, indium, iron, lead, light rare earth elements, lithium, magnesium, manganese, mercury, nickel, niobium, palladium, plastic, platinum, rare earth elements, silver, steel, tellurium, tin, titanium, tungsten, uranium, vanadium, and zinc. The studies were conducted over the years from 1975 to 2020. Since the studies have not yet been vetted with most favored studies and estimates chosen, my histograms present all the elasticity estimates in each elasticity category. The elasticities are divided into those that come from dynamic models and yield both long and short-run elasticities in panels (a) and (c) and those that come from static models in panel (b).

For the short-run, there are more than 500 elasticity estimates shown in figure 17 panel a. They vary across mineral, time, location, and methodology. About a third have a positive price elasticity suggesting no price response with a one tailed test. Although the range of negative elasticities is wide with the most elastic -1.76, the bulk of the rest lie between 0 and -0.2. Since the outliers, which can have a large effect on averages, have not been vetted yet, I report medians and averages in all categories. The median is -0.03 with the average about twice as elastic. Setting all positive elasticities equal to zero raises the average to -0.10.

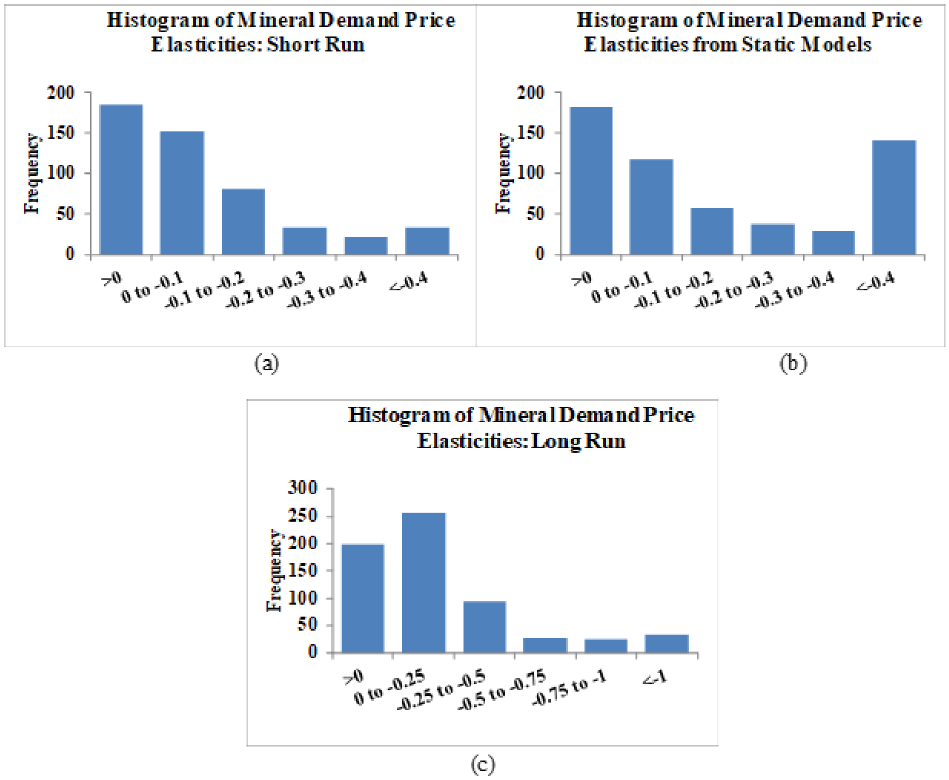


Figure 17: Histogram of price elasticities from 56 mineral demand studies
Source: Dahl (2020a).

There are more than 550 price elasticity estimates from static models. Again about a third are positive. For the remaining negative elasticities, the range is wide with the most elastic response being -5.4 but most cluster more reassuringly between 0 and -0.5. The median of all estimates is -0.08 and the average is-0.20. Setting all positive elasticities to zero changes the average to -0.26.

As authors do not always report the corresponding short-run elasticities, there are about 25% more long-run than short-run elasticities. About 30 % are positive. For the remaining negative elasticities, the range is wide with the most elastic response being an exciting -21.81 but most cluster between 0 and -2. The median of all estimates is -0.11 and the average is -0.20. Setting all positive elasticities to zero changes the average to -0.27. The most extreme negative values (less than -3) come from econometric models with distributed lags on price from three to six years.

Many of the demand studies report income or activity elasticities. This variable is most often GDP or per capita GDP depending on the model specification but in some cases it is industrial production, manufacturing or some manufactured product using the metal in question, such as automobiles or jet engines, is used. Fer17 uses the total consumption of the seven metals so her elasticities show how a metal grows relative to all her chosen metals rather than to income.

There are more than 700 estimates of short-run activity elasticity. The histogram of these elasticities is in figure 18, panel a. About 15% are negative but most of these are not significantly negative. It is conceivable that closer scrutiny may reveal some of these negative elasticities reflect reality. For example, almost half of them are for either lead or tin. The almost universal phase out of lead tetraethyl in gasoline should have had seriously reduced lead consumption while aluminum and plastic have made serious encroachments on the tin can market. For the positive elasticities, the range is extreme with the largest elasticity of 16.198 but most cluster from 0 to 2. All the extremely positive income elasticities (>3) are from estimates on lagged endogenous models with other suspicious results. The price elasticities are positive and/or the coefficient on the lagged endogenous model is close to 0 or negative. The median elasticity is 0.6 and the average is 0.803.

There are almost 350 activity estimates on static models. The histogram of their values is shown in figure 18, panel b. Only four are negative. None find negative elasticities for lead or tin. As usual the range on positive elasticities is wide with the most elastic response at 15.7 but most cluster between 0.5 and 1.5.

There are more than 550 long-run activity elasticities. The histogram of their values is shown in figure 18, panel c. Since negative short-run values usually match up with negative long-run values and extreme short-run values match up with extreme long-run values, the comments made above for the short-run, hold here as well. Most of the elasticities cluster between 0 and 2.

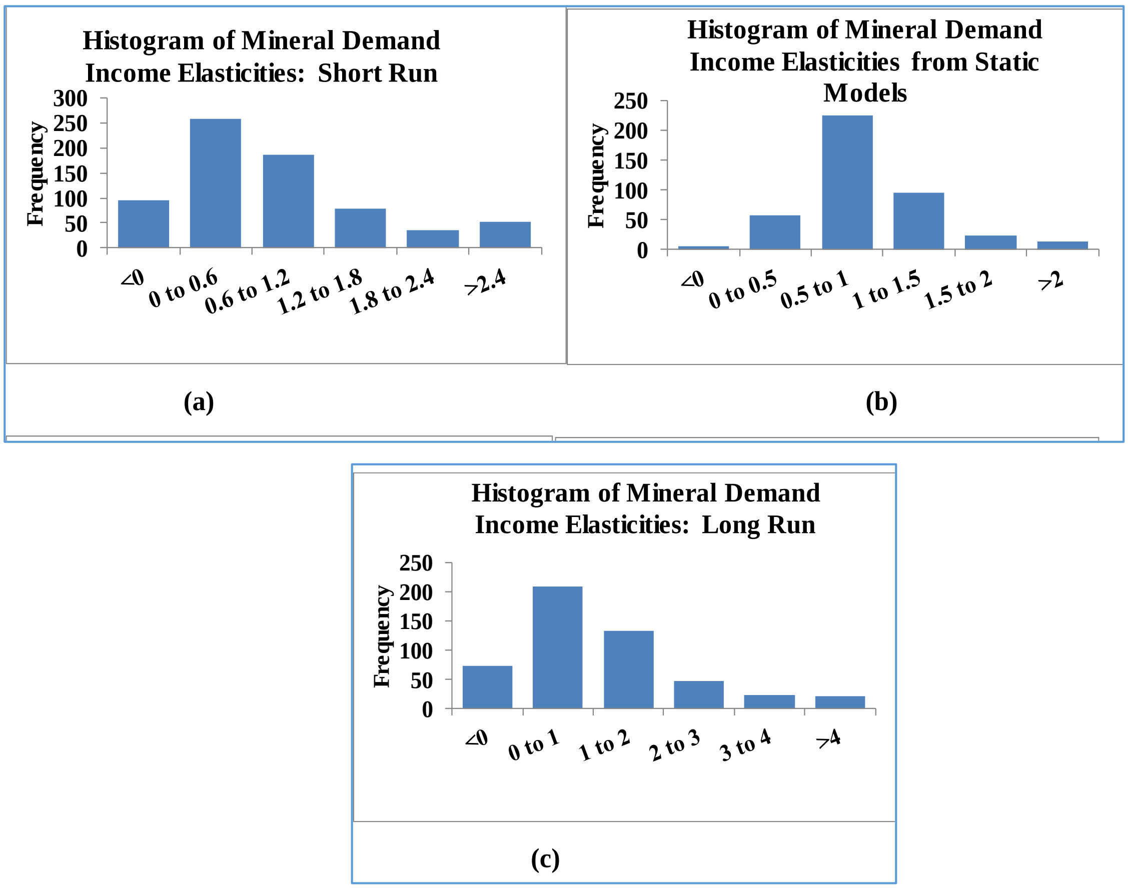


Figure 18: Histogram of income elasticities from 56 mineral demand studies
Source: Dahl (2020a).

She also shows some summary statistics by material group as reproduced in Table 9.

