

Perspective

Barriers to and uncertainties
in understanding and quantifying
global critical mineral and element supplyBrian A. McNulty^{1,*} and Simon M. Jowitt¹

SUMMARY

The critical minerals and elements are natural substances that are essential to modern life but have insecure supply. This lack of a secure supply clashes with the increasing importance of these elements, especially given their use in technologies needed to reduce global CO₂ emissions and mitigate against anthropogenic climate change. In this contribution we review the by-product nature of the critical minerals and elements and the inherent uncertainties in reported critical mineral and element annual production as well as the relationships between these commodities and main-product metals and associated concentrates. We explore the geological and geographical barriers to critical mineral and element supplies, as well as how the lack of available data and the uncertainties in the data that are available hinder our ability to estimate global resources with confidence.

INTRODUCTION

Critical minerals and elements are natural substances that 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 as a result of a variety of factors (e.g., Graedel et al., 2014). They are vital to green energy and low- and zero-CO₂ technologies, such as wind turbines, solar panels, electric vehicles, and storage batteries, as well as being used in numerous defense applications (NRC, 2008; Graedel, et al., 2012). Although the classification of critical minerals and elements 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., 2018a), a common list of minerals and elements is emerging. A hallmark for the definition of criticality is potential supply-chain risk (Hayes and McCullough, 2018). Two important factors that control supply security are the sources of critical mineral and element and their abundance or distribution. Global production of a critical mineral or element is often limited to a few countries. For example, ~70% of global Pt production is from a single country, namely South Africa (USGS, 2021). An additional source restriction is that many of the critical elements are by-products and have both varying main-product metal companionship (e.g., Nassar et al., 2015) and restricted streams of recovery (Jowitt et al., 2018b). One example of this is Co, which is primarily a by-product of Ni and Cu mining. This has led to a situation where Ni and Cu mining is diverse but not all of these mines recover Co, a factor that has led to an increase in the supply-chain risk for this element (e.g., BGS, 2015; Nansai et al., 2017).

The terms main-product, co-product and by-product are strictly a function of mineral economics (e.g., Tilton, 1985). Ore deposits are mined for economic minerals, and those that form the primary source of revenue for a given mining operation are termed main-products. 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 smelting, refining, or other processing used to extract the main- or co-products, activities that typically occur outside of the mining environment (often termed “outside the mine gate”; Tilton, 1985). Metals such as these are present at trace concentration levels in the ores of the host metals and are often considered as “impurities”. In some cases, these impurities are extracted from the final main-product for environmental reasons (e.g., Cd) or, under favorable economic conditions, can be extracted at refineries for a profit (e.g., Nassar et al., 2015). Regardless, these by-products are generally not calculated in resource and reserve estimates, not recorded in mine production annual reports, and sometimes have unquantified smelter and refinery production. This has led to a general lack of reliable assessments of global by-product resources (e.g., Candelise et al., 2012; Fthenakis, 2015; Olivettie et al., 2015; Frenzel et al., 2017).

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In this contribution we focus on factors that hinder our current understanding of critical minerals and elements, specifically uncertainties in reported annual production, uncertainties over the origin of associated main-product concentrates (here termed origin transparency), and uncertainties in the reported global supply of selected elements, namely Cu, Ni, Zn, Mo, Co, Se, Te, Cd, and Re. We explore why we simply do not know the amount of potentially producible critical elements 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 to estimate global resources with confidence.

OVERVIEW OF CRITICAL MINERALS AND ELEMENTS

Some of the main drivers in the demand for critical minerals and elements include: (1) the push toward low-emissions energy production along with energy storage and usage; (2) the increased use, complexity, and prevalence of communication and entertainment technologies; and (3) security and defense applications. Critical minerals and elements 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, the platinum group elements (PGEs), the rare earth elements (REEs), Sb, Sc, Se, Te, Th, and Zr, among others (Jowitt et al., 2018a). In addition, Ga, Ge, In, Nb, Sb, Te, and Y are essential for the production of micro-capacitors, flat screen phosphors, and semiconductors, all of which are necessary for the production of high-tech communications and entertainment devices (Jowitt et al., 2018a). 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., 2018a). This has led to all of these elements being generally considered critical, although different countries and organizations may also add other minerals or elements to this list. This reflects the fact that the definition of a substance'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 35 critical minerals and elements (Fortier et al., 2018), 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.”

This variation is exemplified by the numerous reports that assess the criticality of materials and 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 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 REE and some of the 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). Japan (Hatayama and Tahara, 2015) considers Zn to be a critical element whereas Australia initially considered Zn to be critical (Skirrow et al., 2013) but subsequently removed Zn from their critical element list in 2020 (Austrade, 2020). Further examination reveals that Japan considers Zn to be critical as a result of potential risks in securing metal concentrates for their domestic smelters, whereas Willis and Chapman (2012) concluded that Zn should be considered globally critical as a result of its association with the critical elements Ge and In, which are principally sourced as by-products of Zn mining. These contrasts highlight the importance of viewpoints when considering criticality and which elements or minerals should be considered critical. This complexity in criticality assignments is outlined in Figure 1, highlighting the evolution of mineral and element criticality and the differing positions governments have had on potential supply restrictions, the impacts of these potential supply restrictions, economic importance, and environmental implications for individual substances that are often considered critical. This is just one form of uncertainty associated with determining resources and future supply of critical elements; actually classifying what substances are critical, although as outlined below a gradual consensus seems to be emerging.

