Assessing mineral supply concentration from different perspectives through a case study of zinc

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Abstract

Increasing demand for nonfuel mineral commodities has increased concerns regarding the reliability of their supplies. “Criticality” assessments over the past decade have attempted to capture this concern through a set of indicators, the most common of which quantifies the risk associated with market concentration by applying the Herfindahl–Hirschman Index (HHI) to the world production of a given commodity by country in a given year. Although this approach is useful, it inherently assumes that all of world production is available to the market and is thus potentially at risk. In this analysis, the HHI, as well as HHI weighted by country governance, is calculated for mined and refined zinc via the standard approach of including all world production data and comparing that to the HHI when using the best estimate of what is available to the world market. The results indicate that although the HHI of both mined and refined zinc world production has increased markedly over the past decade, the HHI for what is available to the market for mined and refined zinc has remained relatively constant and low, which is indicative of minimal supply risk. This is mainly owing to the fact that a large and increasing share of the world’s mined and refined zinc production comes from China, but that production supplies domestic consumption as well as small amounts of exports. As a result, the zinc materials that are available to the world market are produced by a relatively large and diverse set of countries. Although these analyses are specific to zinc, they are likely to be comparable for other commodities of which the largest producers are also the largest consumers and highlight the importance of examining different perspectives in criticality assessments.

Keywords Herfindahl–Hirschman Index · Market concentration · Supply risk · Criticality · Critical raw materials

Introduction

Background

Mineral-based commodities, including aluminum, copper, nickel, steel, and zinc, form the basis of every modern

economy. From transportation and infrastructure to communication and defense, mineral commodities provide an indispensable function and their demand is likely to continue to increase in the future. With the increase in demand has been an increase in concern regarding the reliability of supply for these and other mineral commodities. These concerns have been raised in the USA since at least the 1950s (President’s Materials Policy Commission, The 1952). More recently, in 2008, the U.S. National Research Council (NRC) published a report titled “Minerals, Critical Minerals, and the U.S. Economy” that brought greater attention to the issues underlying the risk of a supply disruption (National Research Council 2008). Since then, a number of studies have been released by governments (European Commission 2010, 2014, 2017, 2020; U.S. Department of Energy 2010, 2011; Hatayama and Tahara 2013; Moss et al. 2013; National Environmental Research Council 2015; U.S. National Science and Technology Council 2016; McCullough and Nassar 2017; Nassar et al. 2020a, b; Nassar and Fortier 2021), nongovernmental

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organizations (Morley and Eatherley 2008; Thomason et al. 2010; Glöser et al. 2015), corporations (Granta Material Intelligence 2018; Rosenau-Tornow et al. 2009; Duclos et al. 2010; Zepf et al. 2011; Ku et al. 2018), and academia (Graedel et al. 2012, 2015; Achzet and Helbig 2013; Goe and Gaustad 2014; Calvo et al. 2018; Kolotzek et al. 2018). These studies differ in their assessments of “criticality,” often have different perspectives, and assess different sets of mineral commodities under varying geographic, temporal, and sectoral scopes. Despite their differences, the vast majority of these studies incorporate in their assessment of supply risk some measure of production concentration or its variants (Graedel and Reck 2016; Brown 2018). The rationale underlying this approach is based on the assumption that, all other things being equal, if production is concentrated in a few locations, it is at a higher risk of a supply disruption (U.S. National Science and Technology Council 2016). The indicators used to measure this concentration vary by study but typically use the Herfindahl–Hirschman Index (HHI), which is a commonly used metric for market concentration. HHI is calculated by summing the square of each contributor’s individual market share (U.S. Department of Justice 2018). Its value approaches zero when a market is composed of many contributors of relatively equal share and reaches its maximum value of 10,000 when a market is controlled by a single contributor. The U.S. Department of Justice generally considers markets to be moderately concentrated in which the HHI is between 1500 and 2500 and considers markets to be highly concentrated in which the HHI is greater than 2500 (U.S. Department of Justice 2018).