Table 9 Summary of Demand Elasticities by Material from Dahl Mineral Elasticity of Demand and Supply Database

aluminum	**average**	**-0.087**	**-0.120**	**-0.123**	**1.167**	**0.780**	**1.610**	**0.178**
studies	median	-0.047	-0.032	-0.121	0.842	0.815	1.396	0.138
#=15	stdev	0.359	0.322	0.761	1.236	0.301	1.195	0.361

oldest: 1971	minimum	-1.760	-0.856	-2.135	-2.011	0.159	-2.005	-0.787
newest: 2020	maximum	1.133	0.507	6.020	7.681	1.720	6.332	0.948
	count	78	73	94	114	30	92	68
chromium	**average**		**-2.622**			**10.337**		
studies	median		-2.622			10.337		
#=2	stdev		3.567					
oldest: 1984	minimum		-5.144			10.337		
newest: 2002	maximum		-0.100			10.337		
	count		2			1		
cobalt	**average**	**-0.165**	**-0.601**	**-1.734**	**0.937**	**1.598**	**1.513**	**0.381**
studies	median	-0.070	-0.590	-0.542	0.937	1.040	1.513	0.381
#=5	stdev	0.274	0.228	4.443		2.738		
oldest: 1971	minimum	-1.375	-0.920	-21.810	0.937	0.280	1.513	0.381
newest: 1984	maximum	-0.012	-0.200	0.134	0.937	15.697	1.513	0.381
	count	26	8	24	1	30	1	1
copper	**average**	**-0.029**	**-0.138**	**-0.135**	**0.701**	**0.712**	**0.900**	**0.273**
studies	median	-0.014	-0.083	-0.146	0.508	0.769	1.046	0.275
#=20	stdev	0.330	0.341	0.580	1.131	0.282	1.871	0.374
oldest: 1970	minimum	-1.410	-0.863	-2.880	-3.198	0.124	-8.825	-0.516
newest: 2020	maximum	1.257	1.610	2.061	7.648	1.720	13.232	0.968
	count	85	89	126	116	46	116	75
gold	**average**		**-0.413**			**1.042**		
studies	median		-0.600			1.042		
#=2	stdev		1.520					
oldest: 1986	minimum		-2.500			1.042		
newest: 2002	maximum		2.500			1.042		
	count		9			1		
indium	**average**		**-0.151**			**2.618**		
studies	median		-0.151			2.618		
#=1	stdev		0.149			0.881		
oldest: 2014	minimum		-0.256			1.995		
newest: 2014	maximum		-0.045			3.241		
	count		2			2		
iron	**average**	**-0.184**	**-0.186**	**-0.247**	**0.761**	**1.117**	**1.088**	**0.304**
studies	median	-0.145	-0.070	-0.214	0.770	1.030	1.021	0.280
#=3	stdev	0.180	0.299	0.262	0.325	0.377	0.402	0.195
oldest: 1987	minimum	-0.640	-0.856	-0.901	0.300	0.540	0.685	-0.100
newest: 2011	maximum	-0.040	-0.030	0.000	1.330	1.720	2.078	0.630
	count	10	7	11	11	9	11	11
lead	**average**	**0.008**	**-0.163**	**-0.009**	**0.538**	**0.611**	**0.777**	**0.402**
studies	median	0.019	-0.054	0.015	0.352	0.674	0.537	0.418

#=8	stdev	0.183	0.340	0.261	0.730	0.383	1.164	0.347
oldest: 1996	minimum	-0.888	-0.856	-1.281	-0.839	0.070	-2.640	-0.537
newest: 2020	maximum	0.438	0.621	0.702	3.740	1.720	4.442	0.968
	count	64	72	78	105	29	79	58
lithium	**average**		-0.540					
studies	median		-0.540					
#=3	stdev							
oldest: 2005	minimum		-0.540					
newest: 2018	maximum		-0.540					
	count		1					
magnesium	**average**			**-0.400**				
studies	median			-0.400				
#=1	stdev			0.035				
oldest: 2006	minimum			-0.425				
newest: 2006	maximum			-0.375				
	count			2				
manganese	**average**	**-0.212**	**-0.120**	**-0.359**				**0.408**
studies	median	-0.212	-0.100	-0.359				0.408
#=2	stdev		0.050					
oldest: 1984	minimum	-0.212	-0.178	-0.359				0.408
newest: 1985	maximum	-0.212	-0.083	-0.359				0.408
	count	1	3	1				1
mercury	**average**			**-1.000**				
studies	median			-1.000				
#=1	stdev							
oldest: 1971	minimum			-1.000				
newest: 1971	maximum			-1.000				
	count			1				
metals	**average**			**-0.234**			**0.910**	
studies	median			-0.260			0.918	
#=1	stdev			0.064			0.112	
oldest: 2020	minimum			-0.300			0.732	
newest: 2020	maximum			-0.100			1.138	
	count			16			17	
nickel	**average**	**-0.032**	**-0.233**	**-0.054**	**1.092**	**0.704**	**1.863**	**0.228**
studies	median	-0.030	-0.146	-0.105	0.666	0.830	1.079	0.158
#=7	stdev	0.239	0.602	1.465	2.111	1.164	4.695	0.293
oldest: 1996	minimum	-0.712	-1.840	-2.950	-3.536	-6.412	-10.522	-0.293
newest: 2020	maximum	0.682	3.191	11.690	16.198	1.700	31.241	0.971
	count	58	72	79	98	42	69	53
niobium	**average**		**-1.375**			**4.922**		

studies	median		-1.375			4.922		
#=2	stdev		1.520					
oldest: 1984	minimum		-2.449			4.922		
newest: 2002	maximum		-0.300			4.922		
	count		2			1		
palladium	**average**	**-0.200**		**-0.700**				
studies	median	-0.200		-0.700				
#=1	stdev			–				
oldest: 1974	minimum	-0.200		-0.700				
newest: 1974	maximum	-0.200		-0.700				
	count	1		1				
plastic	**average**	**-0.918**		**-2.083**				
studies	median	-0.918		-2.083				
#=1	stdev							
oldest: 1991	minimum	-0.918		-2.083				
newest: 1991	maximum	-0.918		-2.083				
	count	1		1				
platinum	**average**	**-0.458**	**-2.206**	**-1.279**	**0.585**	**4.103**	**1.300**	**0.590**
studies	median	-0.344	-2.206	-1.150	0.585	4.103	1.300	0.590
#=3	stdev	0.210	2.220	0.716	0.474	4.926	0.665	0.156
oldest: 1974	minimum	-0.700	-3.775	-2.050	0.250	0.620	0.830	0.480
newest: 2004	maximum	-0.330	-0.636	-0.636	0.920	7.586	1.770	0.700
	count	3	2	3	2	2	2	2
REE	**average**		**-0.400**					
studies	median		-0.400					
#=1	stdev		0.141					
oldest: 2014	minimum		-0.500					
newest: 2014	maximum		-0.300					
	count		2					
REE heavy	**average**		**-0.300**					
studies	median		-0.300					
#=1	stdev							
oldest: 2016	minimum		-0.300					
newest: 2016	maximum		-0.300					
	count		1					
REE light	**average**		**-0.500**					
studies	median		-0.500					
#=1	stdev							
oldest: 2016	minimum		-0.500					
newest: 2016	maximum		-0.500					
	count		1					

silver	**average**		**-0.856**			**1.720**		
studies	median		-0.856			1.720		
#=1	stdev							
oldest: 2002	minimum		-0.856			1.720		
newest: 2002	maximum		-0.856			1.720		
	count		1			1		
steel	**average**	**-0.101**	**-0.151**	**-0.805**	**1.167**	**1.191**		
studies	median	-0.017	-0.071	-0.805	1.144	1.071		
#=5	stdev	0.141	0.260		0.116	0.683		
oldest: 1981	minimum	-0.355	-1.000	-0.805	1.026	0.010		
newest: 2018	maximum	0.005	0.201	-0.805	1.621	4.050		
	count	7	62	1	47	49		
tellurium	**average**	**-0.393**	**-0.260**	**-0.501**	**1.016**	**0.777**	**1.344**	**0.288**
studies	median	-0.393	-0.260	-0.501	1.016	0.777	1.344	0.288
#=1	stdev	0.358		0.362	0.690		0.593	0.199
oldest: 2014	minimum	-0.646	-0.260	-0.757	0.528	0.777	0.925	0.147
newest: 2014	maximum	-0.140	-0.260	-0.245	1.504	0.777	1.763	0.429
	count	2	1	2	2	1	2	2
tin	**average**	**-0.103**	**-0.161**	**-0.106**	**0.474**	**0.703**	**0.618**	**0.345**
studies	median		-0.121	-0.104	0.438	0.773	0.338	0.381
#=11	stdev	0.185	0.470	0.501	0.984	0.232	1.567	0.329
oldest: 1972	minimum	-0.550	-1.469	-1.262	-3.962	0.162	-6.021	-0.418
newest: 2020	maximum	0.370	1.262	3.154	3.838	1.385	4.526	1.026
	count	67	77	81	103	29	77	64
titanium	**average**		**0.690**			**-1.386**		
studies	median		0.690			-1.386		
#=1	stdev							
oldest: 2002	minimum		0.690			-1.386		
newest: 2002	maximum		0.690			-1.386		
	count		1			1		
tungsten	**average**	**-0.150**	**-0.500**	**-0.335**	**1.564**	**3.513**	**1.045**	
studies	median	-0.150	-0.500	-0.335	1.137	2.784	0.366	
#=4	stdev	0.000		0.049	1.362	1.885	1.444	
oldest: 1974	minimum	-0.150	-0.500	-0.370	0.500	2.176	0.239	
newest: 1984	maximum	-0.150	-0.500	-0.300	3.482	6.307	3.209	
	count	2	1	2	4	4	4	
uranium	**average**	**-0.078**	**-1.393**	**-0.186**	**0.494**	**0.634**	**0.707**	**0.421**
studies	median	-0.051	-0.049	-0.083	0.553	0.079	0.608	0.387
#=4	stdev	0.079	1.931	0.273	0.294	0.966	0.550	0.464
oldest: 1994	minimum	-0.216	-4.200	-0.780	0.178	0.074	0.176	-0.018
newest: 2011	maximum	0.003	-0.031	0.006	0.840	1.750	1.370	1.180

