Title: Global critical metal resources; why we don't know how much we have

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1 Abstract

The critical minerals are a group of elements that are essential to modern life but have insecure supply as a result of a variety of factors and are of increasing importance given their use in technologies needed to reduce global CO_2 emissions and mitigate against anthropogenic climate change. However, the majority of these critical elements are produced as co- or by-products of other more widely produced metals, meaning that their economic contributions to mining operations are often small and the elements in question are often produced downstream in smelters or refiners. This means that mines may produce a critical element that is unquantified in reserve or resource reporting. Extrapolating this to a global scale yields a situation where we simply are unable to robustly estimate current resources of these crucial elements. This paper reviews the key uncertainties in these areas as well as ways forward to improving the predictability of future production of these critical minerals.

2 Introduction

The critical minerals are a group of elements and minerals that generally provide essential properties to a technology or product, are not easily substituted, are generally not recycled or are recycled at low levels, and are subject to supply-chain risk along with often being of strategic importance (e.g., Graedel et al., 2014). They are vital to green energy and low- and zero-CO_2 technologies, such as wind turbines, solar panels, electric vehicles and storage batteries, as well as being used in a variety of defense applications. Although the minerals and metals considered critical vary from country (or group of countries such as the EU) to country, between different sections of governments, and between different industries (e.g. Jowitt et al., 2018), a common group of minerals and metals has emerged that are generally considered critical as outlined below. However, the production and known resources of a significant proportion of these critical minerals is limited to a small number of countries, some of which may be economically or politically unstable or may have poor international relations with countries that require these critical minerals, creating significant supply risk. One example of this is Pt, where ~70% of global production is focused in a single country, namely South Africa (USGS, 2021). In addition, many of the critical minerals are by-products and have both varying main-product metal companionality (Nassar et al., 2015) and can only be recovered at a limited number of smelting/refining operations as by-products of other metals, both of which enhance their supply-chain risk. One example of this is Co, which is primarily a by-product of Cu and Ni mining. This has led to a situation where global Cu and Ni mining is diverse but not all of these mines recover Co, leading to a potential lack of sources of Co and an increase in the supply-chain risk associated with this element (e.g. Nansai et al., 2017).

Some of the main drivers in the demand for critical metals include: (1) the push towards low-emissions energy production along with energy storage and usage; (2) the increased use, complexity and prevalence of communications and entertainment technologies; and (3) security and defense applications. The critical metals that are currently imperative to the production of wind turbines, photovoltaic cells, nuclear reactors, electric cars, and batteries to achieve low-emissions energy production, storage and usage include C (graphite), Co, Ga, In, Li, PGE, REE, Sb, Sc, Se, Te, Th and Zr, among others (Jowitt et al., 2018). In addition, Ga, Ge, In, Nb, Sb, Te and Y are essential for the production of micro-capacitors, flat screen phosphors and semiconductors that are necessary for the production of high-tech communications and entertainment devices (Jowitt et al., 2018). Finally, the production of nuclear radiation detectors, armor and weapons, and aerospace super-alloys for defense and security purposes require the critical metals Be, Mo, Nb, Re and W (Jowitt et al., 2018). This has led to all of these elements being generally considered critical, although different countries and organizations may also add other elements or minerals to this list. This reflects the fact that the definition of an element's criticality is viewpoint dependent (i.e., industry vs. country; Graedel et al., 2014). For instance, the U.S. Department of the Interior on May 18, 2018 defined a list of 33 critical metals, with this qualifying statement:

> *"This list of critical minerals, while 'final,' is not a permanent list, but will be dynamic and updated periodically to reflect current data on supply, demand, and concentration of production as well as current policy priorities."*

The variation in elements considered to be critical is exemplified by the numerous reports that assess the criticality of elements from the subjective viewpoint of the reviewing organization (Figure 1). For instance, boron, coking coal, natural rubber, phosphate rock and phosphorus are classified as critical metals and materials by the European Union (EU) but not by the vast majority of other governments or organizations (Figure 1; *see caption for references*). In comparison, the rare earth elements (REE) and some of the platinum group elements (PGE; Pd, Pt, Rh and Ru) are and have been considered critical by many countries since 2005, with Dy and Nd listed as critical in all of the 25 criticality reports summarized in Figure 1.

The dynamic and variable nature of criticality can be examined using the base metal Zn (Figure 1). Although the United States, UK and EU do not consider Zn a critical metal, Japan (Hatayama and Tahara, 2015) and Willis and Chapman (2012) do and Australia moved in 2013 to also consider Zn a critical metal (Skirrow et al., 2013) but subsequently removed Zn from their critical metals list in 2020 (Austrade, 2020). The complexity of criticality assignments is outlined in Figure 1, which highlights the evolution of metal and raw material criticality and the differing positions governments have had on potential supply restrictions, impacts of supply restrictions, economic importance and environmental implications for a given metal or raw material. This is just one form of uncertainty associated with determining resources and future supply of the critical metals; actually classifying what metals and minerals are critical, although as outlined below a gradual consensus is emerging.

A comparison of the critical metals and raw materials lists for Australia (Austrade, 2020), the EU (EC, 2020) and the United States (USDOI, 2018) illustrates the recent consensus regarding some of these metals (Table 1). All three reports indicate that Sb, Be, Bi, Co, Ga, Ge, Hf, In, Li, Mg, natural graphite, Nb, PGE, REE, Sc, Ta, Ti, W and V should be considered critical. A significant factor defining criticality is supply risks, which as mentioned above can be ascribed to a variety of geological, geographical, political and metallurgical considerations. However, economic rather than geological reasons mean that the critical metals are invariably by-products of the refining and smelting of the major industrial metals, the so-called ***main-products*** (Table 2). There are a number of implications that arise from the by-product nature of the critical elements that directly impact our understanding and quantification of global critical metal resources. The most important of these can be split into two categories: (1) quantifying pre-mining resources and (2) determining material flows of critical elements from ore to payable product.

Although some critical elements are considered to have security of supply issues that are perhaps geographical or political rather than reflecting an actual lack of supply of the element in question, the one thing that links all of the critical elements together is a perceived risk of demand (including domestic demand met by imports into a given country) exceeding supply. Determining this demand-supply balance requires knowledge of demand (i.e. production) for a given element or mineral, which can be estimated by the examination of current industrial demand and how this has been affected by recent trends, enabling predictions to be made. However, the supply (i.e. resources-reserves) side is problematic, primarily as a result of the by-product nature of the majority of these elements (e.g. Nassar et al., 2015). As mentioned above, the fact that these elements may be produced by a given mine but at a level considered insignificant during resource-reserve reporting (e.g. <1% of contained metal value) means they are often not reported either during this reporting or even in production data for given projects (Jowitt and McNulty, 2021). This is compounded by the fact that these elements are produced at smelters or refineries downstream of a mine; the majority of these downstream operations also process concentrates from multiple mines, meaning the materials flows of these metals are very difficult to track (e.g., McNulty and Jowitt, *in review*). This also presumes that the smelter and/or refinery that is processing the concentrate is able to extract the critical metals that are present within the concentrate at a reasonable recovery rate; this is frequently not the case, meaning that critical metals end up deporting to waste at various stages of mining, beneficiation, mineral processing, smelting, and refining, rather than being produced for sale (e.g. Werner et al., 2017). All of this means that critical element resources and reserves are necessarily under-reported as a function of the nature of these elements and the by-product relationship between these elements and more economically important metals (Figure 2).