Motivation

In most criticality assessments, HHI is used to measure production concentration at the country level by using world production statistics reported on an annual basis from governmental organizations or industry associations. In a few cases, concentration is measured at the company level (e.g., Rosenau-Tornow et al. 2009) and in some cases the concentration is measured for trade into a specific country (e.g., Blengini et al. 2017a, b). When measured at the country level, HHI is typically weighted by the level of governance of the country in question under the assumption that a country that has a low level of governance or high degree of political instability is more likely to have a supply disruption than a country with a high level of governance and low degree of political instability. A number of indicators have been used to assess governance in criticality assessment, with the most widely used being that of the Worldwide Governance Indicators (WGI) published annually by The World Bank Group (2017).

A report by the U.S. National Science and Technology Council (NSTC) used an indicator combining both HHI and

WGI in its assessment of supply risk and found that, across all nonfuel mineral commodities examined, the overall risk of a supply disruption has increased over the past few decades, driven mainly by an increase in production concentration (U.S. National Science and Technology Council 2016). In this and other assessments, world production by country is used to measure the concentration of supply. The inherent assumption with using a world-production-by-country concentration approach is that all world production is available for consumption by any country. This assumption, however, may not always be representative. Indeed, the increased production concentration for most commodities is the result of China’s increased share of global production. However, some of the raw materials that China produces are consumed in China and are thus not available for consumption by others. While China’s share of world production has increased markedly over the past few decades for many commodities, so has its consumption of these materials (Gulley et al. 2018; Nassar et al. 2020a). This would, of course, not be restricted to China and would apply to any country that is both a major producer and consumer and that does not export the majority of its production. For example, the USA is the world’s leading producer and consumer of beryllium.

To address the risk of a supply disruption more accurately, we suggest that, under certain circumstances, it may be more appropriate to examine market availability rather than production. For simplicity, market availability is defined here as the quantity of materials exported by each country (i.e., material exported for consumption outside the producing country). This is, of course, not an entirely accurate quantification of what is available to the market. Exported materials may, for example, be “spoken for” via long-term offtake agreements and domestically consumed materials are not necessarily unavailable to other countries. This definition of market availability is thus a rough measure of what was available to other countries at the time and not what could be available. Note that using import sourcing as the basis for market concentration assumes that the country in question cannot obtain the materials elsewhere, while using world production as the basis for market concentration assumes that all the material is available to other countries. In a sense, these two approaches are two extremes. The proposed approach is thus somewhere in between these two extremes and, although not perfect, might provide a useful perspective, especially for evaluating scenarios in which a producing country continues to produce to meet domestic needs but intentionally cuts-off supplies to other countries (as opposed to scenarios in which a country’s production is halted unintentionally and disrupts both domestic and foreign consumption).

Zinc was selected as the study material based on the availability of granular global trade data and a rapidly increasing zinc world production concentration during the

past two decades mainly owing to increased production in China (U.S. National Science and Technology Council 2016; McCullough and Nassar 2017). Zinc is also one of only two mineral commodities that was recently recommended for inclusion on the U.S. Critical Minerals List (Nassar and Fortier 2021). Results of the standard method of measuring world production concentration were compared to this new approach of measuring the concentration of market availability for both mined and refined zinc using the HHI indicator, as well as the HHI weighted by WGI. To be thorough, the concentration of US imports of refined zinc was also examined to provide a comparison of the other extreme (U.S. Geological Survey 2018).

Methodology

Data

To evaluate the differences in supply risk results (i.e., different HHI values), three different supply concentration perspectives were used for both mined and refined zinc: world production, market availability, and US imports.