A comparison of the critical mineral and element lists for Australia (Austrade, 2020), the EU (EC, 2020), and the United States (USDIO, 2018) illustrates a general agreement on the critical nature of some of these substances (Table 1). All three reports suggest that Sb, Be, Bi, Co, Ga, Ge, Hf, In, Li, Mg, natural graphite, Nb, the PGE, the REE, Sc, Ta, Ti, W, and V should be considered critical. A significant factor defining criticality is

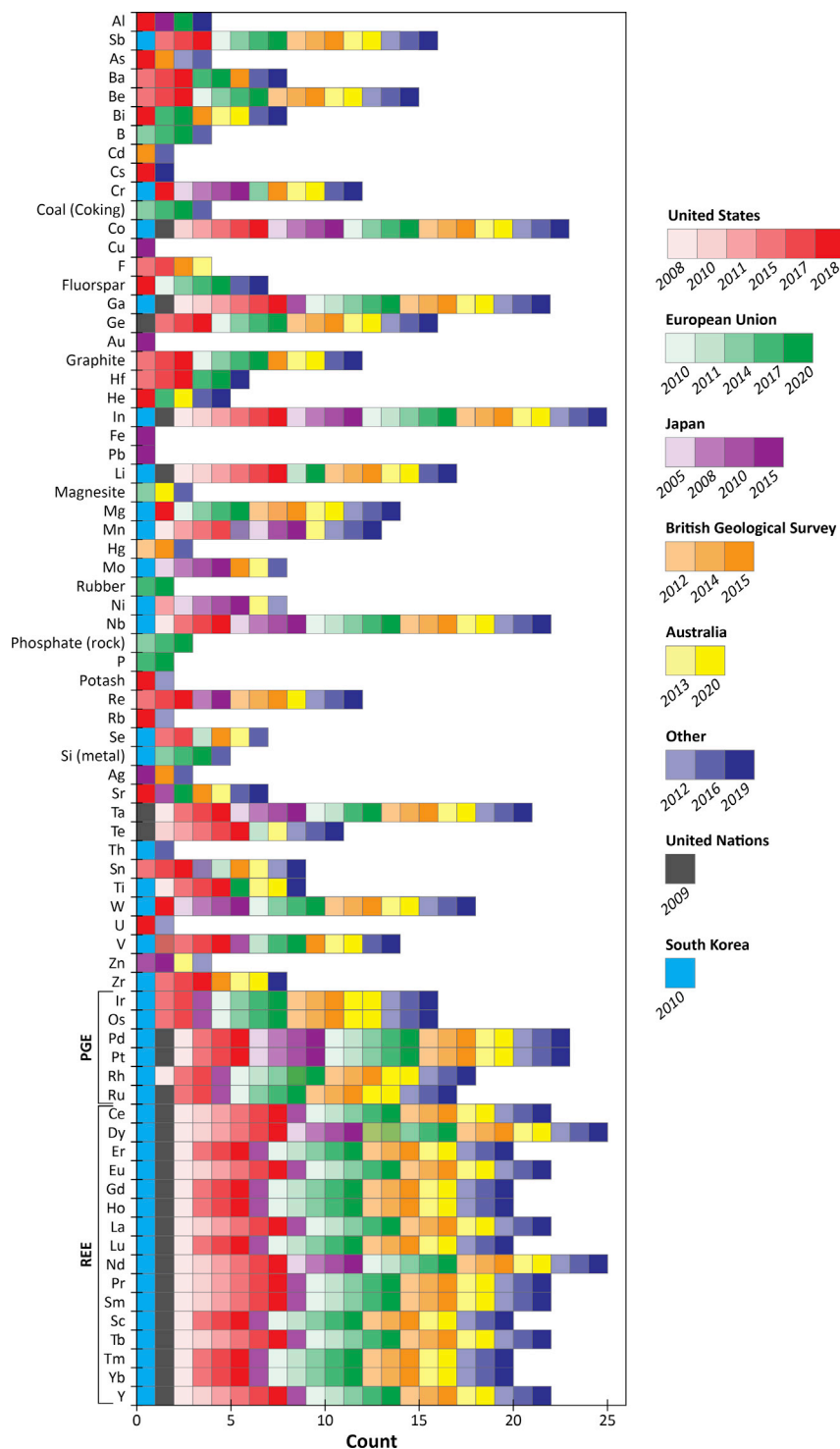


Figure 1. Frequency of the minerals and elements included in 25 different criticality assessment lists from 2005 to 2020 (updated from Sykes et al., 2016 and Hayes and McCullough 2018)

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 EU (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; USDOD, 2018) along with three independent publications of critical metals and materials lists

Figure 1. Continued

(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.

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 many of the critical elements are 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 element 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 minerals and 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 substance in question, the one characteristic that links all of the critical minerals and 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 substance, 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; e.g. Jowitt and McNulty, 2021) side is problematic, primarily as a result of the by-product nature of the majority of these elements (e.g. Nassar et al., 2015). The fact most of these substances may be extracted by a given mine but at a level considered insignificant during resource-reserve reporting (e.g. <1% of contained metal value) means that they are often not quantified in resource-reserve estimates nor in annual production technical reports (Jowitt and McNulty, 2021). This is compounded by the fact that these elements are produced at smelters or refineries downstream of a mine, despite not being reported in the associated reserves or resources for the mine in question. The majority of these downstream operations also process mineral concentrates from multiple mines, meaning the materials flows of these critical elements are very difficult to track (e.g., Zimmermann, 2017; Nedelciu et al., 2020; 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 elements that are present within the concentrate at a reasonable recovery rate, or even at all. This is frequently not the case, meaning that critical minerals and elements 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., 2017a; Werner et al., 2017b). All of this means that critical mineral and 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. These uncertainties are associated with and are compounded by uncertainties in production statistics for by- and co-product metals, as outlined in the following section.