In this contribution we focus on factors that hinder our current understanding of critical metals, namely uncertainties in reported annual production, origin transparency of main-product concentrates, and uncertainties in reported global supply of selected critical elements. We explore why we simply don't know the amount of potentially producible critical metals as a result of the uncertainties related to metal by-product recovery and discuss options for advancement in key knowledge gaps to improve our ability estimate global resources with confidence.

3 Global Critical Metals Production

Many of the critical metals are not currently economically feasible to mine on their own but rather are by-products of the mining of main-product metals such as Cu, Ni and Zn (Table 2; Figure 2). The terms main-product, co-product and by-product are strictly a function of mineral economics. Ore deposits are mined for economic minerals, which here are termed main-product elements and form the primary source of revenue for a given mining operation. Cases where an ore deposit contains multiple economically significant elements that are only feasible to mine collectively involve the mining of co-products. In comparison, by-products are incidental products generated during the smelting, refinement, or other processing to extract the main- or co-products, activities that typically occur downstream outside of the mining environment (often termed “outside the mine gate”). Metals such as these are present at trace concentration levels in the ores of the host metals and, under favorable economic conditions, can still be extracted at smelters or refineries (e.g., Nassar et al., 2015), but are often not calculated in resource and reserve estimates, recorded in mine production annual reports, and sometimes are not quantified by smelters and refineries. This study uses global production data for select main-product metals and their critical metal by-products to demonstrate two important mineral economic themes that have implications for the future of critical metals production, namely uncertainties in annual production data and the ratios of production of main and by- and co-product metals.

3.1 Uncertainties in annual production data

Worldwide historic metal production data is typically publicly sourced from two entities, the U.S. Geological (USGS) and the British Geological (BGS) surveys. In addition, private firms collate commodity production data and generate market predictions and reports, such as Wood Mackenzie Chemicals Co., whereas Mining Data Solutions provides limited open access (full access with a paid membership) to collated mining, production and operation data and industry reports for select mining operations. An important consideration when assessing trends in annual production data is recognition of inherent uncertainty in the data and unclear sourcing of the information being presented, with this being a particular problem for the by-product metals. We demonstrate this concept in Figure 3, which shows the annual production of Cu, Ni, Zn and Mo along with their associated critical metal by-product production—Se, Te, Co, Cd and Re from 1970 through 2018.

3.1.1 Main Product vs By-Product Metal Production

The annual global production of Cu, Zn, Ni and Mo has increased between 1970 and 2018 with both the USGS and BGS reporting similar annual production trends (Figure 3A). The most notable exception to this is Mo production before 1977 (Figure 3A). Over this period the BGS reports an average Mo production rate of ~140,000 t/yr, which is some 60,000 t/yr greater than the reported production by the USGS, 82,000 t/yr. However, this consistency is poorer when considering some of the critical metals, where USGS and BGS annual production estimates vary significantly (Figure 3B).

This is illustrated by annual Co production, with fiscal year (FY) differences in reported worldwide production that peak at ~60,000 t/yr for a maximum percentage difference of 42.9% [here defined as Δ% = [(max−min)/max)*100] in 2011. In addition, several other years of Co production have discrepancies of <20,000 t/yr (FYs 1972-1975 with Δ% between 49.7–58.6%; FYs 2008-2018 with Δ% between 15.3–42.9%). In comparison, USGS and BGS worldwide Re production estimates differ by >5 t/yr (Δ% between 0.8–9.6%), with the exception of annual production estimates for 2006 and 2007, which differed by 10 t/yr (Δ% between 18.1–18.5%). Of the by-product metals presented in Figure 3B, reported Cd production has been the most consistent between the USGS and BGS. From 1970 to 2018 worldwide by-product Cd production ranged from 15,200 t/yr to 26,000 t/yr, with the greatest difference in 2003 of 6,787 t/yr (Δ% of 26.9%) and the lowest difference in 1983 of

2 t/yr (Δ% of 0.01%; Figure 3B). In addition, Re and Se production data illustrate that the periods of reported production data are not always uniform between the surveys (i.e. one survey does not consistently over-estimate relative to the other), providing another form of uncertainty relating to the critical metals (Figure 3B).

A comparison of the annual country-by-country production for Se and Te in 2018 further highlights a further lack of transparency and/or uniformity in by-product metal production reporting (Figure 4A-B). The USGS reports smaller amounts of annual worldwide Se production (39% or 1,077 t/yr) and Te (11% or 54 t/yr) compared to the BGS (Figure 4A-B). This is in part because US domestic production of Se and Te is proprietary information and is withheld from USGS reporting (USGS, 2020). It is also important to note that this variation between reported annual production values from the USGS and BGS does not mean that one survey is right or wrong, but rather there is inherited uncertainty in these data that must be considered when discussing metal and mineral criticality and supply. Tellurium typifies this, where BGS estimates indicate steady, annual growth in Te production since 2010, a positive sign for the security of supply of this critical element. However, the USGS data for the same period of time suggests that Te production nearly quadrupled after 2015 (Figure 3B). This apparent difference in annual production can be explained by the fact that Chinese Te production was not reported by the USGS until after 2015 (McNulty and Jowitt, *in review*), leading to a likely underestimate in global Te production using pre-2015 USGS data. This also means that any assessments of supply risks or criticality using these data may over-estimate the criticality or potential under-supply of this element, adding uncertainty to any modeling of supply and demand for this element. It is also possible for the opposite to occur, where overestimates of production for whatever reason lead to an underestimate of criticality and supply risk and hence a lack of forward planning relating to securing supplies of the critical mineral or metal in question. All of this highlights the uncertainty in one of the more robust areas of knowledge of the critical metals and minerals – how much we actually produce.