	count	7	5	7	5	3	5	7
vanadium	**average**		**0.233**			**-1.541**		
studies	median		0.233			-1.541		
#=2	stdev		0.754					
oldest: 1984	minimum		-0.300			-1.541		
newest: 2002	maximum		0.767			-1.541		
	count		2			1		
zinc	**average**	**-0.034**	**-0.124**	**-0.264**	**0.669**	**0.714**	**0.847**	**0.113**
studies	median	-0.007	-0.046	-0.067	0.485	0.769	0.664	0.102
#=12	stdev	0.242	0.372	0.850	1.775	0.723	1.988	0.356
oldest: 1975	minimum	-1.241	-0.721	-7.337	-7.768	-3.159	-7.317	-0.743
newest: 2020	maximum	0.826	1.572	0.946	8.982	3.560	10.289	0.926
	count	100	72	116	109	66	87	62
all	**average**	**-0.063**	**-0.198**	**-0.200**	**0.803**	**0.926**	**1.136**	**0.255**
studies	**median**	-0.034	-0.082	-0.110	0.600	0.801	0.897	0.249
#=56	**stdev**	0.272	0.552	1.183	1.352	1.256	2.612	0.363
oldest: 1970	**minimum**	-1.760	-5.144	-21.810	-7.768	-6.412	-10.522	-1.141
newest: 2020	**maximum**	1.257	3.191	11.690	16.198	15.697	33.333	1.180
	count	511	567	643	717	344	559	408

Source: Dahl (2020b), Table 3.

Notes: # under studies shows the number of studies for the material, while oldest and newest indicate the dates of the oldest and newest studies. Stdev= standard deviation for the elasticities for each material and each elasticity category. Psr indicates short-run price elasticity, Pstat indicates price elasticities from static models, and Plr indicates long-run price elasticities from dynamic models. Ysr, Ystat, and Ylr are similar elasticities for income or activity elasticities. Qt-1 is the coefficient on a lagged endogenous model for those models that estimate dynamics in a model using one lagged endoge Notes nous model. Count is the number of elasticity estimates for each material and elasticity category.

From the Table 7 and 9 and Dahl (2020a), I have developed some initial guesses of what econometric studies suggested might be representative supply and demand elasticities by material group in Table 10. I have included minerals from my Table 3 critical list whether there were elasticity estimates or not. After studying all the elasticities in a category from Dahl (2020b), median elasticities in table 7 and table 9 were used where they seemed to be good candidates. These elasticities are indicated by the table used under source.

Table 10: Some summary supply and demand elasticities

	Supply		Demand		Demand			Source *	
Material	**Ps_sr**	**Ps_lr**	**Pd_sr**	**Pd_lr**	**Yd_sr**	**Yd_lr**	**Ps**	**Pd**	**Yd**
antimony	–	–	–	–	–	–	–	–	–
aluminum	0.24	0.58	-0.05	-0.21	0.84	1.40	MT7	b	MT9
beryllium	–	–	–	–	–	–	–	–	–
chromium	–	–	–	U	–	U	–	MT9	MT9

cobalt	0.23	0.40	-0.07	-0.54	0.94	1.09	MT7	MT9	j
copper	0.19	0.72	-0.03	-0.23	0.51	1.05	MT7	c	MT9
gallium	–	–	–	–	–	–	–	–	–
germanium	–	–	–	–	–	–	–	–	–
gold	U	0.74	-0.23	-0.68	0.59	1.30	MT7	d	k
indium	0.07	0.12	-0.10	-0.35	–	U	MT7	d	MT9
iron	0.16	0.42	-0.10	-0.21	0.59	1.02	MT7	MT9	MT9
lead	0.17	0.7	-0.01	-0.07	0.35	0.54	MT7	e	MT9
lithium	–	–	-0.20	-0.74	–	–	–	d	MT9
magnesium	–	–	–	-0.40	–	–	–	MT9	MT9
manganese ore	0.10	0.32	-0.21	-0.36	–	–	MT7	MT9	MT9
mercury	U	U	-0.30	-1.00	–	–	MT7	f	MT9
nickel	0.75	2.01	-0.03	-0.10	0.67	1.08	MT7	MT9	MT9
niobium	–	–	–	U	–	U	–	MT9	MT9
palladium	–	–	-0.20	-0.70	–	–	–	MT9	–
plastic	–		-0.92	-2.08	–	–	–	MT9	MT9
platinum	–	–	-0.34	-1.15	0.59	1.30	–	MT9	MT9
REE	–	–	-0.11	-0.40	–	–	–	f	MT9
REE heavy	–	–	-0.08	-0.30	–	–	–	f	MT9
REE light	–	–	-0.14	-0.50	–	–	–	f	MT9
silver	–	–	-0.26	-0.97	–	–	–	MT9	MT9
steel	–	–	-0.02	-0.80	0.80	1.20	–	MT9	k
rhenium	–	–	–	–	–	–	–	–	–
tantallum	–	–	–	–	–	–	–	–	–
tellurium	0.03	0.08	-0.40	-0.50	1.02	1.34	MT7	MT9	MT9
tin	0.30	0.91	-0.08	-0.14	0.44	0.76	*a*	g	g
titanium	–	–	–	–	–	–	–	MT9	MT9
tungsten	0.11	0.5	-0.15	-0.56	U	–	MT7	MT9	h
uranium	0.10	U	-0.05	-0.08	0.55	0.61	MT7	MT9	MT9
vanadium			-0.19	-0.69	–	–	–	MT9[i]	MT9
zinc	0.18	0.51	-0.01	-0.07	0.49	0.67	MT7	MT9	MT9
all	0.15	0.63	-0.03	-0.11	0.60	0.90	MT7	MT9	MT9

Sources: Developed from Table 7 and Table 9 and Dahl (2020a, Appendix).

Notes: MT7 = created from medians in Table 7. MT9 = created from medians in Table 9. Other sources are:

a. Polli (2016) Instrumental variable estimates

b. Pd_sr: Median table 9, Pd_lr:medians from Baffes, Kabundi, and Nagle (2020)

c. Studies from medians in Table 9 but only studies from 2017 and later

d. Prorated from Pd_Stat with Table 0 (all)

e. MT9 without Pei (1996) or Pei and Tilton (1999)

f. Pd_sr prorated from P_lr with MT9(all), Pd_lr: MT9

g. MT9 medians by metal and category without Baffes et al. (2020)

h. Pd_sr:MT9, Pd_lr: prorate from Pd_Stat with MT9(all)

i. Prorated from Pd_Stat in Radeski (1984) with MT9(all)

j. Prorated from Yd_Stat with MT9 (all) and adjusted to Y=GDP

k. Prorated from Yd_Stat with MT9 (all)

So what do these summary statistics imply for the critical minerals identified in table 3. We only have tentative supply elasticities for three of the critical minerals – cobalt, indium, and tungsten. All their long run price elasticities are in elastic and 0.5 or less. We are able to fill in initial tentative long-run demand price elasticities for more but not all of the critical minerals. Cobalt, indium, lithium, tungsten and vanadium have estimates between -0.35 to -0.74. For the platinum metal group, National Research Council (2008) considers only platinum, palladium, and rhodium to be critical, especially in their roles in catalytical converters in internal combustion engines. We have estimates for two of these –palladium (-0.7) and platinum (-1.15). Platinum is the only critical metal with an elastic price response. The last critical mineral group with price elasticities are the rare earths. The three price elasticities found for rare earth group (-0.4), the light rare earths (-0.5) and the heavy rare earths (-0.3). All appear to be based on expert judgment, but I included them as there is no other available estimates. Rare earths consist of more than a dozen elements. However, only a minority of these elements are likely to be critical–the light rare earth–neodymium for its use in permanent magnets, the heavy rare earths–europium, terbium, and yttrium for their phosphorescent qualities in lighting and screens and dysprosium for its use in permanent magnets (The Critical Metals Report (2012b), U. S. Department of Energy (2011), U.S. Energy Information Administration (2014). However, as of yet no econometric work has been done on their demands. Economic activity elasticities are even more sparse for our critical minerals – cobalt (1.09) and platinum at (1.3).

As some of the studies used to compute these summary statistics are now quite dated and the studies have not yet been carefully vetted, they should be updated with more careful study before use to make actual decision in current markets. Further, it is not clear that the econometric work found so far very accurately represent long term adjustment, and long-run demand and supply may be more elastic than many of the studies to date suggest. However, they are a starting point for initial analysis and we do a simple application in the next section.