GLOBAL PRODUCTION OF CRITICAL MINERALS AND ELEMENTS

Many of the critical minerals and elements are not currently economically feasible to mine on their own but rather are by-products of the mining of main-products such as Cu, Ni and Zn (Table 2). Our analysis used global production data for select main-product metals (Cu, Ni, Zn, and Mo) and their critical element by-products (Co, Se, Te, Cd, Mo, and Re) to demonstrate two important mineral economic themes that have implications for the future of critical element production. These are the uncertainties prevalent in annual production data for these critical minerals and elements and the variations present in by-product annual production rates that can be quantified using main and by- and co-product production ratios. The key resources for this analysis are summarized in Table 3.

Uncertainties in annual production data

Worldwide historic metal production data are typically publicly sourced from the two entities that collate publicly accessible global data, namely the U.S. Geological Survey (USGS) and the British Geological Survey (BGS). 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

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

Critical Metals	2019 Price (USD)	Estimated 2019 Global Market Value (million USD)	EU	USA	AUS	Major Producer - EU		Major Producer - USA		Major Producer - AUS	
<i>Sb</i>	\$944.44/t+	\$153 [^]	y	y	y	Turkey	62.0%	China	62.5%	China	63.0%
<i>Be</i>	\$60,000.00/t+	\$15 [^]	y	y	y	USA	88.0%	USA	65.4%	USA	65.0%
<i>Bi</i>	\$2,417.06/t+	\$51 [^]	y	y	y	China	49.0%	China	73.7%	China	74.0%
<i>Co</i>	\$10,944.44/t+	\$1,576[^]	y	y	y	DRC	68.0%	DRC	71.4%	DRC	71.0%
<i>Ga</i>	\$15,028.4/kg+	\$5,275 [^]	y	y	y	Germany	35.0%	China	96.9%	China	97.0%
<i>Ge</i>	\$21,793.89/kg+	\$2,855 [^]	y	y	y	Finland	51.0%	China	65.4%	China	65.0%
<i>Hf</i>	unknown	\$5,275 [^]	y	y	y	France	84.0%	-	-	-	-
<i>In</i>	\$390/kg*	\$377*	y	y	y	France	28.0%	China	39.5%	China	39.0%
<i>Li</i>	\$23,000/t+	\$1,978 [^]	y	y	y	Chile	78.0%	China	46.7%	Australia	61.0%
<i>Mg</i>	\$31.03/t+	\$841 [^]	y	y	y	China	93.0%	China	67.9%	China	68.0%
<i>natural graphite</i>	\$310/t+	\$341 [^]	y	y	y	China	47.0%	China	63.6%	China	63.0%
<i>Nb</i>	\$163.97/kg+	\$15,905 [^]	y	y	y	Brazil	85.0%	Brazil	87.8%	Brazil	88.0%
<i>Ta</i>	\$161/kg*	\$297*	y	y	y	DRC	36.0%	DRC	41.1%	DRC	41.0%
<i>Ti</i>	\$22,425/t+	\$4,485 [^]	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%
<i>W</i>	\$6,813/t+	\$571 [^]	y	y	y	China	69.0%	China	82.4%	China	82.0%
<i>V</i>	\$58,744/t+	\$5,099 [^]	y	y	y	China	39.0%	China	54.8%	China	54.0%
<i>PGE - Pd</i>	\$1,544.31/oz	\$11,270*	y	y	-	Russia	40.0%	Russia	41.0%	-	-
<i>PGE - Pt</i>	\$866.94/oz	\$5,853*	y	y	-	South Africa	71.0%	South Africa	72.2%	-	-
<i>PGE - undifferentiated</i>	-	\$51,234 [^]	-	-	y ⁴	-	-	-	-	South Africa	57.0%
<i>REE</i>	\$19.72/t	\$4,338 [^]	y	y	y	China	98.5%	China	62.9%	China	72.0%
Al (bauxite)	\$32/t*	\$11,456	y	y	n	Guinea	64.0%	Australia	27.0%	-	-
As	\$192/t*	\$6.2*	n	y	n	-	-	China	72.7%	-	-
Ba (barite)	\$179/t*	\$1,587.7*	y	y	n	China	38.0%	China	30.5%	-	-
B (borate)	\$373/t*	\$1,354*	y	n	n	Turkey	98.0%	-	-	-	-
Cs	unknown	unknown	n	y	n	-	-	-	-	-	-
Cr	\$9.11/t+	\$408 [^]	n	y	y	-	-	South Africa	38.6%	South Africa	37.0%
coking coal	\$175/t	\$192,500	y	n	n	Australia	24.0%	-	-	-	-
fluorspar	\$292/t*	\$2,219*	y	y	n	Mexico	25.0%	China	57.1%	-	-
He	\$30.16/m ³ +	\$4,826 [^]	n	y	y	-	-	USA	55.6%	US	53.0%
Mn**	\$5.63/t*	\$110*	n	y	y	-	-	Australia	16.8%	South Africa	29.0%
natural rubber	\$1,730/t	\$22,232	y	n	n	Indonesia	31.0%	-	-	-	-
phosphate rock	\$67.98/t*	\$15,431*	y	n	n	Morocco	24.0%	-	-	-	-
P	-	-	y	n	n	Kazakhstan	71.0%	-	-	-	-
potash	\$480/t*	\$19,824*	n	y	n	-	-	Canada	32.4	-	-
<i>Re</i>	\$1,300/kg*	\$69.16	n	y	y	-	-	Chile	55.1	Chile	55.0%
Rb	unknown	unknown	n	y	n	-	-	-	-	-	-
Sc	unknown	\$4,338	y	n	y	China	66.0%	-	-	-	-
Si (metal)	\$2,336/t*	\$19,653*	y	n	n	Norway	30.0%	-	-	-	-
Sr	\$82/t*	\$10.4*	y	y	n	Spain	100.0	Spain	40.9%	-	-
<i>Te</i>	\$66,000/t*	\$34.3*	n	y	n	-	%	China	61.7%	-	-
Sn	\$1,865/kg*	\$552,072*	n	y	n	-	-	China	27.4%	-	-
U	\$56,526/t	\$3,034	n	y	n	-	-	-	-	-	-
Zr	\$286/t+	\$407 [^]	n	y	y	-	-	Australia	39.3%	South Africa	26.0%
PGE - Ir	\$1,485.80/oz*	\$393	y	n	n	South Africa	92.0%	-	-	-	-
PGE - Rh	\$3,918.78/oz*	\$2,990	y	n	n	South Africa	80.0%	-	-	-	-
PGE - Ru	\$262.59/oz*	\$307	y	n	n	South Africa	93.0%	-	-	-	-
<i>Se</i>	\$44,092/t*	\$127*	n	n	n	-	-	-	-	China	38.2%
<i>Mo</i>	\$26,500/t*	\$7,791*	n	n	n	-	-	-	-	China	44.2%
<i>Cd</i>	\$2,670/t*	\$65.1	n	n	n	-	-	-	-	China	33.6%