World production data were sourced from the world production tables for both zinc mine and refinery production in the Zinc chapter of the Minerals (U.S. Geological Survey 2018). Trade data were sourced from Global Trade Atlas (GTA) (Global Trade Information Services 2018). Mined zinc trade data were compiled using Harmonized System (HS) code 260800 (zinc ores and concentrates) and refined zinc trade data were compiled using HS codes 790111 (zinc; unwrought, not alloyed, containing 99.99% or more by weight of zinc) and 790112 (zinc; unwrought, not alloyed, containing less than 99.99% Zn by weight) (Global Trade Information Services 2018). Similarly, US imports of refined zinc were obtained from GTA. Because the USA is a net exporter of mined zinc (U.S. Geological Survey 2018), US imports of mined zinc were not included in this analysis. World exports of mined and refined zinc were used in this analysis as a proxy for market availability. Note that the same trade data should be derived from the perspective of the exporting country (i.e., exports as reported from exporting country “i” to importing country “j”) or from the importing country (i.e., imports as reported by importing country “j” from exporting country “i”). Although these represent the same trade flow from different reporting perspectives, they rarely correspond perfectly in the trade statistics owing to a variety of reasons (Gaulier and Zignago 2010). Because import data are generally more granular (often for tariff purposes, for example), “export data” were obtained by compiling the data as reported by the importing country perspective.

To provide context as to how the results have changed over time, these analyses were performed for 1997–2015. Although production data are available for a longer time series, the analyses were constrained owing to the limited availability of robust trade information and because the first year of data for the WGI is 1996.

Indicator calculations

In this analysis, the HHI as well as the HHI weighted by WGI (“*R*”) is calculated using the following equations, as described by the U.S. National Science and Technology Council (2016) and introduced in the European Commission (2010) report on critical raw materials:

$$HHI_{m,t} = \sum S_{i,m,t}^2 \quad (1)$$

$$R_{m,t} = \sum S_{i,m,t}^2 WGI_{i,t} \quad (2)$$

where *S* is country *i*’s share of commodity *m* in year *t*, and WGI is the composite Worldwide Governance Indicator score. In this analysis, *S* will be the share of world production, market availability, and US imports under the three different supply concentration perspectives.

Note that the WGI is a set of six individual indicators that cover different dimensions of governance: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, role of law, and control of corruption (World Bank Group, The 2017). In this analysis, the aggregation and normalization method described by the U.S. National Science and Technology Council (2016) is used to provide a single WGI value for each country that ranges from a minimum of 0 for countries with the highest level of governance (lowest risk) to a maximum of 1 for countries with the lowest level of governance (highest risk).

Results and discussion

World production and market availability of mined and refined zinc, as well as US imports of refined zinc, by country contribution, are displayed as sets of stacked bar graphs in Fig. 1A and 1B, respectively, for 2000, 2005, 2010, and 2015. In general, both mined and refined zinc world production figures show a similar trend of China representing an increasingly larger portion of an increasing total world production over time. Compared to world production, market availability of both mined and refined zinc were significantly less in terms of absolute quantity (at roughly two-thirds to three-quarters of the world’s mined zinc quantity and at roughly one-fourth to one-third of the world’s refined

Fig. 1 Annual world production, market availability, and US imports for both mined (A) and refined zinc (B) in thousand metric tons of contained zinc for 2000, 2005, 2010, and 2015 by country contribution. US imports are not displayed for mined zinc because the USA is a net exporter of mined zinc. World production of mined zinc

includes 43 countries in the “other” countries category, and market availability of mined zinc includes 169 countries in the “other” countries category. Similarly, world production of refined zinc includes 30 “other” countries, market availability of refined zinc includes 95 “other” countries, and US imports include 14 “other” countries

zinc production). Furthermore, while market availability increased for both mined and refined zinc over this time period, it did so at a much lower rate as compared to overall world production. This, along with notable differences in country contribution between the two perspectives, is largely the result of China’s increasing share of world production and its noticeable absence in the quantity that is available to the market, presumably because China consumed most of the zinc that it produced domestically.

While the USA is the leading global importer of refined zinc, the overall quantity is relatively small in comparison to both world production and market availability and decreased between 2000, 2005, and 2010 before increasing in 2015. A review of the mix of import sources indicates that most of the refined zinc material imported into the USA originated from Canada and Mexico.