Application to Asteroid Mining

In Dahl et al. (2020) we apply some of these elasticities to consider the potential for asteroid mining. Here I develop some of the inputs for that exercise and do some back of the envelope calculations to see what a potential influx from space mining might imply for the platinum market. Elvis (2014) suggests that for an asteroid to be economically mined, it would need to be 100 meters in diameter (d) with a radius (r) of 50. If such an asteroid were round it would be about 523,600 cubic meters ($m^3=(4/3)\pi r^3$), if it were a cube it would be 1,000,000 cubic meters (100^3). Since asteroids are neither of these nice shapes but are irregular, let's suppose that our asteroid is a 750,000 cubic meter metallic asteroid. If it were solid iron, its density would be 7.87 grams per cubic centimeter (g/ct^3), (Angstrom Science (2013). Since there are a million grams in a tonne and a million cubic centimeter in a cubic meter, its density would also be 7.87 tonnes per cubic meter. It would then weigh around 6 million tonnes:

$$\left(7.87\frac{t}{m^3}*750,000m^3 = 5,902,500\ t\right)$$

But metallic asteroids tend to be a more interesting mix of metals. Much of our information about metallic asteroids comes from study of metallic meteorites that have made it to earth without before disintegrating in the atmosphere. Such meteorites have been studied for more than a century. For example, the widely cited source classifying meteorites (Wasson (1974)) cites a 3 volume set (Meteoritenkunde) by Cohen (1894, 1903, 1904) which summarizes 19th century data on the structure and mineral composition of meteorites.

I turn to such work, to develop my metallic asteroid. Atkinson (2015) suggests that a typical metallic type asteroid might be mostly iron, with the remainder being more valuable heavier metals including nickel, cobalt, iridium, palladium, platinum, gold, osmium, ruthenium and rhodium. Using more detailed information on the shares of each of these metals, I turn to surveys of meteorite composition studies – Kargel (1994), for precious metal content, and Buddhue (1946) for a breakdown the remaining metals – to develop the representative metallic asteroid in table 11.

Table 11 Representative Metal Meteorite

	A#	**Weight (g/t)**	**<=Sources (Concentration)**	**Density g/ct³ =t/m³**
FE	26.00	897,000.0	Buddhue (1946), p 247, Table 1	7.87
CO	27.00	6,200.0	Buddhue (1946), p 247, Table 1	8.90
NI	28.00	93,000.0	Buddhue (1946), p 247, Table 1	8.91
RU	44.00	21.5	Kargel (1994), p. 21,133, Table 1, column 4	12.37
RH	45.00	4.0	Kargel (1994), p. 21,133, Table 1, column 4	12.41
PD	46.00	16.5	Kargel (1994), p. 21,133, Table 1, column 4	12.02
OS	76.00	14.5	Kargel (1994), p. 21,133, Table 1, column 4	22.60
IR	77.00	14.0	Kargel (1994), p. 21,133, Table 1, column 4	22.40
PT	78.00	29.0	Kargel (1994), p. 21,133, Table 1, column 4	21.45
AU	79.00	0.6	Kargel (1994), p. 21,133, Table 1, column 4	19.32
Asteroid	(10 metals)	996,300.1	Kargel (1994), p. 21,133, Table 1, column 4	7.92

Source: Angstrom Science (2013). Density for asteroid authors computations.

Notes: g/ct^3= grams per cubic centimenter. t/m^3 = metric tonnes per cubic meter.

Each metals contribution to the asteroid is given in parts per million by weight or grams per tonne in column 3 (divide by 10,000 to get their percents or by 1,000,000 to get their share – s_i with i=1 for Fe, 2 for Co, 3 for Ni, . . ., 10 for Au). Next to get the density of such an asteroid, column 5 of table 11 contains the density of each of the metals (d_i with i=1 for Fe, 2 for Co, 3 for Ni, etc.in grams per cubic centimeter. The overall density of the asteroid is

$$\text{Asteroid Density}=\sum_{i=1}^{10} s_i d_i = 7.87*0.897+8.90*0.0062+8.91*0.093$$
$$+12.37*0.0000215+12.41*0.0000040+12.02*0.0000165+22.60*0.0000145$$
$$+22.40*0.0000140+21.45*0.0000290+19.32*0.0000006=7.92 \text{ t/m}^3$$

We can find the weight of an asteroid with this density and a diameter (d) as follow. If the asteroid is a sphere, we know that

$$Weight = Density*Volume = \frac{Weight}{Volume}*Volume = 7.72\frac{g}{ct^3}*\frac{4}{3}\pi\left(\frac{d}{2}\right)^3$$

$$=7.92\frac{\text{t}}{\text{m}^3}*\frac{4}{3}*3.1416*\left(\frac{100}{2}\right)^3\text{ m}^3 = 4{,}146{,}912\text{ t}$$

If the asteroid is a cube, its weight is

$$Weight == 7.72\frac{\text{t}}{\text{m}^3}*\text{d}^3\text{in m}^3 = 7.72 = 100^3 = 7{,}920{,}000\text{ t}$$

Average these two values and rounding down to the nearest million tonnes gives us an asteroid of 6 million tonnes. The amount of platinum in our asteroid would be $=29*10^{(-6)}*6000000=174$ tonnes. Let's see what would happen if we put that amount of platinum into Earth's market. Reported values for platinum's price and quantity in 2018 were P= 29.048 million dollars a tonne with 241.58 tonnes of production, yielding revenues of 7.0174 billion dollars. If the price elasticity of demand is -1.15 as hypothesized in Table 10, and we add 174 tonnes to the market with no earthly supply response we can come up with a simple estimate of the new price and revenues in the platinum market. The additional information to do so for platinum and the other metals in our asteroid is given in Table 12.

In this example, we move along the demand curve as space resources enter the market and drive down the price. Earth production is assumed to be fixed. Let the demand for platinum before (1) and after (2) the space mining be:

$$Q_1 = \alpha \boldsymbol{P}_1^{\beta} \text{ and } \text{Q}_2 = \alpha \boldsymbol{P}_2^{\beta} \rightarrow \frac{Q_2}{Q_1} = \frac{\alpha \boldsymbol{P}_2^{\beta}}{\alpha \boldsymbol{P}_1^{\beta}} \rightarrow \left(\frac{P_2}{P_1}\right)^{\beta} = \frac{Q_2}{Q_1} \rightarrow P_2 = \left(\frac{Q_2}{Q_1}\right)^{(1/\beta)} P_1$$

Now substitute in the values from Table 12.

$$P_2 = \left(\frac{Q_2}{Q_1}\right)^{(1/\beta)} P_1 = \left(\frac{Q_2}{Q_1}\right)^{(1/\beta)} P_1 = \left(\frac{241.58+174.00}{241.58}\right)^{(1/-1.15)} 29.048\times10^6 = 18.124\times10^6$$

$$\text{with } \frac{P_2}{P_1} = 0.62,\ \frac{Q_2}{Q_1} = \frac{415.58}{241.58} = 1.72,\ \frac{\text{total revenue 2}}{\text{total revenue 1}} = 1.07$$

Platinum from the asteroid would increase the quantity supplied by almost 75% with quite a dramatic reduction in price, from more than $29 million to near $18 million a tonne. With slightly elastic demand, revenues would increase a bit (7%). Space miners would increase revenues, but earth miners with fixed supply in this case would lose the same percent as the price fall. I do the same computations for the other metals in Table 13. There is little effect on the gold market because our asteroid is rather poorly endowed with gold. For all other markets with inelastic demand, the price falls by a larger percent than quantity increases and total revenue falls. Thus, Earth miners lose more than space miners gain.

Table 12 Representative asteroid metal content, 2018 price, quantities, total revenue and demand elasticity for those metals on Earth

	Share of each metal	Metal in a 6000000 tonne asteroid	Price (P1) 2018 $/tonne	Source P1	Consumption (Q1) 2018 tonnes	Source Q1	Revenues 2018 P1*Q1	ε_p
FE	0.8970000	5,382,000	338	https://www.steelonthenet.com/cost-eaf.html	1,200,000,000	https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-feste.pdf	405,600,000,000	-0.214
CO	0.0062000	37,200	82,519	https://www.cobaltinstitute.org/statistics.html	125,000	https://www.cobaltinstitute.org/statistics.html	10,314,875,000	-0.542
NI	0.0930000	558,000	10,559	https://knoema.com/ydolvrc/nickel-prices-forecast-long-term-2018-to-2030-data-and-charts	2,199,000	https://www.statista.com/statistics/388081/global-nickel-consumption-projection/	23,219,241,000	-0.105
RU	0.0000215	129	6,108,900	http://www.platinum.matthey.com/documents/new-item/pgm20market20reports/pgm_market_report_may_2018.pdf	41.99	http://www.platinum.matthey.com/documents/new-item/pgm20market20reports/pgm_market_report_may_2018.pdf	256,512,711	*-0.925*
RH	0.0000040	24	54,656,000	http://www.platinum.matthey.com/documents/new-item/pgm20market20reports/pgm_market_report_may_2018.pdf p28	31.91	http://www.platinum.matthey.com/documents/new-item/pgm20market20reports/pgm_market_report_may_2018.pdf	1,744,072,960	*-0.925*
PD	0.0000165	99	33,083,000	https://elemetal.com/prices/platinum	317.82	http://www.platinum.matthey.com/documents/new-item/pgm20market20reports/pgm_market_report_may_2018.pdf	10,514,439,060	-0.700
OS	0.0000145	87	12,860,000	https://www.metalary.com/osmium-price/	1.50	https://www.rwmmint.com/products/osmium	19,290,000	*-0.925*
IR	0.0000140	84	31,186,000	http://www.platinum.matthey.com/documents/new-item/pgm20market20reports/pgm_market_report_may_2018.pdf	7.18	http://www.platinum.matthey.com/documents/new-item/pgm20market20reports/pgm_market_report_may_2018.pdf	223,915,480	*-0.925*
PT	0.0000290	174	29,048,000	https://elemetal.com/prices/platinum	242	http://www.platinum.matthey.com/documents/new-item/pgm20market20reports/pgm_market_report_may_2018.pdf	7,017,415,840	-1.150
AU	0.0000006	4	40,245,000	https://www.gold.org/goldhub/data/gold-prices	4,345	https://www.gold.org/goldhub/data/gold-prices	174,868,549,500	-0.413
				Sum→	1,202,328,587	Sum →	633,778,311,551	

Notes: Non-italicized demand elasticities come from Table 10. Italicized elasticities for the four missing PGM are the average for palladium and platinum**.**

Table 13 Asteroid's effect on earth metal markets, earth supply perfectly inelastic.