3.2 By-Product and Main Product Metal Production Ratios

Although as outlined above there can be significant uncertainty in the annual production values for the by-product metals we assessed changes in their relative production over time using a ratio of the by-product to main-product annual production, herein referred to as *metal production ratios* (Figure 5). These ratios essentially provide insights into our ability to produce by-product metals; for example, an increase in the metal production ratio for a given critical metal would indicate that we are producing more of that critical metal per unit of main-product metal production – in other words, we are improving production of this by-product. Cases where metal production ratios remain relatively unchanged from year-to-year indicate that the annual by-product metal production is proportionally the same to its main-product metal counterpart. However, this trend is only sporadically observed over relatively short periods of time (~5 years of production) in both the USGS and BGS datasets and for all of the metals considered in this study (Figure 5). Instead, metal production ratios are more variable, with annual increases in metal production ratios indicating increased production rate of the by-product compared to the main-product, and vice versa in the case of annual decreases in the metal production ratio.

The most pronounced example of by-product growth relative to main-product annual production is that of Co (Figure 5A). As outlined above, the majority of Co production is as a by-product of Cu or Ni, with the exception of production in Morocco and artisanal mines in the Democratic Republic of the Congo (DRC; Figure 2; e.g. USGS, 2020). Data from the USGS suggest that since the early 1990s annual Co production has been increasing relative to its main-metal products of Cu and Ni (i.e., increasing Co production ratio), with a notable exception between 2011 and 2013 when the Co production ratio decreased (Figure 5A). In comparison, data from the BGS show a pronounced U-shaped pattern (Figure 5B). From 1972 to 1975, annual Cu and Ni production remained at a similar level (7.02–7.24 Mt Cu; 0.63–0.75 Mt Ni) whereas Co production nearly doubled, resulting in a significant increase in Co production ratios (Figure 5B). After 1975, Co production dropped back to pre-1972 production levels with Co production ratios annually increasing from 2000 to 2010, similar to the trend observed in the USGS data. This again illustrates the uncertainties in critical metal and mineral production data, hampering efforts in examining whether the mining industry is improving their production capacity of these vital commodities or whether more of these commodities are being lost to waste.

Another example that is worth investigating is Cd production, a metal that is crucial for CdTe solar panel production among other uses. The majority of Cd is produced as a by-product of Zn mining (Figure 2) with a smaller, un-quantified amount annually recovered from the recycling of end-of-life NiCd batteries (e.g., USGS, 2020). The overall apparent trends from both the BGS and the USGS sources suggest that Cd recovery has decreased relative to the recovery of Zn since 1970 to 2011 (Figure 5B). Post 2011 and 2012 (Figure 5B), there is a slight increase in the Cd production ratio suggesting an improvement in Cd recovery. This apparent improvement in Cd recovery could be the result of added Cd supply from recycling end-of-life NiCd batteries although this again remains uncertain. Equally, the fact that NiCd batteries are being phased out (sales decreasing at 6% per year between 2002 and 2012; Zhao et al., 2021) barring specialty uses for these batteries means that this recycling source of Cd is likely to further diminish over time. This suggests that we may see a further lowering of the Cd production ratio if recycling-based sources of Cd decrease unless there is an increased focus on Cd recovery from smelters and refiners.

The historic variations in the metal production ratio for the by-product metals Se, Re and Te provide insights into numerous changes in production of critical metals over time (Figure 5B-

D). The global supply of Se is almost entirely sourced as a by-product of Cu mining barring minor production as a by-product of Ni (Figure 2 e.g., USGS, 2020). The relatively unchanged Se production ratio suggests that the recovery of this metal has kept pace with the annual production of Cu and there have been no changes to optimize Se recovery from Cu concentrates (Figure 5B). In contrast, the historic Re production ratios show an inverted U-shape with increasing Re production ratios from the 1970s to 1990, relatively unchanged Re production ratios from 1990 to the early 2000s, and decreasing Re production ratios post-2005 (Figure 5C). This inverted U-shape trend suggests that between 1973 and 1990 Re recovery increased, remained steady between 1990 and 2005, and then decreased relative to Mo production post-2005. Molybdenum, from which Re can be a by-product, can originate as a primary metal product from porphyry Mo deposits (e.g., Climax mine; Freeport-McMoRan, 2019) or as a co-product derived from porphyry Cu deposits (Figure 2 e.g., USGS, 2020). The recent decrease in the Re recovery rate could be the result of a change in Re abundance in the primary Mo concentrates and/or the Mo concentrates are being processed at smelters/refineries not equipped with a Re recovery circuit. The decrease in the Re production ratio post-2005 corresponds to an increase in the Mo production ratio (Figure 5C). This could suggests that there is a difference in Re source concentration (Mo main-product mining versus Mo by-product from Cu main-product mining) and/or by-product Mo refined from Cu metal concentrates are being processed at operations that do not have a Re recovery circuit. Examining the data for Te yields a Te production ratio with a broad U-shaped pattern from 1970 to 2018 (Figure 5D). The majority of global refined Te is again a by-product of Cu mining (i.e., Cu anode slimes; Figure 2; e.g., Goldfarb et al., 2017) as well as an unknown amount from residues generated and recovered in China from Pb, Ni, PGE, and Zn smelting activities (USGS, 2020). In addition, between 40-50 t/yr of refined Te are produced as a co-product from the Kankberg Au-Ag-Te mine in Sweden (Voigt et al., 2019). The increase in the Te production ratio since 2010 is likely the result of the addition of non-Cu related Te production rather than the improvement of Te recovery from Cu anode slimes (McNulty and Jowitt, *in review*). Similarly, the elevated Te production ratios in the 1970s (e.g., Colbert, 1980; BGS website) were likely the result of refined Te from the Emperor gold mine in Fiji (e.g., Fornadel et al., 2019).

The above variations in by-product metal production ratios illustrate the numerous factors and inherent uncertainties involved in understanding the nature of historic and current global by-product metal resources and production. These fundamentally include the abundance of by-products in the main-product metal concentrates prior to refining and the capacity for by-product recovery at the refinery operation. The fact that by-products tend to represent >1% of the recoverable metal value from main- or co-product metal concentrates means that mining operations tend to not invest time and resources into quantifying the amount of by-product metals contained in main-product ores or optimize the concentration of these by-product metals during mineral processing. As a result, these main-product metal concentrates may not be shipped to refineries with the appropriate by-product recovery circuits and the potential value adds from these by-products, which are often classified as critical metals, is lost. This highlights the need for new research in materials flows within the mining value chain to fully comprehend and quantify the controls on the supply of critical metals that are primarily sourced as by-products of main-product metal mining and refining. Equally important is the fact that criticality assessments often include some of the data outlined above without considering their inherent uncertainties or how these data change over time. Case in point the variation in annual production values for Te. This could potentially mean that focused investment and research based on these criticality assessments is essentially targeting the wrong metals; if we do not know how much we produce or where this production is occurring, then how can we assess the security of supply of these elements?