HHI indicator

The HHI calculation (Eq. 1) was applied to the data described above, with the results for mined and refined zinc being displayed by country contribution in Fig. 2A and 2B, respectively. Calculations of HHI result in a single number because the squared market shares are summed. However, Fig. 2A and 2B also show the individual country’s contribution towards the overall HHI calculated. The world production HHI values for both mined and refined zinc show a consistent increase over time from 2000 through 2015. For mined zinc production, the HHI was 1080 for 2000 and increased to 1660 in 2015. Of those HHI values, China contributed approximately 38% of the total in 2000, and 75% of the total in 2015 (Fig. 2A). The HHI of refined zinc production showed a similar trend of increasing steadily from a value of 800 in 2000 to 2100 in 2015. Of those HHI values, China contributed 60% of the total in 2000, and 91% of the

Fig. 2 HHI results for mined (A) and refined zinc (B) for world production, market availability, and U.S. imports for 2000, 2005, 2010, and 2015 by country contribution. Note that A and B do not have uniform vertical axis scales

total in 2015 (Fig. 2B). As noted earlier, the U.S. Department of Justice generally considers markets to be moderately concentrated when the HHI is between 1500 and 2500 (U.S. Department of Justice 2018). Although technically derived for the purposes of horizontal assessment of mergers and acquisitions at the company level, this categorization suggests that mined zinc production perhaps can be categorized as moderately concentrated starting in 2012 and refined zinc production can be categorized as a moderately concentrated since 2009. In general, zinc world production, as compared with that of other nonfuel mineral commodities, is not highly concentrated (McCullough and Nassar 2017). However, as indicated in Fig. 2A and 2B, the HHI of zinc mined and refined world production has been steadily increasing, mainly owing to China's increasing share of production. If China continues to increase its share of the total, zinc world production, especially refinery production, would become categorized as highly concentrated in the future.

In contrast to the HHI of world production, the results indicate that the HHI of market availability for mined zinc has remained relatively constant throughout the time period examined. HHI ranged between 1110 and 1270, and averaged 1210 for 2000, 2005, 2010, and 2015. Australia and Peru accounted for the majority (58–78%) of mined zinc available to the market, and China was noticeably absent (Fig. 2A). The HHI of market availability for refined zinc decreased in 2005 from 2000 before remaining relatively constant in 2010 and 2015. The HHI ranged between 870 and 590, and averaged about 700 for 2000, 2005, 2010, and 2015. China was a contributor in the global market in 2000, representing 47% of market availability, but was not present in the later years (Fig. 2B).

Importantly, the lower HHI of market availability as compared with the HHI of world production for both mined and refined zinc indicates that there may be a relatively lower degree of supply risk in the zinc market than one might assume when performing the standard world

Fig. 3 Results for both mined (A) and refined zinc (B) for world production, market availability, and US imports for 2000, 2005, 2010, and 2015 by country contribution. Note that A and B do not have uniform vertical axis scales

production-based HHI analysis. This is, again, a reflection of the fact that Chinese production (which is largely responsible for the increasing HHI value in the standard analysis) has not been available to the world market. The HHI of US imports for consumption of refined zinc were significantly higher than the HHI of world production and market availability. This is because the USA imported refined zinc from a limited number of countries each year (11 to 15 unique countries in a given year), and the majority of imports (89 to 95%) originated from Canada. The HHI ranged from 3700 to 5400 and averaged 4400 for 2000 through 2015 (Fig. 2B).

R indicator

The results for the *R* indicator (Eq. 2) for both mined and refined zinc production, displayed in Fig. 3A and 3B, respectively, show similar trends to the HHI results (Fig. 2A and 2B). Specifically, the *R* values for mined zinc world production increased continuously between 2000, 2005, and

2015, although the *R* results for market availability of mined zinc are somewhat lower than those of world production and remain generally constant in the years examined. The *R* results for refined zinc world production increased between 2000, 2005, 2010, and 2015, but the *R* results for market availability of refined zinc are notably lower than those for world production and generally decrease over time. For both mined and refined production, China is the largest contributor for the *R* world production results, but not for market availability. These and other similarities are also evident in Fig. 4A and 4B for both HHI and *R*, respectively, which display the overall results, excluding country contributor, for each perspective (world production vs. market availability) for each year of the analysis. For example, although the HHI and *R* indicator values for world production and market availability for both mined and refined zinc were similar in magnitude in the late 1990s, they have since diverged such that the world production values for both the HHI and *R* indicators are now notably greater than those for market

Fig. 4 Time-series results HHI (A) and R (B) indicator results for mined and refined zinc and for world production and market availability. Note that A and B do not have uniform vertical axis scales

availability of both mined and refined zinc. This is mainly due to the simultaneous increase in zinc production and consumption in China, which increases the HHI of world production but not for market availability.