¹ ilmenite; ² metal sponge; ³ rutile; ⁴ undifferentiated platinum group elements (PGE); *USGS (2021); [^]Austrade (2020); +calculated by dividing Austrade (2020) market value by USGS (2020) production

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 EC, 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).

Natural rubber 2020 price data from Tiseo, (2021a).

Natural rubber 2019 production data from Tiseo, (2021b).

Uranium 2019 production data source from the World Nuclear Association (2020).

Uranium 2019 average spot price data from (Cameco, 2021).
 Rhodium 2019 production data source NRCAN (2021b).
 Iridium 2018 production data from Garside (2021a).
 Ruthenium 2018 production data source Garside (2021b).
 Coking (metallurgical-grade) coal 2019 average price data from NRCAN (2021a).
 Coking (metallurgical = grade) coal 2019 production data from MINING.com (2020).

information being presented, with this being a particular problem for by-products. We demonstrate this concept in Figure 2, which presents the annual production of Cu, Ni, Zn, and Mo along with their associated critical element by-product production—Se, Te, Mo, Co, Cd, and Re from 1970 through 2018 (Table S1).

Main product vs by-product metal production

The annual global production of Cu, Ni, Zn and Mo has increased between 1970 and 2018 with both the USGS and BGS reporting similar annual production trends (Figure 2A). The most notable exception to this is Mo production before 1977 (Figure 2A). Over this period the BGS reports an average Mo production rate of ~140,000 t/year, which is some 60,000 t/year greater than the 82,000 t/year of reported production outlined by the USGS. Of these metals Cu, Ni, and Zn are primarily produced as main- or co-products from base metal sulfide ores (e.g., Nassar et al., 2015). In comparison, Mo is produced as both a main-product from porphyry Mo deposits (e.g., Climax and Henderson mines, USA; Freeport-McMoRan, 2019) and as a co- or by-product from porphyry Cu-Mo deposits (e.g., Bingham Canyon mine, USA; e.g., Nexhip et al., 2015). This split is demonstrated by the fact that some 46% of global Mo production is a co- or by-product of Cu mining (Nassar et al., 2015). This has implications for the supply of the critical element Re as 100% of its global production is as a by-product of Mo (Nassar et al., 2015; USGS, 2021) and presents a supply situation where a critical element is a by-product of a by-product.

The general consistency of global production data for Cu, Ni, Zn, and Mo from the USGS and BGS data sets is poor when considering some of the critical element by-products and comparing these data to main products (Figure 2B). This is illustrated by annual Co production, with yearly differences in reported worldwide production that peak at ~60,000 t/year for a maximum percentage difference of 42.9% [here defined as $\Delta\% = ((\max - \min) / \max) * 100$] in 2011. In addition, several other years of Co production have discrepancies of <20,000 t/year (1972–1975 with $\Delta\%$ values between 49.7 and 58.6%; 2008–2018 with $\Delta\%$ between 15.3 and 42.9%). In comparison, USGS and BGS worldwide Re production estimates differ by >5 t/year ($\Delta\%$ between 0.8 and 9.6%), with the exception of annual production estimates for 2006 and 2007, which differed by 10 t/year ($\Delta\%$ between 18.1 and 18.5%). Of the by-product elements presented in Figure 2B, reported Cd production has been the most consistent between the compiled USGS and BGS statistics. From 1970 to 2018 worldwide by-product Cd production ranged from 15,200 t/year to 26,000 t/year, with the greatest difference in 2003 of 6,787 t/year ($\Delta\%$ of 26.9%) and the lowest difference in 1983 of 2 t/year ($\Delta\%$ of 0.01%; Figure 2B). Finally, Re and Se production data demonstrate that the periods of reported production data are not always uniform between the surveys, providing another form of uncertainty relating to the supply of critical elements (Figure 2B).