	Metal in a 6000000 tonne asteroid ΔQ	Price (P1) 2018 $/tonne	Consumption (Q1) 2018 tonnes	Revenues 2018 P1*Q1	ε_p	P2/P1	P2	Q2	Q2/Q1	TR2	TR2/TR1
FE	5,382,000	338	1,200,000,000	405,600,000,000	-0.214	0.98	331	1,205,382,000	1.0	398,987,999,041	0.98
CO	37,200	82,519	125,000	10,314,875,000	-0.542	0.62	51,028	162,200	1.3	8,276,712,594	0.80
NI	558,000	10,559	2,199,000	23,219,241,000	-0.105	0.12	1,225	2,757,000	1.3	3,378,404,034	0.15
RU	129	6,108,900	41.99	256,512,711	-0.925	0.22	1,338,730	171	4.1	228,909,403	0.89
RH	24	54,656,000	31.91	1,744,072,960	-0.925	0.55	29,807,588	56	1.8	1,666,542,229	0.96
PD	99	33,083,000	317.82	10,514,439,060	-0.700	0.68	22,457,730	417	1.3	9,360,830,839	0.89
OS	87	12,860,000	1.50	19,290,000	-0.925	0.01	156,605	89	59.0	13,859,566	0.72
IR	84	31,186,000	7.18	223,915,480	-0.925	0.06	1,998,431	91	12.7	182,216,977	0.81
PT	174	29,048,000	242	7,017,415,840	-1.150	0.62	18,123,922	416	1.7	7,531,939,465	1.07
AU	4	40,245,000	4,345	174,868,549,500	-0.413	1.00	40,164,379	4,349	1.0	174,662,833,981	1.00
			1,202,328,587	633,778,311,551					Sum	604,290,248,130	0.953

Source: Columns 1-6, table 2. The remaining columns, author's computations.

In the above example, I assumed that earth production is fixed. However, unless earthly supply is totally inelastic, as prices fall, earth's production would also fall. Then price would not fall as much and space miners would receive a higher price. To see how much higher, let's continue with a slightly more complicated example.

Let the initial demand and supply equations for a metal be:

$$Q_d = \alpha P_1^{\beta} \text{ or } \alpha = \frac{Q_d}{P_1^{\beta}} \text{ and } Q_s = \gamma P_1^{\delta} \text{ or } \gamma = \frac{Q_s}{P_1^{\delta}}$$

To see the price and quantity change for this third case, first set initial Q_d equal to Q_s, then shift the supply curve by adding the amount from space:

$$\alpha P_3^{\beta} = \gamma P_3^{\delta} + \Delta Q_2 \qquad (1)$$

In the above equation, we have values by asteroid metal for all but the supply price elasticities (δ). Table 10 has guesses for the supply elasticities for iron, cobalt, nickel, and gold but not for any of the platinum metal group. For these others, I estimate their elasticities as follow, British Geological Survey (2009) has a nice description of the platinum reserves for large global producers of the platinum group metals including major deposits in South Africa, Zimbabwe, Russia, Canada, and the United States. They indicate that most platinum group elements are produced with nickel and copper and present some concentrations for some of the major types of producing fields. These concentration or grades are shown for the asteroid metals and copper in Table 14, column 5. Concentrations, where available, are taken from averaging concentrations of various formations from the British Geological Survey (2009). They did not include information on grade for ruthenium, iridium and osmium but indicated that the crustal abundant of ruthenium and iridium was 1/5 that of palladium and platinum the British Geological Survey (2009), p. 1). Using this weight, I made the grades for the three missing metals (Ru, Ir, Os), 1/5 of the average grade of palladium and platinum.

As by-products of copper and nickel production, I expect the platinum metals to be less price elastic than either of these metals and the more valuable the reserves the more elastic. So next I took a weighted average of the copper and nickel supply elasticities, with the weights the price of the metal times the grade shown in column 7 of Table 14. This gives a weighted average supply elasticity of for nickel and copper of 1.65. Last this elasticity is prorated by the value weight of the missing metal divided by the value weight of nickel and copper.

Table 14 Sources of price elasticity of supply

	Price (P1) 2018 $/tonne	ε_{sp}		Grades (ppm)	Source Grade	Weight =P×Grade
Cu	6,466	0.72	Table 10	11,000	BGS09, p. 8	71,127,009.8
Cu&Ni	–	*1.65*	$\frac{(\varepsilon_{spCu}W_{cu}+\varepsilon_{spNi}W_{Ni})}{(W_{cu}+W_{Ni})}$			255,909,509.8
FE	338	0.42	Table 10			
CO	82,519	0.40	Table 10			
NI	10,559	2.01	Table 10	17,500	BGS09, p. 8	184,782,500.0
RU	6,108,900	*0.02*	$\varepsilon_{spCu\&Ni}*W_{Ru}/(W_{Cu}+W_{Ni})$	*0.48*	=1/5(Grade Pd+Grade Pt)/2	2,932,272.0
RH	54,656,000	*0.16*	$\varepsilon_{spCu\&Ni}*W_{Rh}/(W_{Cu}+W_{Ni})$	0.45	BGS09, p. 4	24,595,200.0
PD	33,083,000	*0.38*	$\varepsilon_{spCu\&Ni}*W_{Pd}/(W_{Cu}+W_{Ni})$	1.80	BGS09, p. 4	59,549,400.0
OS	12,860,000	*0.04*	$\varepsilon_{spCu\&Ni}*W_{Os}/(W_{Cu}+W_{Ni})$	*0.48*	=1/5(Grade Pd+Grade Pt)/2	6,172,800.0
IR	31,186,000	*0.10*	$\varepsilon_{spCu\&Ni}*W_{Ir}/(W_{Cu}+W_{Ni})$	*0.48*	=1/5(Grade Pd+Grade Pt)/2	14,969,280.0
PT	29,048,000	*0.56*	$\varepsilon_{spCu\&Ni}*W_{Pt}/(W_{Cu}+W_{Ni})$	3.00	BGS09, p. 4	87,144,000.0
AU	40,245,000	0.74	Table 10			

Sources: BGS09 is British Geological Survey (2009)

With these supply elasticities, we now have all the information to apply formula (1) to platinum: above as shown. β is the demand elasticity and δ is the supply elasticity. First compute α and γ.

$$\alpha = \frac{Q_d}{P_1^{\beta}} = \frac{242.58}{29{,}048{,}000^{-1.15}} = 92{,}394{,}186{,}973 \text{ and } \gamma = \frac{Q_s}{P_1^{\delta}} = \frac{242.58}{29{,}048{,}000^{0.56}} = 0.01535$$

Now write the objective function as an implicit function, substitute all the information into the objective function, and solve with a non-linear solver.

$$\alpha P_3^{\beta} = \gamma P_3^{\delta} + \Delta Q \rightarrow \alpha P_3^{\beta} - \gamma P_3^{\delta} - \Delta Q_2 = 0$$

$$92{,}394{,}186{,}973 P_3^{-1.15} - 0.01535 P_3^{0.56} - 174.58 = 0 \rightarrow P_3 = 20{,}045{,}922$$

$$\frac{P_3}{P_2} = \frac{20{,}045{,}922}{18{,}123{,}922} = 1.016, \quad \frac{Q_3 \text{ Earth}}{Q_2 \text{ Earth}} = \frac{196.10}{241.58} = 0.811 \quad \frac{TR_3 \text{ Earth}}{TR_2 \text{ Earth}} = \frac{3{,}930{,}930{,}465}{4{,}378{,}377{,}054} = 0.898$$

$$\frac{TR_3 \text{ Space}}{TR_2 \text{ Space}} = \frac{3{,}487{,}990{,}464}{3{,}153{,}562{,}411} = 1.106$$

As earth production falls in this case, the platinum price is 1.6% higher than when earth production is fixed. Although the price is higher, Earth mining loses revenue, while space mining increases. Table 15 shows these same computations for all the metals in our asteroid.

Table 15 Asteroid's effect on earth metal markets, earth supply with estimated supply elasticities.