4 Global Critical Metals Resources

The production and supply-related uncertainties in the critical mineral and metals space is further compounded by a lack of high quality information on the resources and reserves of these metals and minerals (e.g., Weng et al., 2013; Mudd et al., 2017; Werner et al., 2017a; Werner et al., 2017b; Jowitt et al., 2018). These data are often used to predict challenges and the security of future metal supply, and without these it is nearly impossible to accurately predict future trends in the supply of these crucial commodities. One of the major challenges in the realm of understanding global critical metal resources and production potential is that very few critical metal resources are well quantified. There are exceptions; for example Pt, Pd, and Co, although this reflects the fact that these metals are often produced as main- or co-products (Nassar et al., 2015). This reflects the fact that Pd and Pt are high value precious metals (2020 annual average metal price of $2,200.47 and $885.71 USD/troy ounce, respectively; ("Precious Metals," 2021). These high values (and larger demand) for Pd and Pt means that these critical metals are generally co-products as they add significant value to the mining operations they originate from, and as a result are estimated in resources and reserves modeling. Cobalt is considered a minor metal and in 2020 had an average metal price of ~$31.00 USD/kg ("LME Cobalt," 2021) although its produced in larger amounts than most typical critical metals and minerals. These factors are reflected in the size of the Pd, Pt, and Co mining sectors, where 2020 production value for Pd was ~14.7 billion USD, for Pt was ~4.8 billion USD and for Co was ~4.3 billion USD. However, the economic importance of these metals still does not guarantee that they will be reported in reserve and resource estimates for individual mines that produce (or have the potential to produce) these metals (e.g. Mudd et al., 2013).

The situation is exacerbated for the majority of critical minerals and metals for a number of different reasons, as illustrated by a comparison between Co and Te. Global Co production in

2020 was 140,000 tonnes compared to 490 tonnes of Te (USGS, 2021), meaning that it is currently economically beneficial for a mining operation to invest in the estimation of resources and reserves for Co but not for Te. This leads to a situation where although the 2020 annual metal price for Te was between \$60 and \$65 USD/kg (USGS, 2021), the small demand for this critical metal means that total global revenue from Te production was only 0.029-0.032 billion USD (compared to ~4.3 billion USD market for Co).

All of this means that mineral economics factors have a crucial role in the lack of reporting of critical metal resources and reserves as the financial cost in generating resource and reserve estimates is very high (e.g., Jowitt and McNulty, 2021). This means that not all metals that can be recovered and sold from a given mineral deposit will be quantified in reserve and resource reporting, a situation that is compounded by the fact that reserve and resource reporting regulations would typically preclude the reporting of commodities that generate <1% of the revenue expected from a given mine (e.g. Jowitt and McNulty, 2021). This in turn means that resource and reserve estimates for critical metals reflect the economic importance of the metal in question to a given deposit rather than their criticality or even the fact that they will be produced by a mine (or by a downstream smelter or refiner). This leads to a situation where (for example) the vast majority of Te and Se producing mines do not report resources or reserves for these elements despite the fact they can produce significant amounts of these elements although whether they are produced or not depends on the approaches used during metal extraction.

All of this has generated a situation where proxies for unreported critical metal resources are needed to assess the global resources (and hence likely future supply) of these metals and minerals. One example of this is the critical metal In, where approximately 95% of global production is as a by-product of refining Zn from sphalerite-rich mineralization, a zinc sulfide, with the remaining 5% as a by-product of Cu from chalcopyrite-rich ores (Schwarz-

Schampera, 2014). This geological relationship combined with available In resource data as well as Pb-Zn and Cu resource data (Mudd et al., 2013; Mudd et al., 2017) has been used to estimate a global In resource of about 356,000 tonnes contained in 1,512 mineral deposits (Werner et al., 2017b). In this case, the proxy approach provides the only estimate of global In resources, with the USGS in 2021 stating "quantitative estimates of reserves are not available" (USGS, 2021). These figures provide a more robust guide to long term metal and mineral supply than can be estimated using reserves (e.g. Jowitt et al., 2020) and in some cases are the only data that may be available (e.g. Jowitt et al., 2018), such as the case for global In resources.

A significant proportion of the uncertainties outlined above reflect the lack of fundamental understanding of the "life cycle" of critical elements from mining through processing to final product—for example Se and Te In the United States there are three electrolytic copper refineries; however the ASARCO Amarillo plant in Texas is the only active operation that recovers by-product PGE, Se and Te from Cu concentrates that originate from the Mission Cu-Mo, Silver Bell Cu, and Ray Cu-Ag porphyry mines in Arizona and 3rd party concentrates, as well as scrap copper metal (www.arsarco.com). Although the ASARCO Amarillo plant refined ~50 t of Te and ~150 t of Se in 2018 (BGS website), GrupoMexico (the owner of ASARCO) only reports mineral reserves of Cu and Mo for the Mission mine, Cu and Ag for the Ray mine and Cu for the Silver Bell mine (GrupoMexico, 2018). As a result, the mine origin and quantity of these by-product metals cannot be reconciled and therefore predictions on the future supply of Te and Se from these mines are very difficult.

This in turn leads to challenges in estimating global critical metal resources that are produced as by-products. The USGS estimates Se global resources based on identified Cu deposits and average Se content and states that data on Te resources were not available in 2020 (USGS, 2021) with the exception of Boliden's Kankberg Au-Ag-Te deposit in Sweden

(Voigt et al., 2019). In addition to the lack of mineral resource data for these critical metals, for reasons outlined above, it is also very difficult to estimate metal resources based on current production because smelting/refining operations often process a mixture of Cu concentrates (e.g. McNulty and Jowitt, *in review*). One case in point is, US domestic Te and Se production. If we assume that Te and Se are equally recovered from Cu concentrates produced only by the Mission, Ray and Silver Bell mines, we can estimate the potential Te and Se resources for the United States based on the anticipated life of mine for each operation. The Mission, Silver Bell and Ray mines have 12, 13 and 23 year mine lives, respectively ("Mining Data Solutions," 2020). Therefore, assuming that the 2018 Se and Te production values of 50 t/yr and 150 t/yr, respectively (BGS website), remain unchanged than the United States has ~800 t Te and ~2,400 t of Se resources remaining in these current operations. This contrasts with 2021 USGS Mineral Year Book Report, which estimated domestic resources of 3,500 t Te and 10,000 t Se (USGS, 2021).

This epitomizes the challenge of estimating global critical metal resources when there is limited or no data for mineral resources, productions and/or refining of the saleable critical metals. In addition to a lack of data, the mining industry is also dynamic. For example, Rio Tinto's Bingham Canyon Cu-Au-Mo-Ag porphyry mine in Utah is scheduled to begin production of Te in the fourth quarter of 2021 with the addition of a 20 t/yr by-product recovery circuit to its Kennecott smelter ("Rio Tinto to build new tellurium plant at Kennecott mine," 2021). Assuming a $70 USD/kg Te price, the 2.9 million USD capital cost could be paid off in just over two-years of production. Unlike the ASARCO Amarillo plant, the Kennecott smelter only refines Cu concentrate from the Bingham Canyon mine. Not only will the new Te production expand US annual production by ~25% and global Te production by ~4% it will also provide an example of the economic benefit of recovering this critical metal, although this benefit can only be achieved by understanding the mineralisation present within a mineral deposit and the abundances of the critical metals contained therein.