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
<i>Cobalt</i>	Indium	<i>Niobium</i>	<i>Cobalt</i>	Palladium	Gallium	REE	<i>Antimony</i>
<i>Molybdenum</i>	Germanium	<i>Tantalum</i>	PGM	Rhodium		<i>Niobium</i>	Bismuth
PGE	Cadmium	Indium	Scandium	Ruthenium		Vanadium	Thallium
<i>Tellurium</i>				Osmium			
<i>Rhenium</i>				Iridium			
<i>Selenium</i>							
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.

Table 3. Key resources table for the data analysis presented in this paper

Resource	Source	Identifier
Global & country copper, nickel, zinc, molybdenum, rhenium, cobalt, selenium, tellurium, and cadmium annual production values from 1970 - 2018.	BGS World mineral statistics data (2021)	https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS
Global & country copper, nickel, zinc, molybdenum, rhenium, cobalt, selenium, tellurium and cadmium annual production values compiled from Bureau of mines minerals Yearbook reports for 1970–1993.	Bureau of Mines Minerals Yearbook (1970–1993)	https://www.usgs.gov/centers/nmic/bureau-mines-minerals-yearbook-1932-1993
Global & country copper, nickel, zinc, molybdenum, rhenium, cobalt, selenium, tellurium and cadmium annual production values compiled from USGS minerals yearbook - metals and Mineral's reports for 1994–2018.	USGS, Minerals Yearbook (2021)	https://www.usgs.gov/centers/nmic/minerals-yearbook-metals-and-minerals

A comparison of the annual country-by-country production for Se and Te in 2018 further highlights another lack of transparency and/or uniformity in by-product production reporting (Figure 3; Table S2). The USGS reports smaller amounts of worldwide Se production (39% or 1,077 t/year) and Te (11% or 54 t/year) compared to the BGS (Figure 3). 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 serves to highlight the inherent uncertainty in these data that must be considered when discussing material and element criticality and supply. Tellurium typifies this, where the BGS estimates indicate steady, annual growth in Te production since 2010 (Figure 2B), which can be taken as 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 2B). 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

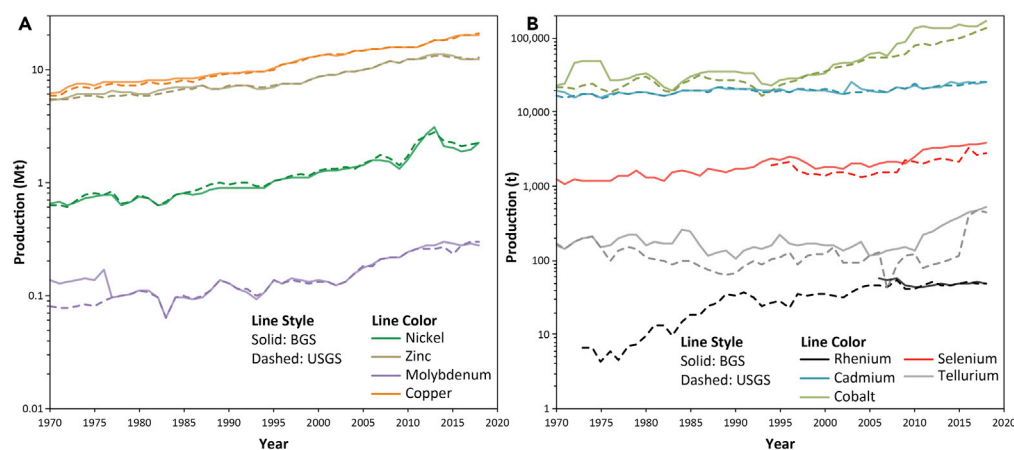


Figure 2. Comparison of annual main-product production and by-product metal production between 1970 and 2018 based on USGS and BGS publicly available data (Bureau of Mines, 1993; USGS, 2021; Table S1)

(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.

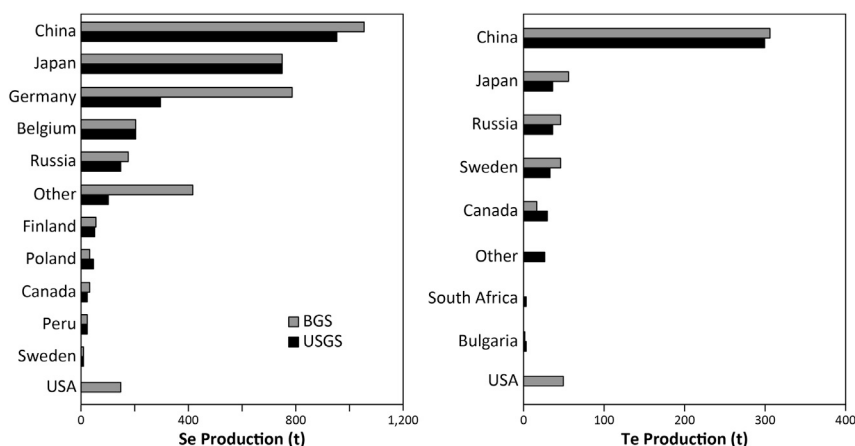


Figure 3. Breakdown of select by-product metal production by country for the year 2018 (data from BGS, 2021; USGS, 2020; Table S2)

Total Se global production in 2018 was between 2,755 and 3,832 tonnes and worldwide Te production was between 470 and 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. Also of importance, the USGS withholds the annual production of domestic Se and Te, hence the discrepancy between the two surveys.

to any modeling of supply and demand. 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 material or element in question. All of this highlights the uncertainty in one of the more robust areas of knowledge of the critical minerals and elements – how much we actually produce.