Despite these general similarities in trends across the HHI and *R* results, there are a few notable exceptions. Most notable among these exceptions is that the *R* indicator values for US imports are lower than *R* indicator values for refined zinc world production (Fig. 3B), which is converse to the results of the HHI (Fig. 2B). This is generally owing to the high governance score (low WGI) for Canada, which is the largest import source for the USA, relative to that of the major world producers.

Although *R* and HHI indicator values can be compared by production stage (mined vs. refined), by perspective (world production vs. market availability), and over time, the *R* indicator values cannot not be compared to their HHI counterpart on an absolute basis (i.e., the vertical scale of

Fig. 4A to 4B); an *R* value is inherently lower or equal to the corresponding HHI value owing to the *R* indicator being weighted by WGI values ranging from 0 to 1. Because of this issue, a direct comparison of the HHI and *R* values requires that they are normalized. In this analysis, the HHI and *R* values are normalized to 1 for year 1997 (Fig. 5A and 5B). These normalized values provide the clearest illustration of how the HHI and *R* trends for both mined and refined zinc have diverged for world production relative to market availability during the past decade.

Conclusions

The HHI indicator, along with HHI weighted governance (*R*), has been used by the majority of raw material criticality assessments. Inherent in this type of analysis is the assumption that all world production is available for consumption

Fig. 5 Time-series results for normalized HHI (A) and R (B) indicator results for mined and refined zinc and for world production and market availability. Values are normalized such that the values in 1997 are set to 1

in the market. In the current analysis, the HHI and *R* analyses are based on estimated market availability using zinc as a case study. The results indicate that, in contrast to the standard analysis based on world production, the market availability of mined and refined zinc has not become more concentrated over the past decade. The standard method for calculating concentration using world production may therefore over inflate the supply risk for a material when the production concentration is high, but the concentration of market availability is low. The increasing production in China, which was the reason for the higher HHI values, was not exported to the global market owing to increasing domestic consumption in China and so did not decrease supply risk for the world. The same situation is likely to be the case for other mineral commodities for which the largest producers are also the largest consumers. However, it is important to note that not all mineral commodities will follow the pattern displayed in this zinc example; different

mineral commodities will have varying patterns within production and supply availability, and resulting implications will likely be nuanced to that particular industry.

In the current analysis, only the supply chain up to the refined metal was examined. For many countries, import reliance may occur further down the supply chain at the semifinished and finished goods stage, for which the supply risk will be different. If supplies from the mining or refining stages are limited, the ability of countries to manufacture semifinished and finished goods may be at risk. Also, countries planning to use the output from mining or refining may find that the prices that they must pay for that output are higher than acceptable for viable manufacturing.

The type of analysis presented here can be used for other mineral commodities, but such applications are limited by the availability of granular trade data. Such data may be especially limited in the case of byproduct metals, such as germanium and tellurium, where trade data are aggregated

to include multiple commodities. While some countries have detailed trade codes for those mineral commodities, most countries do not. Moreover, while the current analysis focused on the USA, it needs to be expanded to other countries or regions to determine its usefulness before being recommended for broader use.

Finally, it is also important to note that no single indicator or set of indicators can precisely capture the complexities of the market. Commonly, for example, supply contracts and offtake agreements between companies restrict what is available to the market for immediate purchase. Nevertheless, the market availability analysis presented here provides an alternative assessment of the risk of a supply disruption that is associated with market concentration than simply using world production.

Declarations

Conflict of interest The authors declare no competing interests.

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