5 Discussion

The critical minerals comprise numerous raw materials and elements that are deemed essential but have perceived supply-chain risk (Figure 1). These potential supply-chain risks could result in disturbances and bottlenecks of raw materials that may lead to volatility in commodity pricing and in turn have an adverse effect on sustainable economic development. Factors that need to be considered when assessing potential supply-chain risk of a given raw material include geological and economical finiteness for resources, as well as technological, geopolitical, regulatory and social risk factors (Erdmann and Graedel, 2011; Klinglmair et al., 2014; Schneider et al., 2014; Drielsma et al., 2016; Helbig et al., 2016; Jasiński et al., 2018; He et al., 2021). All of these factors have their challenges in practice as well as their own inherent uncertainties that need to be considered when completing a mineral criticality assessment (e.g., Glöser et al., 2015; Helbig et al., 2016).

As presented in this paper, many of the critical metals are by-products of major- and co-product mining and refining (Figure 2). Currently, the mining and mineral exploration industry lacks reporting protocols for these by-products because they tend to represent >1% of the metal/mineral value in a deposit (e.g. Jowitt and McNulty, 2021). As a result, accurately quantifying minimum estimates of global mineral resources for these by-products is impossible because there is a paucity of available and/or consistently collected data. One solution to this problem is developing by-product proxies based on geological criteria (i.e. Indium; Werner et al., 2017b). However, while this approach is an excellent first step, perhaps a better and longer term solution is to develop a separate reporting standard for by-product metals so that these elements are no longer ignored based on their perceived limited economic value (Jowitt and McNulty, 2021).

The emphasis on the limited economic value add, for some of the critical elements, has resulted in a lack of research in understanding the mineral deportment of these metals and the underreporting of these raw materials in mineral deposits. Without these quantified inputs for by-product metals, which are often classified as critical, production cannot be maximized at the mine, smelter or refinery levels and as a result these non-renewable natural resources are reporting to waste rather than a salable product.

In addition to the lack of resource data for these critical by-product metals there are also challenges and uncertainties in the annual reported production values for these metals as well as their deposit/mine origins. This is demonstrated by the discrepancies in the reported annual by-product metal production by the USGS and BGS investigated in this study, which can vary by more than 50% (Figure 3B). In addition to the uncertainty in reported annual production values there is also a lack of transparency in the source and quantity of metal concentrates processed at refineries. This particular challenge is exemplified by worldwide Te production. Over ~90% of the world's refined Te production is a by-product of refining Cu concentrates however of the seven countries that produced Te in 2018 none of the operations refined Cu concentrate from a single origin (McNulty and Jowitt, 2021 *in review*). The combination of different Cu concentrates by refineries makes it impossible to reconcile the origin of the by-product metal. Without knowing the origin of the Cu concentrate or the amount of Te in said concentrate it is impossible to accurately estimate Te global resources based on historic production. This lack of transparency is not unique to Te and is a function of mineral economics not geological abundances. This then leads to the most significant knowledge gap in critical metals accounting, how can we classify something as critical if we don't know how much we have?

These discussed uncertainties could be removed by a combination of research and policy change. Fundamental and applied research in mineral deportment of the critical metals is needed to, at a minimum, establish new proxies to estimate the abundance of important elements that are not routinely analyzed and, more preferably, develop new tools that industry can apply to efficiently and accurately assess mineral deportment throughout the mineral exploration and mining value chain. New research in extracting critical elements from tailings piles, for example, is providing a path forward in this research space (e.g., Drif et al., 2018; Parbhakar-Fox et al., 2018; Guanira et al., 2020), but there is also mineral resource and economic opportunity for proactive mineral deportment research done prior to and/or during mining activities. This will not only provide the world with the critical raw materials for a sustainable future but also allow mining operations to extract the most value from their ores. Finally, there is a need to update the resource reporting protocol and encourage industry to report mineral resource estimates for by-product metals (e.g. Jowitt et al., 2013). While these mineral resource estimates will have greater uncertainty compared to code compliant mineral resource and ore reserve estimates, it will fulfill a significant void in supply data that is required to estimate global critical mineral resources with confidence.

6 Conclusions

The critical metals are crucial to modern life, advanced technology, low- and zero-CO_2 power generation and transport, and the defense sector. These metals are considered because they are subject to supply risk as a function of variety of different factors, leading policymakers, researchers, and industry to consider a variety of approaches to reduce this supply risk. However, the knowledge base that funding, investment and policy decisions surrounding this criticality is deficient in a number of key areas. This study highlights some of these that (among other factors) reflect the systemic lack of resource reporting and fundamental knowledge of the critical elements. One of the most significant knowledge gaps forms the focus of this paper. The first of these is the fact there is significant unrealized potential for critical metal production as a function of a lack of knowledge of the deportment and processing behavior of these metals; put simply, we do not know how much of these metals are present within known mineral resources and ore reserves nor accurately and precisely how much of these metals we actually already produce. This leads back into criticality assessments; how can we consider something critical without knowing how much we have already identified and how much we produce (and from where)? All of this highlights the need for further research and policy developments to reduce the uncertainties that surround the critical metals to ensure secure global supplies of the critical raw materials needed for a sustainable future as well as ensuring we make the most of mineral resources that are naturally finite. This also requires a change in resource reporting practices that ensure that the mining industry considers by-product metals in their resource and reserve reporting. These changes can only ensure a more secure supply of these vital commodities that will most likely be subject to increasing demand driven by efforts to mitigate anthropogenic climate change and CO_2 emissions.