By-product and main product metal production ratios

Although there can be uncertainty in the annual production values for by-products there is still significance in assessing changes in these values over time. Here, we use an approach based on ratios of by-product to main-product annual production, herein referred to as *metal production ratios* (Figure 4). These ratios essentially provide insights into our ability to produce by-product metals although the underlying causal levers that affect these ratios are diverse. In particular, the by-product minerals and elements often do not conform to traditional supply and demand mineral economics and as a result can display price volatility (e.g., Slade, 1991; Humphreys, 2011; Redlinger and Eggert, 2016). This reflects the fact that although recovering a mineral or element as a by-product has the advantage that the majority of the cost associated with mining and processing is supported by the extraction of the main-product, the added value can be variable due to fluctuations in the by-product market price. As a result by-product recovery circuits may be “switched” on or off, or by-products could be stockpiled; all in an effort to take full economic advantage of favorable market prices (e.g., Scoullous et al., 2001).

The visible trends in the metal production ratios compiled during this study highlight periods of apparent increase, decrease or stability of the production of select co- and by-product elements over time, demonstrating the dynamic and often volatile nature of the supply of these critical minerals and elements. In general, increasing metal production ratios indicate an increase in production of that critical element per unit of main-product metal production. In comparison, decreasing metal production ratios suggest the opposite has occurred, with stable ratio values with limited change from year-to-year suggesting only limited change in by-product recovery relative to main-product production. Interestingly, this trend of “stability” is only sporadically observed over relatively short periods of time (~5 years of production) for all of the elements considered in this study (Figure 4). Instead, metal production ratios are variable, primarily as a result of the iteration of several possible causal levers such as geology (opening or closure of mines), mineral economics (supply vs demand), geopolitical (government stockpiling or initiation of tariffs), and technology (new recovery methods). Although the quantification of these levers is beyond the scope of this paper,

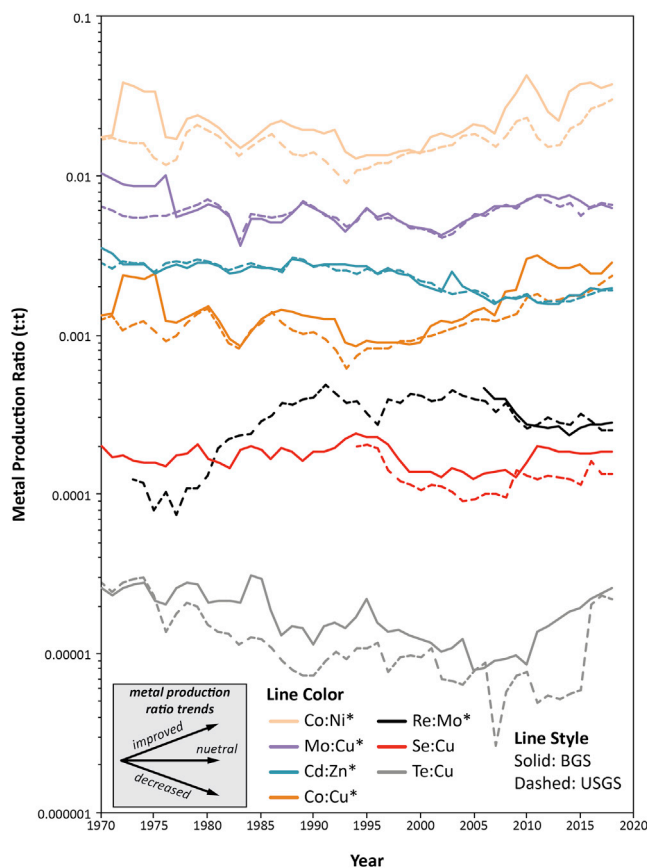


Figure 4. Annual metal production ratios between 1970 and 2018 (Table S1) for select by-product critical elements based on data compiled from the BGS (2021) and from the Bureau of Mines (1993) and the USGS (2021)

The estimated percentage of companionship for appropriate co- and by-products have been applied to the calculated metal production ratios and noted by an asterisk (*). 100% of Cd is recovered as a by-product of Zn; 90% of Se, 46% Mo, and 35% Co are recovered as a by-product of Cu; 71% of Re production is recovered as a by-product Cu-Mo; and 50% of Co production is recovered from Ni by-products (Nassar et al., 2015). These companionship percentages have undoubtedly changed over time, however historical data is unavailable and as result these percentages have been assumed to be static in the metal production calculations.

here we empirically present and discuss some of these factors as they pertain to select examples of variations in by-product metal ratios over time.