	Price (P1) 2018 $/tonne	**Consumption (Q1)Earth 2018 tonnes**	ε_{dp}	ε_{sp}	α	**α**	γ	P3 $/tonne	Qd3 tonnes
FE	338	1,200,000,000	-0.214	0.42	4,172,241,321	4,172,241,321	104,000,693	335.6	1,201,819,338.58
CO	82,519	125,000	-0.542	0.40	57,767,325	57,767,325	1,349.85907	60,644.0	147,710.49
NI	10,559	2,199,000	-0.105	2.01	5,817,088	5,817,088	0.01798	9,215.3	2,230,653.94
RU	6,108,900	41.99	*-0.925*	*0.02*	79,462,398	79,462,398	31.24182	1,348,817.3	169.81
RH	54,656,000	31.91	*-0.925*	*0.16*	458,397,046	458,397,046	1.88716	31,434,614.9	53.23
PD	33,083,000	317.82	-0.700	*0.38*	58,331,701	58,331,701	0.40971	25,151,381.2	385.04
OS	12,860,000	1.50	*-0.925*	*0.04*	5,651,180	5,651,180	0.78144	157,068.4	88.26
IR	31,186,000	7.18	*-0.925*	*0.10*	61,381,450	61,381,450	1.35581	2,038,602.2	89.52
PT	29,048,000	241.58	-1.150	*0.56*	92,394,186,973	92,394,186,973	0.01535	20,045,922.1	370.10
AU	40,245,000	4,345.10	-0.413	0.74	6,008,220	6,008,220	0.01025	40,216,087.9	4,346.39
Total		1,202,328,587							1,204,203,205

	Qs3 Earth	Qs Space tonnes	Total Revenue (TR3)	TR3 Earth (2018 USD)	TR3 Space (2018 USD)	P3/P2	Earth Q3/Q2	Earth TR3/TR2	Space TR3/TR2
FE	1,196,437,338.58	5,382,000.00	403,349,379,481	401,543,096,048	1,806,283,433	1.014	0.997	1.011	1.014
CO	110,510.49	37,200.00	8,957,751,564	6,701,795,605	2,255,955,959	1.188	0.884	1.051	1.188
NI	1,672,653.94	558,000.00	20,556,112,818	15,413,983,522	5,142,129,296	7.520	0.761	5.720	7.520
RU	40.81	129.00	229,038,320	55,040,889	173,997,430	1.008	0.972	0.979	1.008
RH	29.23	24.00	1,673,198,326	918,767,586	754,430,740	1.055	0.916	0.966	1.055
PD	286.04	99.00	9,684,410,601	7,194,423,871	2,489,986,730	1.120	0.900	1.008	1.120
OS	1.26	87.00	13,862,636	197,683	13,664,953	1.003	0.839	0.842	1.003
IR	5.52	84.00	182,489,163	11,246,581	171,242,582	1.020	0.768	0.784	1.020
PT	196.10	174.00	7,418,920,929	3,930,930,465	3,487,990,464	1.106	0.812	0.898	1.106
AU	4,342.79	3.60	174,794,795,999	174,650,018,082	144,777,916	1.001	0.999	1.001	1.001
Tota	1,198,225,405	5,977,800.60	626,859,959,836	610,419,500,335	16,440,459,501		0.997	1.029	1.501

In some cases and markets, depending on supply and demand, earth miners lose and in some they gain. Overall Earth gains about 3% in total revenues compared to the case where Earth has fixed supplies, while space gains about 50%.

A last case I do is to assume that demands and supplies are linear.

$$Q_{d1} = a + bP_1 \text{ and } Q_{s1} = c + dP_1 \text{ with } b < 0 \text{ and } d > 0$$

I again create the needed demand and supply curves around 2018 price, quantity and **price elasticities:**

$$\varepsilon_d = \frac{Q_{d1}}{dP}\frac{P_{d1}}{Q_{d1}} = b\frac{P_{d1}}{Q_{d1}} \rightarrow \text{ b=} \varepsilon_d \Big/ \frac{P_{d1}}{Q_{d1}} \text{ and a=Q}_{d1} - bP_{d1}$$

$$\varepsilon_s = \frac{Q_{s1}}{dP}\frac{P_{s1}}{Q_{s1}} = d\frac{P_{s1}}{Q_{s1}} \rightarrow \text{ d=} \varepsilon_s \Big/ \frac{P_{s1}}{Q_{s1}} \text{ and c=Q}_{s1} - dP_{s1}$$

Using these demand and supply curves, generic new price and quantity with an influx of ΔQ from space can be solved as follows:

$$Q_{d2} = a + bP_2 = \text{Q}_{s2}\text{=c+dP}_2\text{+}\Delta Q \rightarrow \text{ (b-d)P}_2\text{=c-a+}\Delta Q \rightarrow P_2 = \frac{\text{c-a+}\Delta Q}{(b-d)}$$

$$\text{Q}_{d2} = a + bP_2 = a + b\left[\frac{\text{c-a+}\Delta Q}{(b-d)}\right] \text{ and total revenue from mining is } P_2 * Q_2$$

Now solve for the demand and supply parameters by substituting in the values from the example for platinum.

$$\text{b=} \varepsilon_d \Big/ \frac{P_{d1}}{Q_{d1}} = -1.15 \Big/ \frac{29{,}048{,}000}{241.58} = -0.0000096 \text{ and}$$

$$\text{a=Q}_{d1} - bP_{d1} = 241.58 - (-0.0000096) * 29{,}048{,}000 = 519.40$$

$$Q_d = 519.40 - 0.0000096P$$

$$\text{d =} \varepsilon_s \Big/ \frac{P_{s1}}{Q_{s1}} = 0.56 \Big/ \frac{29{,}048{,}000}{241.58} = 0.0000047$$

$$\text{c=Q}_{s1} - dP_{s1} = 241.58 - 0.0000047 * 29{,}048{,}000 = 105.72$$

$$Qs = 105.72 + 0.0000047P$$

Now insert the space minerals and see what happens to P and Q in the platinum market.

$$Q_d = 519.397 - 0.0000096P$$

$$Q_s = 105.724 + 0.0000047P$$

$$P_4 = \frac{\text{c-a+}\Delta Q}{(b-d)} = \frac{105.724\text{-}519.397+174}{-0.0000096-0.0000047} = 16,829,781.02$$

$$Q_{d4} = 519.397 - 0.0000096 * 16,829,781.02 = 358.44$$

$$Q_{s4} \text{ (Earth)} = 105.724 + 0.0000047 * 16,829,781.02 = 184.44$$

$$Q_{s4} \text{ (space)} = 174.58$$

$$\text{TR (Earth)= } P_4 * Q_{s4} = 16,829,781.02 * 184.44 = 3,104,015,090$$

$$\text{TR (space)= } P_4 * Q_{s4} = 16,829,781.02 * 174.58 = 2,928,381,898$$

$$\frac{P4}{P3} = 0.840,\ \frac{Q4}{Q3}\text{(Earth)} = 0.941,\ \frac{Q4}{Q3}\text{(space)} = 1,\ \frac{TR4}{TR3}\text{(Earth)=0.790},\ = \frac{TR4}{TR3}\text{(space)=0.841}$$

Now the asteroid entry into the market drops the platinum price even further to $16.8 million per per tonne. In this example, as we move down earth's demand and supply curve, both get less elastic and price has to do more of the adjustment. Earth's consumers benefit from lower prices and higher quantities but both earth and space miners do more poorly than in case 3. This simple example shows that not only given elasticities but also the shape of demand and supply can influence the outcome of a space mining adventure.

Table 16 shows the results of the asteroid's effect on the other metal markets and the whole model is posted at http://dahl.mines.edu/MetalMarkets.xlsx in worksheet model for anyone who wants to change the assumptions to see the effect they have for these four cases. For three of the metal markets (ruthenium, osmium, and iridium), the influx is so large it would drive the price negative if the demand and supply curves were extended in the negative price orthant. I drop these metals out of the market. If we assume they got trashed in space, market values would go back to the original 2018 values. Alternately one could experiment to determine whether trashing only part of the asteroid content or stockpiling for later use would improve revenues. In the largest market (iron: Fe), the infusion of the asteroid metal does not change the elasticities much as price falls and the percentage fall in revenues from case 3 is less than a hundredth of a percent. In gold, the infusion is so small the change in revenues is also unnoticeable at a hundredth of a percent.

Nickel is another interesting example. Nickel is the only one of the metals with a negative intercept. Its supply is already rather elastic (2.01). As we move down such a supply, it get more not less elastic and revenues for space and terrestrial miners increase compared to the constant elasticity case.

This simple example demonstrates that a number of factors will need to be considered to determine how much revenues might come in from bringing space metals to earth: how large the infusion is relative to the earth market, demand and supply elasticities, and how the demand and supply elasticities change with the infusion of the space metals. But surely this is not the end of the story. I expect space mining, like earth mining, will be capital intensive and long lived. Thus cost, interest rates, and the growth of demand on earth will also need to be considered. We can turn to this considerably more complicated challenge in Dahl et al (2020) and Dahl (2020b).

Table 16 Asteroid's effect on Earth metal markets, Earth supply and demand linear supply elasticities.

	Metal in a 6000000 tonne asteroid ΔQ	Price (P1) 2018 $/tonne	Consumption (Q1)Earth 2018 tonnes	ε_{dp}	ε_{sp}	a	b	c	d	P4=	Qd4=
FE	5,382,000	338	1,200,000,000	-0.214	0.420	1,456,800,000	-759,763.314	696,000,000.0	1,491,124.2603550	335.61	1,201,816,637.22
CO	37,200	82,519	125,000	-0.542	0.400	192,750.00	-0.8210230	75,000.0	0.6059211	56,449.30	146,403.82
NI	558,000	10,559	2,199,000	-0.105	2.010	2,429,895.00	-21.8671276	-2,220,990.0	418.59929918	9,292.16	2,226,702.13
RU	129	6,108,900	41.99	-0.925	0.019	80.83	-0.0000064	41.2	0.0000001	-13,773,571.40	–
RH	24	54,656,000	31.91	-0.925	0.159	61.43	-0.0000005	26.8	0.0000001	16,724,051.57	52.39
PD	99	33,083,000	317.82	-0.700	0.384	540.29	-0.0000067	195.7	0.0000037	23,578,846.50	381.73
OS	87	12,860,000	1.50	-0.925	0.040	2.89	-0.0000001	1.4	0.0000000	-760,204,900.23	–
IR	84	31,186,000	7.18	-0.925	0.097	13.82	-0.0000002	6.5	0.0000000	-325,949,583.97	–
PT	174.00	29,048,000	241.58	-1.150	0.562	519.397	-0.0000096	105.7	0.0000047	16,829,781.02	358.44
AU	4	40,245,000	4,345.10	-0.413	0.740	6,139.63	-0.0000446	1,129.7	0.0000799	40,216,080.86	4,346.39