7 Acknowledgements

To write following the review

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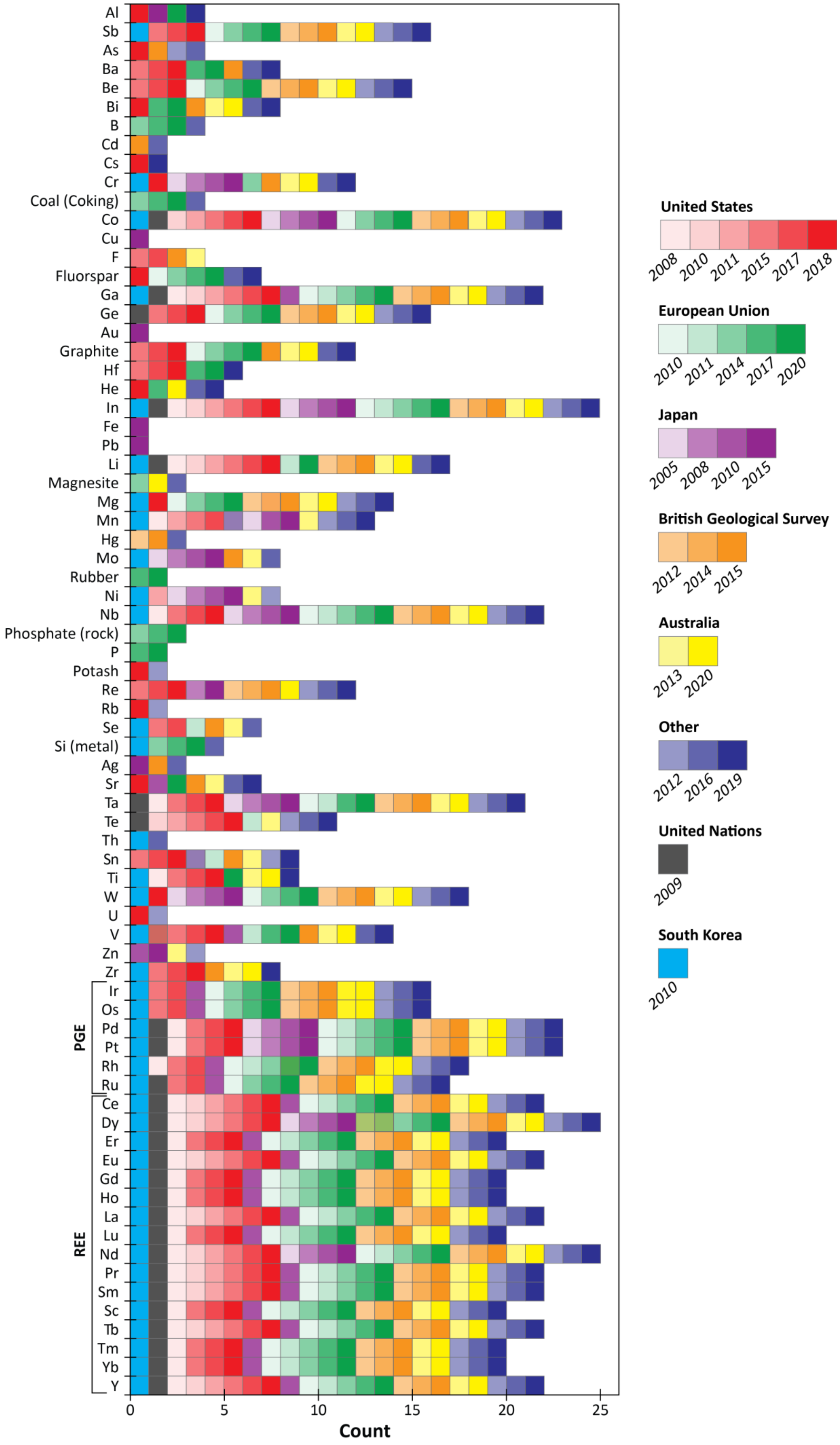
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Mo
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Ni
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Figure 1. Frequency of the metals and materials included in 25 different critical metals and materials lists from 2005 to 2020. The figure is a compilation of critical metal lists from South Korea (n=1; Bae, 2010), the United Nations (n=1; Buchert et al., 2009), Australia (n=2; Skirrow et al., 2013; Austrade, 2020), the British Geological Survey (n=3; BGS, 2012; Gunn, 2014; BGS, 2015), Japan (n=4; NEDO, 2009; Hatayama and Tahara, 2015), the European Union (n=5; EC, 2010; EC, 2011; EC, 2014; EC, 2017; EC, 2020) and the United States (n=6; USNAS, 2008; Bauer et al., 2010; Bauer et al., 2011; USDOD, 2015; Schulz et al., 2017; USDOI, 2018) along with three independent publications of critical metals and materials lists (Willis and Chapman, 2012; Sykes et al., 2016; Conca, 2019). The cell colors correspond to the source and date of publication. For each metal/material the sources are organized in chronological order to highlight changes in criticality over time for each organization.

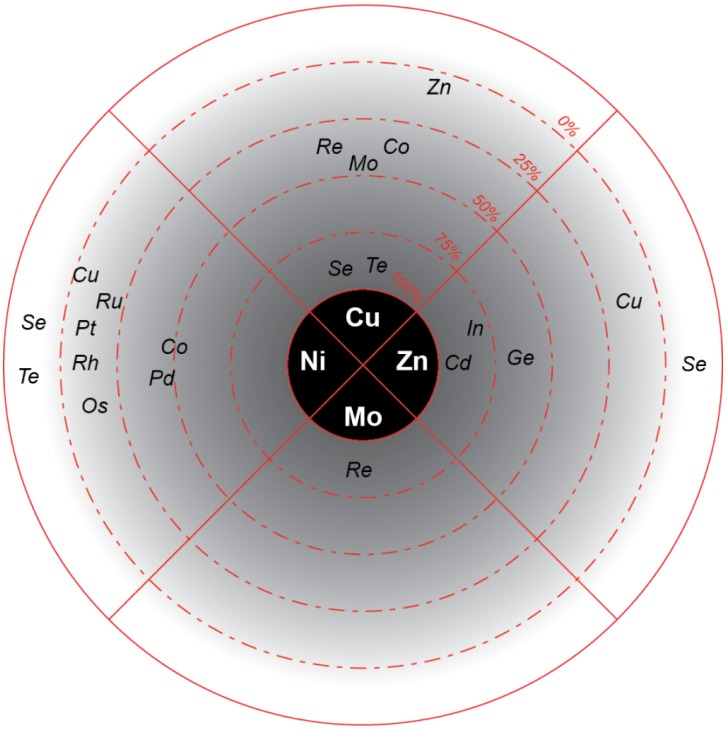

Figure 2. Modified wheel of metal companionality showing select main product metals and their by-product metals which are discussed in this contribution (after Nassar et al., 2015).