The most pronounced example of by-product growth relative to main product annual production is that of Co (Figure 4). Approximately 50% and 35% of the global supply of Co is a by-product of Ni and Cu mining, respectively (Nassar et al., 2015 supplemental data), with some main-product Co production in Morocco and artisanal mines in the Democratic Republic of the Congo (DRC; 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 ratios), with a notable exception between 2011 and 2013 when the Co production ratio decreased (Figure 4). In comparison, BGS Co metal production ratio data from 1970 to 2018 define a U-shaped pattern (Figure 4) where annual Cu and Ni production remained at similar levels between 1972 and 1975 (7.02–7.24 Mt Cu; 0.63–0.75 Mt Ni), whereas Co production nearly doubled, resulting in a significant increase in the Co production ratio (Figure 4). This was followed by a period of decreased Co production back to pre-1972 production levels before Co production ratios increased from 2000 to 2010, similar to the trend observed in the USGS data. The variation in the USGS and BGS data sets again illustrate 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.

Although there are differences in the data from the USGS and BGS the potential causes behind the changes in the Co production ratio outlined above are still worth discussing. Some of the trends in the data are linked to specific events. For example, from 2011 to 2013, the Co:Ni production ratio decreased as a result of an increase of global Ni production from new Ni-laterite mines in Indonesia and the Philippines. However during this period of increased Ni production, there was not an increase in Co production from these two countries. Instead, Indonesia and the Philippines reported increases Co production after 2013, yielding an associated increase in the Ni:Co ratio (Figure 4). This delay in Co production from Indonesia and the Philippines from new Ni-laterite mines could be the result of geology, where initial production of ores from these were not amenable to Co recovery or mine stockpiling or these new laterite mines encountered initial issues with processing and Co recovery; the latter is common with the development of new laterite mines (e.g., Mudd and Jowitt, 2014; Mudd et al., 2018). However, even given these probable causes the fluctuations in the average annual Co metal price do not directly correspond with Co:Ni production ratio trends between 2011 and 2014, with annual average prices of \$36,100, \$30,500, \$27,900, and \$30,600 per tonne Co, respectively (data from Jowitt et al., 2020). This again indicates the lack of relationship between supply and demand balance and prices for these by- and co-product metals where Co recovery increased (hence increased supply) irrespective of variations in price. This also reflects the long lead-in time for mining and mineral processing infrastructure and developments, a factor in critical mineral and element production that is compounded by the uncertainties outlined in this paper. In other words, it is hard for mining companies to justify significant expenditure relating to critical mineral or element production if the price of the resulting mineral or element is likely to be volatile.

Not all metal production ratios have increased over time or show the same variations as the Co metal production ratios outlined above. One example of this is the trend for the Cd:Zn ratio, where both BGS and USGS data suggest that Cd recovery has decreased relative to the recovery of Zn since 1970 to 2011 (Figure 4) before increasing after 2011 (for the USGS) and 2012 (for the BGS), suggesting an improvement in Cd recovery. This apparent improvement is perhaps as a result of environmental regulation, which means that Cd needs to be separated from other metals and disposed of in a different manner to other waste as a result of its toxicity. Current worldwide Cd consumption is primarily attributed to NiCd battery manufacturing, as well as its use in alloys, anticorrosive coatings, pigments, polyvinyl chloride stabilizers, radiation-detecting imaging equipment, and in semiconductors for CdTe solar panels (USGS, 2021). The slight increase in the Cd:Zn ratio post-2011 is coincident with annual increase in Te production (Figure 2B), likely a result of thin-film CdTe PV manufacturing. However, the future demand for Cd remains uncertain as its primary use is in the production of NiCd batteries, which are being phased out as a result of the negative environmental impact of Cd, with replacements by lithium-ion and nickel-metal hydride batteries (USGS, 2021) leading to a decrease in sales of NiCd batteries at a rate of 6% per year between 2002 and 2012 (Zhao et al., 2021). This may lead to a situation, where Cd could be stockpiled by smelters and refiners without a market for this metal, creating issues over safe storage and disposal rather than any issues over the security of supply of this metal. This is obviously a cost to smelters and refiners but is likely to be significantly less economically damaging than the severe environmental issues potentially caused by the release of Cd to the environment.

The majority of Cd is produced as a by-product of Zn refining (e.g., Scoullous et al., 2001) with a smaller, unquantified amount annually recovered from the recycling of end-of-life NiCd batteries (USGS, 2021). Sphalerite is the principal Zn-bearing sulfide ore from which Zn is recovered and the process of smelting sphalerite ore to recover Zn involves a purification step that extracts, among other elements, Cd (e.g., Lokanc et al., 2015). This process essentially provides Zn smelters/refineries with two options a) refine saleable Cd or b) stockpile Cd in an “intermediate” form such as Cd sludge or sponge (e.g., Scoullous et al., 2001) for subsequent refining and potential sale or (if prices remain low) potentially for environmentally safe disposal. This potential for smelters and/or refineries to stockpile intermediate products makes it difficult to reconcile the underlying causal levers of variations in Cd:Zn metal production ratios. This means that any decrease in the ratio could be a function of geology, i.e. sphalerite ore processed in the past naturally had higher Cd concentrations than the present day ore; or the ratio is artificial and is a result of stockpiling intermediate Cd products in response to mineral economic drivers, or a combination of multiple factors including others outside of these two variables. The current short-term apparent improvement in Cd recovery could be the result of sold stockpiled Cd intermediates or added Cd supply from recycling end-of-life NiCd batteries to meet elevated demand for CdTe solar PV production, although this remains uncertain. Equally, the fact that NiCd batteries are being phased out (Zhao et al., 2021) barring specialty uses for these batteries means that this recycling source and demand for Cd is likely to further diminish over time.