	Earth Qs4=	Space Qs4=	Total Revenue (TR4)	TR4 Earth (2018 USD)	TR4 Space (2018 USD)	P4 / P3	Qd4 / Qd3	Earth Q4 / Q3	Earth TR4 / TR3	Space TR4 / TR3
FE	1196434637.22	5,382,000.00	403,340,411,560	401,534,164,228	1,806,247,332	1.000	1.004	1.000	1.000	1.000
CO	109,203.82	37,200.00	8,264,393,716	6,164,479,638	2,099,914,078	0.931	1.325	0.988	0.920	0.931
NI	1,668,702.13	558,000.00	20,690,874,910	15,505,849,012	5,185,025,898	1.008	1.331	0.998	1.006	1.008
RU	–	–	–	–	–	–	–	–	–	–
RH	28.39	24.00	876,256,584	474,879,346	401,377,238	0.532	1.793	0.972	0.517	0.532
PD	282.73	99.00	9,000,819,012	6,666,513,209	2,334,305,804	0.937	1.335	0.988	0.927	0.937
OS	–	–	–	–	–	–	–	–	–	–
IR	–	–	–	–	–	–	–	–	–	–
PT	184.44	174.00	6,032,396,988	3,104,015,090	2,928,381,898	0.840	1.828	0.941	0.790	0.840
AU	4,342.79	3.60	174,794,751,815	174,649,973,924	144,777,891	1.000	1.001	1.000	1.000	1.000

Conclusion

Mineral industries remain cyclical and worries about mineral shortages are not new. But worries about which minerals are critical changes over time. In this paper, I looked broadly at a century of mineral use and prices, looked at the size of some of the major mineral markets by sales, and looked a little closer at recent mineral growth and China's role in the growth of some of them. It's phenomenal growth and control of some key mineral markets, such as rare earths, has again spotlighted some potential vulnerabilities and spawned dozens of recent government studies on critical minerals. From these studies, I identify the following 14 elements or material groups considered critical in the majority of studies. lithium, beryllium, vanadium, cobalt, gallium, germanium, niobium, indium, antimony, tantalum, tungsten, rhenium, the platinum metal group, and rare earth elements.

Continuing, I consider what makes minerals critical–typically high commercial or strategic value and markets failing to adjust rapidly to situations where quantity demanded exceeds quantity supplied unless prices spike high enough for long enough to cause significant losses to society. Insecure supply can result for geological, economic, or political reasons. Since most elements are quite abundant in earth's crust, physical depletion is not yet much of a threat. However, concentrations may become so low that it becomes prohibitively expensive to extract an element and opening new mines can be a long and costly process. Market concentration of producing companies can lead to monopoly rents that increase prices. While concentrations of supplies from politically unstable and poorly governed countries can raise the specter of physical disruption. If a resource is a byproduct, its supply may not be governed by its own price, but rather that of its host's price. The normal response of increasing primary production when prices increase may then not happen. While ease of recycling can help in such a situation.

Mining and refining metals and other materials is quite a dirty and disruptive process, which can impact supply. Where companies have behaved badly, sometimes under the sanction of corrupt governments, they may have lost the trust of local neighbors to their mining and refining operations. This loss of trust can lead to a loss of their social license to operate and disrupt supply.

On the demand side, technical change that can reduce the use of a critical material or good substitutes can reduce criticality as can more gradual structural changes that give markets more time to adjust to increasing demand. As with bi-products, complementary inputs may make demanders more responsive the cross-price of another more expensive complementary input reducing the normal demand response of the material to its own rising or falling price.

Thus, rapid shifts in demand as well as inelastic response to own price can contribute to the criticality of a material. As our world is rapidly shifting to a digital era with a need to shift away from fossil fuels, there has been a recent rise in interest in critical minerals. This is especially so for use in new medical, electronic, and communication devices, national defense, and renewable energy production. There has also been a renewed interest in demand and supply elasticities.

Supply curves in competitive industries may come from cost curves, and I present some collected costs for mining and refining of metals. They show huge economies of scale and indicate the need for large projects to keep costs down. We can also try to derive supply elasticities by estimating supply curves econometrically in competitive industries. In the database appendix of Dahl(2020a), I have found studies that have supply elasticity estimates for 15 metals with most studies either before 1980 or after 2000. Histograms of supply price elasticities and summary statistics from that database have been reproduced here. They show elasticities in the short run and from static models to cluster below 0.5 and those for the long run cluster below 1. I have more confidence in shorter term elasticities than those in the long-run. Those for the long run are more erratic with most estimated using lagged endogenous variables. Given the long time it takes to develop and produce new reserves, the adjustment time implied by the lagged endogenous model seems suspiciously short. Hence, the estimated long-run elasticities are likely biased down.

Likewise, demand equations can be estimated econometrically. Again I turned to Dahl (2020a). Some studies estimate both supply and demand elasticities but considerable more estimate demand elasticities (56 demand studies versus 36 for supply). The studies contain demand elasticities for 30 materials or groups (the only non-metal is plastic) with mort studies either before 1990 or after 2010. Again histograms of demand price elasticities and summary statistics from that database have been reproduced here. A disappointing share of the short run demand price elasticity estimates are positive. Most price elasticities in the short run and from static models cluster in the region less elastic than -0.2. However, a cluster, mostly from static translog models are more elastic than -0.4. The role of the translog model and including cross-prices should be considered more carefully. Long-run demand price elasticities are quite inelastic as well. A significant portion are positive and most are less elastic than -0.25. I have the same reservations as for the supply price and the often used lagged endogenous model. Given how capital intensive industries that use metals are, the adjustment time implied by the lagged endogenous model again seems suspiciously short. Hence, I suspect the estimated long-run elasticities also biased towards being too inelastic. It would be prudent to investigate whether we might be able to come up with better estimates of the dynamics in these markets.

For income or activities, most demand short-run income elasticities cluster from 0 to 1.2. Those from static models are a bit higher and cluster between 0.5 to 1.5, while long run estimates cluster between 0 and 2 with a median of 0.9. In using elasticities, it is important to pay attention to how activity is measured. If it is the product produced from the metal, one would expect is to be near to 1. If the activity is GDP, which is more often the case in the collected studies, it measures the combined effect of changes in product and how that products share changes with GDP. These activity elasticity also tend to fall considerably with inclusion of a time trend as an exogenous variable. Its role when included should be more carefully considered. Again the most suspicious activity elasticities tend to come from lagged endogenous models.

Table 10 contains a cautious summary of what the econometric work to date suggests the supply and demand price elasticities and demand activity elasticities might be for the minerals for which I have found elasticities.

Appendix

Table A1 Minerals Studied for Criticality, Uses, Crustal Abundance and Annual Production

Atomic								
#	Sym.	Element Name	Major uses include	Earth's mantle, crust and core by mass	Production (2016, metric kilotonnes)		Stud	Crit
2	He	Helium	magnetic resonance imaging, scientific & engineering, lifting, welding, leak detection	0.008 ppm	26.40	*	5	3
3	Li	Lithium	batteries, ceramics, glass, lubricating greases, polymer production	20 ppm	35.00		25	11
4	Be	Beryllium	copper & aluminum alloys	2.6 ppm	0.22		19	14
5	B	Boron	glass, ceramics, soaps & detergents	10 ppm	9,400.00		15	2
6	C	Carbon	hydrocarbons for fuel & petrochemical feedstocks, manufacturing iron & steel,carbon fiber, industrial diamonds, in nanotechnology	480 ppm	N/A		16	12
9	F	Fluorine	for uranium hexafluorid to enrich uranium, sulfur hexafloride gas as transformer insulation, hydrofluric acid for etching, solvents, teflon, goretex	130 ppm	N/A		17	9
11	Na	Sodium	powder detergents, textile industry	23,000 ppm	255,000.00		1	-
12	Mg	Magnesium	for light weight auto parts	23,000 ppm	1,010.00		18	14
13	Al	Aluminum	in vehicles, containers, packaging, construction, electrical applications, consumer durables, machinery & equipment	82,000 ppm	57,600.00		18	4

14	Si	Silicon	produce chemicals for Iron, steel, & alluminum production & semiconductors.	277,000 ppm	7,200.00		12	5
15	P	Phosphorus	fertilizer & animal feed supplement & chemical applications	1000 ppm	241,000.00	*	9	5
16	S	Sulfur	for sulfuric acid	260 ppm	69,300.00		5	-
17	Cl	Chlorine	to treat drinking water, in consumer products, PVC, used in making pharmaceuticals	950 ppm	N/A		1	-
19	K	Potassium	fertilizer	21,000 ppm	40,600.00	*	8	3
20	Ca	Calcium	reducing & alloying agent for other metals, building stone, in cement,	41,000 ppm	N/A		1	1
21	Sc	Scandium	aluminum-scandium alloys, solid oxide fuel cells, ceramics, electronics, lasers, lighting, & radioactive isotopes	16 ppm	N/A		6	4
22	Ti	Titanium	white pigment production, welding-rod coatings, alloys of aluminum	5,600 ppm	6,600.00		19	5
23	V	Vanadium	alloy with iron & steel, catalysts	160 ppm	76.00		24	11
24	Cr	Chromium	stainless steel & other alloys	100 ppm	26,000.00		23	10
25	Mn	Manganese	Mostly steel alloys, some aluminum alloys	950 ppm	16,000.00		22	10
26	Fe	Iron	iron & steel, magnets	41,000 ppm	1,150,000.00		15	3
27	Co	Cobalt	alloyed for magnets, high temperature metals, blue paint pigment, electroplating	20 ppm	123.00		27	21
28	Ni	Nickel	as alloy to improve corrosion resistance	80 ppm	2,250.00		26	5
29	Cu	Copper	electrical equipment, construction, industrial machinery (e.g. heat exchangers)	50 ppm	19,400.00	*	21	3
30	Zn	Zinc	galvanize other metals, for die-castings, zinc oxide many uses in paints, rubber, plastics, pharmaceutical, cosmetics	75 ppm	11,900.00		19	4
31	Ga	Gallium	silicon substitute in electronics, semiconductors, LED lights, solar panels	18 ppm	0.47		28	20