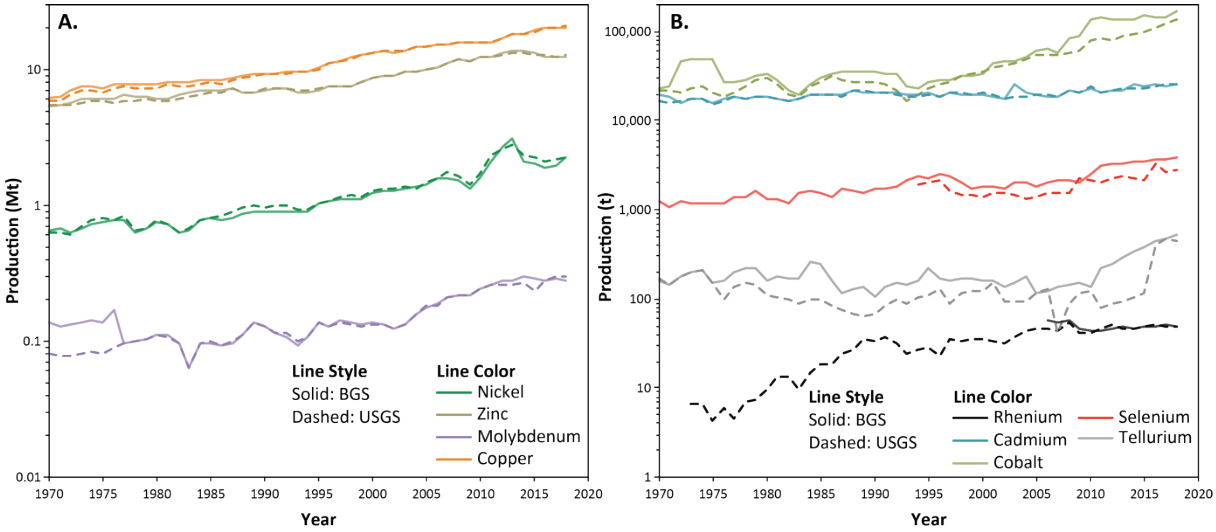

Figure 3. Comparison of annual main production and by-product metal production between 1970 and 2018 based on USGS and BGS publicly available data (BGS 2020; Jowitt et al., 2020). **A.** Main product metal production values for Cu, Zn, Ni and Mo. Note the general agreement in the worldwide annual metal production reported by the USGS and BGS for the main product metals. **B.** By-product metal production values for Co, Cd Se, Te and Re. These data illustrate that some by-products have greater uncertainty than others.

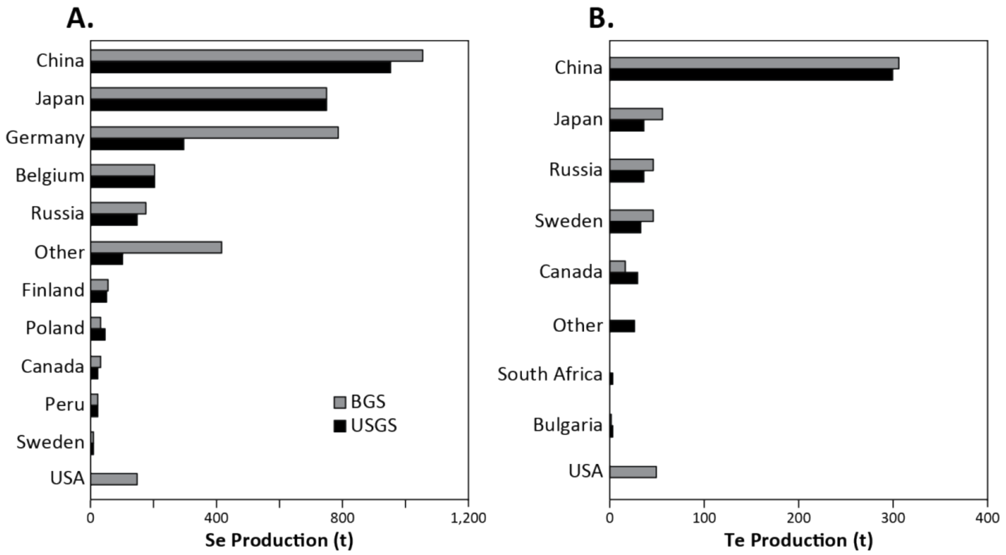

Figure 4. Breakdown of select by-product metal production by country for the year 2018 (data from BGS, 2020; USGS, 2020). Total Se global production in 2018 was between 2,755–3,832 tonnes and worldwide Te production was between 470–524 tonnes. In general, for the same reported country, the BGS reports higher annual production values than the USGS. In addition, there is variability in the reported countries by each survey. In the case of Se, the BGS reports an additional 300 tonnes from countries not reported by the USGS, while the USGS reports an additional 25 tonnes of Te from countries not reported by the BGS.

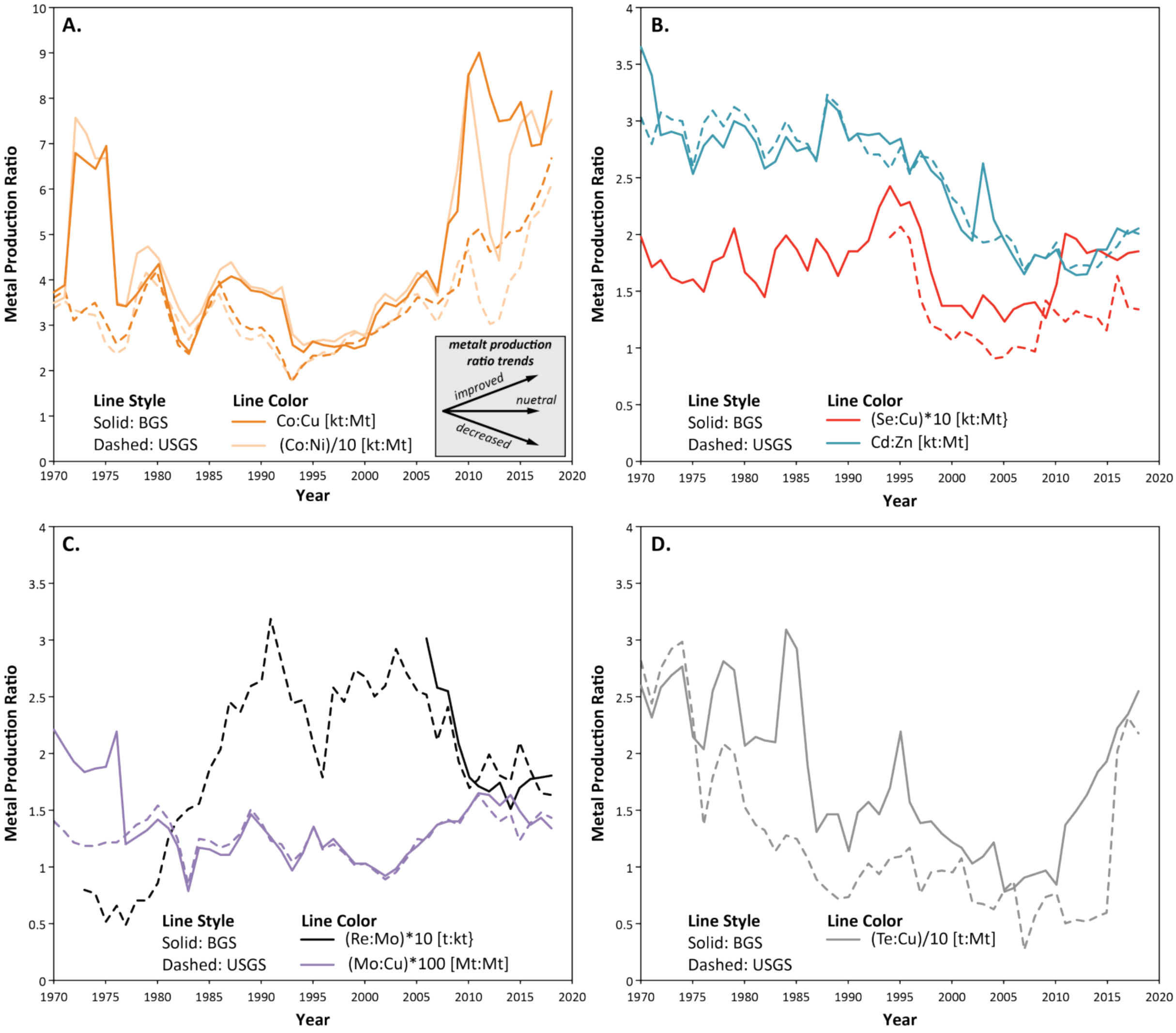

Figure 5. Annual metal production ratios between 1970 and 2018 for select by-product critical metals. Annual production data compiled from the BGS (BGS, 2020) and from the USGS compiled by Jowitt et al. (2020). **A.** Cobalt production ratio. **B.** Selenium and cadmium production ratios. **C.** Rhenium and molybdenum production ratios. **D.** Tellurium production ratio. See Text for discussion. Abbreviations: kt, kilo tonne; Mt, million tonne; t = tonnes.

Table 1. Critical metals/materials according to the European Union, United States and Australia.

Critical Metals	EU	USA	AUS	Major Producer - EU		Major Producer - USA		Major Producer - AUS	
Sb	y	y	y	Turkey	62.0%	China	62.5%	China	63.0%
Be	y	y	y	USA	88.0%	USA	65.4%	USA	65.0%
Bi	y	y	y	China	49.0%	China	73.7%	China	74.0%
Co	y	y	y	DRC	68.0%	DRC	71.4%	DRC	71.0%
Ga	y	y	y	Germany	35.0%	China	96.9%	China	97.0%
Ge	y	y	y	Finland	51.0%	China	65.4%	China	65.0%
Hf	y	y	y	France	84.0%	-	-	-	-
In	y	y	y	France	28.0%	China	39.5%	China	39.0%
LI	y	y	y	Chile	78.0%	China	46.7%	Australia	61.0%
Mg	y	y	y	China	93.0%	China	67.9%	China	68.0%
natural graphite	y	y	y	China	47.0%	China	63.6%	China	63.0%
Nb	y	y	y	Brazil	85.0%	Brazil	87.8%	Brazil	88.0%
Ta	y	y	y	DRC	36.0%	DRC	41.1%	DRC	41.0%
Ti	y	y[1]	y[1]	China	45.0%	China	30.0%	China	27.0%
		y[2]	y[2]			China	40.0%	China	40.0%
		y[3]	y[3]			Australia	23.3%	Australia	29.0%
W	y	y	y	China	69.0%	China	82.4%	China	82.0%
V	y	y	y	China	39.0%	China	54.8%	China	54.0%
PGE - Pd	y	y	-	Russia	40.0%	Russia	41.0%	-	-
PGE - Pt	y	y	-	South Africa	71.0%	South Africa	72.2%	-	-
PGE	-	-	y[4]	-	-	-	-	South Africa	57.0%
REE	y	y	y	China	98.5%	China	62.9%	China	72.0%
Al (bauxite)	y	y	n	Guinea	64.0%	Australia	27.0%	-	-
As	n	y	n	-	-	China	72.7%	-	-
Ba (barite)	y	y	n	China	38.0%	China	30.5%	-	-
B (borate)	y	n	n	Turkey	98.0%	-	-	-	-
Cs	n	y	n	-	-	-	-	-	-
Cr	n	y	y	-	-	South Africa	38.6%	South Africa	37.0%
coking coal	y	n	n	Australia	24.0%	-	-	-	-
fluorspar	y	y	n	Mexico	25.0%	China	57.1%	-	-
He	n	y	y	-	-	USA	55.6%	US	53.0%
Mn	n	y	y	-	-	Australia	16.8%	South Africa	29.0%
natural rubber	y	n	n	Indonesia	31.0%	-	-	-	-
phosphate rock	y	n	n	Morocco	24.0%	-	-	-	-
P	y	n	n	Kazakhstan	71.0%	-	-	-	-
potash	n	y	n	-	-	Canada	32.4	-	-
Re	n	y	y	-	-	Chile	55.1	Chile	55.0%
Rb	n	y	n	-	-	-	-	-	-
Sc	y	n	y	China	66.0%	-	-	-	-
Si (metal)	y	n	n	Norway	30.0%	-	-	-	-
Sr	y	y	n	Spain	100.0%	Spain	40.9%	-	-
Te	n	y	n	-	-	China	61.7%	-	-
Sn	n	y	n	-	-	China	27.4%	-	-
U	n	y	n	-	-	-	-	-	-
Zr	n	y	y	-	-	Australia	39.3%	South Africa	26.0%
PGE - Ir	y	n	n	South Africa	92.0%	-	-	-	-
PGE - Rh	y	n	n	South Africa	80.0%	-	-	-	-
PGE - Ru	y	n	n	South Africa	93.0%	-	-	-	-

[1] ilmentite; [2] metal sponge; [3] rutile; [4] undifferentiated platinum group elements (PGE)

Critical metals/materials that all three organization agree on are shown in ***BOLD ITALICS***

Critical metals in RED are discussed in more detail in this contribution.

EU = list of critical metals and 2020 global production data from European Commision (2020)

USA = list of critical metals from US DOI (2018) and 2020 global production data from USGS (2020)

AUS = list of critical metals and 2020 global production data from Austrade (2020)

Table 2. By-product metals derived from the production of major industrial metals (modified from Graedel et al., 2014)

Copper	**Zinc**	**Tin**	**Nickel**	**Platinum**	**Aluminum**	**Iron**	**Lead**
cobalt	Indium	*Niobium*	*Cobalt*	Palladium	Gallium	*REE*	*Antimony*
molybdenum	Germanium	*Tantalum*	*PGM*	Rhodium		*Niobium*	Bismuth
PGE	Cadmium	Indium	Scandium	Ruthenium		Vanadium	Thallium
Tellurium				Osmium			
Rhenium				Iridium			
Selenium							
Arsenic							

BOLD - selected major industrial metals

Italics - metals that may also be derived from their own ores

Critical metals in RED are discussed in more detail in this contribution.

Abbreviations: PGE, platinum-group elements; REE, rare earth elements