32	Ge	Germanium	camera & microscope lenses, fluorescent lamps, alloy, & catalyst	1.8 ppm	0.16		24	21
33	As	Arsenic	poultry feed, semiconductor, doping agent, bronzing, ammunition	1.5 ppm	36.50		8	5
34	Se	Selenium	Glass additive to decolorize, give red color, reduce light transmission, pigments, photocells, solar cells, photocopiers, rectifiers	0.05 ppm	2.20		18	7
35	Br	Bromine	in agricultural chemicals, dyes, insecticides, pharmaceuticals, flame retardants (being phased out)	0.37 ppm	342.00	*	5	1
38	Sr	Strontium	red color in fireworks & flares, glow in dark paint & plastic, strontium-90 for remote electricity	370 ppm	350.00		13	8
39	Y	Yttrium	alloys, radar, catalyst, lasers, LED lights, camera lenses, superconductors	30 ppm	6.00		9	5
40	Zr	Zirconium	alloy for nuclear reactor tubing & super conductors, very strong ceramics & crucibles	190 ppm	1,460.00		15	7
41	Nb	Niobium	alloy to improve low temperature stength for use in rockets, jet engines, pipelines, off shore oil & gas rigs	20 ppm	64.00		28	20
42	Mo	Molybdenum	alloy for metal strength electrical conductivity, corrosion resistance, petroleum refining catalyst	1.5 ppm	227.00		25	8
44	Ru (PG)	Ruthenium	electronics for chip resistors & electrical contacts, hardening alloy for palladium & platinum	0.001 ppm	N/A			
45	Rh (PG)	Rhodium	catalytic converters for NOx reduction & catalyst in chemical industry	0.0002 ppm	2.8			
46	Pd (PG)	Palladium	in catalytic converters, ceramic capacitors used in laptop computers & mobile phones	0.0006 ppm	0.21			

47	Ag	Silver	mirrors; alloys for dental solder, electrical contacts & batteries; paints for printed circuits; photographic applications, jewellry	0.07 ppm	27.00		20	8
48	Cd	Cadmium	phasing out use rechargeable batteries, electroplating for metal protection in airplanes, oil platforms, nuclear control rods	0.11 ppm	23.00		15	5
49	In	Indium	for touch screens, TVs, solar panels, transistors, microchips, window glazing	0.049 ppm	0.66		31	26
50	Sn	Tin	erosion reduction coating, alloy in superconducting magnets, in glass manufacture, clothing dye fixant, ceramics, gas sensors & fire retardant	2.2 ppm	280.00		20	10
51	Sb	Antimony	in semiconductors, batteries, flame retardents, paints, glass, pottery; alloy for strength & hardness	0.2 ppm	130.00		20	19
52	Te	Tellurium	alloy to improve machinability, acid resistance, strength, hardness; vulcanize rubbers, tint glass & ceramics, as oil refining catalysts & in semiconductors	0.005 ppm	2.20		19	9
53	I	Iodine	used in pharmaceuticals, disinfectants, photographic chemicals, printing inks, dyes, catalysts, animal feed supplements, LCD displays	0.14 ppm	31.60		5	1
55	Cs	Cesium	in drilling fluid, optical glass, radiation monitoring equipment, atomic clocks, mobile phone & GPS networks	3 ppm	<0.025		1	1
56	Ba	Barium	in drilling fluid for oil & gas wells, paint, glass, green color in fireworks, medical uses	500 ppm	7,410.00	*	14	6

57	La (RE)	Lanthanum	in alloy for storing hydrogen, battery anodes in hybrid cars, carbon lighting applications, optical glasses, petroleum refining catalyst, in flints	32 ppm	N/A			
58	Ce (RE)	Cerium	in self cleaning ovens, catalytic converters, red pigment, TV & low energy lighting, in flints	68 ppm	N/A			
59	Pr (RE)	Praseodymium	alloy for aircraft engines, in flints, in permanent magnets, carbon arc lighting, yellow color in glass, enamel, glaze, protective welding goggles	9.5 ppm	N/A			
60	Nd (RE)	Neodymium	alloy for permanent magnets in electronic devices, in protective welding goggles, violet coloring for glass, in lasers, catalysts for polymerization	38 ppm	N/A			
61	Pm (RE)	Promethium	radioactive research, atomic batteries in pace makers, guided missiles & radios	not found in nature	N/A			
62	Sm (RE)	Samarium	in powerful magnets, optical lasers, neutron absorber in nuclear reactors, glass, ceramics, carbon arc lighting	7.9 ppm	N/A			
63	Eu (RE)	Europium	in Eurobank notes, low energy lights, control rods, lasers, thin superconductors	2.1 ppm	N/A			
64	Gd (RE)	Gadolinium	an alloy to improve workability, high temperature resistance, oxidation for magnets, electronic components, data storage, MRI, control rods	7.7 ppm	N/A			
65	Tb (RE)	Terbium	doping agent in solid state devices, for low energy & mercury lighting, medical x-rays, lasers, loudspeakers	0.0011 ppm	N/A			
66	Dy (RE)	Dysprosium	an alloys for magnets in motors, generators, wind turbines, electric vehicles, nuclear control rods & halide discharge lamps	6 ppm	N/A			

67	Ho (RE)	Holmium	in nuclear control rods & magnets	1.4 ppm	N/A			
68	Er (RE)	Erbium	alloy to improve workability, infrared absorbing glasses, pink color in glass, in glass fiber to enhance signal carrying capacity	3.8 ppm	N/A			
69	Tm (RE)	Thulium	portable X-ray & laser surgical applications	0.48 ppm	N/A			
70	Yb (RE)	Ytterbium	in memory devices, tunable lasers, as industrial catalyst	5.3 ppm	N/A			
71	Lu (RE)	Lutetium	research, refinery catalyst for hydrocarbon cracking	0.51 ppm	N/A			
72	Hf	Hafnium	used in nuclear control rods for submarines, plasma welding torches, electrical insulators in microchips, catalysts for polymerization	3.3 ppm	N/A		8	4
73	Ta	Tantalum	in mobile phones capacitors, surgical implants, neon light electrodes, rectifiers, special glass, turbine blades, rocket nozzles, supersonic aircraft	2 ppm	1.10		26	20
74	W	Tungsten	in alloys for high temperature applications, for very hard drilling & cutting tools used in metal working, mining & petroleum industries, in fluorescent lighting	1 ppm	86.40		24	21
75	Re	Rhenium	in alloys for oven filaments, x-ray machines, electrical contacts, single-crystal turbine blades, in catalysts for hydrogenation reactions	0.0004 ppm	0.05		21	11
76	Os (PG)	Osmium	limited uses, alloy to enhance hardness used in needles, fountain pen tips, instrument pivots, electrical contacts & as a catalyst	0.0001 ppm	N/A			
77	Ir (PG)	Iridium	alloy for hardness in pen nibs & spark plug contacts	0.000003 ppm	N/A			

78	Pt (PG)	Platinum	in catalytic converters, as catalyst for more fuel cell efficiency, in computer hard disks, thermocouples, optical fibers, LCD sceens, turbine blades, spark plugs, medical applications, jewelry	0.001 ppm	0.19			
79	Au	Gold	used in jewelry, art, electro plating, computer chips, electrical connectors, catalyst for vinyl acetate	0.0011 ppm	3.10		13	5
80	Hg	Mercury	use restricted because of toxicity, still used as catalyst in chemical industry	0.05 ppm	4.50		10	7
81	Tl	Thallium	toxicity limits use, in photoelectric cells, special glass, low temperature thermometers in switches	0.6 ppm	0.01		2	2
82	Pb	Lead	toxicity limits use, still used in car batteries, pigments, ammunition, weights, glass, radiation protection, solders, roofing & stained glass windows	14 ppm	4,820.00		15	2
83	Bi	Bismuth	an alloy in fire extinguishers & detectors, solders, electric fuses, in yellow cosmetics and paint pigment, indigestion tonic	0.048 ppm	10.20		14	11
90	Th	Thorium	alloy & industrial catalyst, could be used for nuclear power fuel	12 ppm	N/A		4	2
92	U	Uranium	nuclear power & nuclear weapons	2.4 ppm	74.12		7	2
		PGM			0.47	*	28	26
		REE			130.00		29	27

Sources: Elements in column 3 include those studied for demand criticality in the 31 studies from Hayes and McCullough (2018). Column 8 indicates how many of the studies concluded the element was critical and column 98 indicates how many studies considered the element for criticality. Columns 1, 2 and 5 are taken from Boudreaux (2020). Column 4 and 6 are taken from USGS Mineral Commodity Surveys (2017) and Royal Society of Chemistry (2019).

Notes: # indicates the atomic number. sym = the elements symbol, ppm = parts per million, REE = rare earth elements (highlighted in yellow), PGM = platinum group metals highlighted in green, production for phosphorus is phosphate rock, barium is barite, rare earth elements are earth oxides.

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