Historic variations in the metal production ratio for the by-product elements Se, Re, and Te provide further insights into the numerous changes involved in the production of critical elements over time (Figure 4). Approximately, 90% of the global supply of Se is sourced as a by-product of Cu mining (Nassar et al., 2015) with minor production as a by-product of Ni (USGS, 2020). The relatively unchanged Se production ratio suggests that the Se recovery has not changed relative to the annual production of Cu (Figure 4). However, other methods for refining Cu, such as solvent extraction and electrowinning (SXEW), do not recover Se (Stillings, 2017). Although the Se:Cu production ratio suggests that the rate of Se recovery has not changed much over time, the reliance on Se by-product recovery from Cu anode slimes generated in electrolytic production suggests this may be concerning for the future security of the supply of Se.

Rhenium exemplifies a critical element that is a by-product of another by-product with the majority of global Re produced as a by-product of Mo production predominantly associated with porphyry-type deposits (e.g., Millensifer et al., 2014; John and Taylor, 2016). Molybdenum, from which Re is a by-product, can originate as a main-product from porphyry Mo deposits (e.g., Climax mine; Freeport-McMoRan, 2019) or as a co-product derived from porphyry Cu-Mo deposits (Kennecott mine; Rio Tinto, 2021) as mentioned above. However, primary deposits such as the Climax and Henderson mines in the United States have Re-in-molybdenite concentrations $\ll 100$ ppm, which is insufficient to justify recovery efforts compared to the < 150 ppm Re concentrations in co- or by-product molybdenite from porphyry Cu deposits (Millensifer et al., 2014). As a result, 71% of global Re is produced from co- and by-product Mo ($\sim 46\%$ of global Mo production) produced from main-product Cu mining (Nassar et al., 2015).

Historic Re production ratios define 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 4). 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 co- and by-product Mo production after 2005. It is difficult to ascertain the geological and/or technological factors behind Re production before the early 1990s. This is partly because free trade in Re was extremely limited until the breakup of the Soviet Union (Naumov, 2007; Millensifer et al., 2014). The major producers of mined Re worldwide are Chile (Molybmet Corp), Poland (KGHM), Kazakhstan (Jeskazgan and Yuzhpolimetal), China (Jiangxi Copper), and the USA (Rio Tinto) (Naumov, 2007; Millensifer et al., 2014; Wang and Wang, 2018) with $\sim 1\%$ of annual Re production sourced from recycling of Pt-Re catalysts (e.g., Millensifer et al., 2014). It is unclear what the recent decrease in Re:Mo ratio represents, but it could be the result of a change in Re concentrations in Mo-Cu concentrates sourced from porphyry Cu deposits as suggested by the increase Mo:Cu production ratio over the same period of time (Figure 4). The extraction of Re from porphyry Cu-Mo deposits involves the separation of Re-bearing molybdenite from Cu (e.g., chalcopyrite and bornite) by froth flotation (e.g., Anderson et al., 2013). This suggests that a possible reason for the recent decrease in Re:Mo ratio could be the increased use of SXEW hydrometallurgical techniques to generate Cu concentrates via the heap leaching of lower-grade Cu ores, potentially leaving any Mo and Re within the pads rather than mobilizing these metals into solution. This is similar to the behavior of Te within Cu ores processed using SXEW, where Te is not mobilized during the leaching of the Cu ores but instead remains trapped in the heap leach pad (e.g., Goldfarb et al., 2017).

Examining the data for Te yields a Te:Cu production ratio with a broad U-shaped pattern from 1970 to 2018 (Figure 4). The majority of global refined Te is again a by-product of Cu mining (i.e., Cu anode slimes; 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 and 50 t/year 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 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 (e.g. [Jowitt and McNulty, 2021](#)). 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 elements, 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 elements 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. A clear case in point is the variation in annual production values for Te ([Figure 2B](#)). 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 and where this production is occurring, then how can we assess the security of supply of these elements?

GLOBAL RESOURCES OF CRITICAL MINERALS AND ELEMENTS

The production and supply-related uncertainties in the critical minerals and elements space is further compounded by a lack of high quality information on the resources and reserves of these minerals and elements (e.g., [Weng et al., 2013](#); [Frenzel et al., 2016](#); [Frenzel et al., 2017](#); [Mudd et al., 2017](#); [Werner et al., 2017a](#); [Werner et al., 2017b](#); [Jowitt et al., 2018a](#)). 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 mineral and element resources and production potential is that very few critical element 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](#); [Mudd et al., 2018](#)) as a result of the fact these are high value precious metals ([Table 1](#)). These high prices (and larger demand) for Pd and Pt mean that these critical elements 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 although it is produced in larger amounts than most critical minerals and elements ([Table 1](#); [Mudd et al., 2013](#)). These factors are reflected in the size of the Pd, Pt, and Co mining sectors, which in 2019 were \$11.27, \$5.85, and \$1.58 billion USD, respectively ([Table 1](#); *references therein*). However, the economic importance of these metals still does not guarantee that they will be reported in resource and reserve estimates for individual deposits and/or 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 the critical minerals and elements that have considerably smaller markets ([Table 1](#)).

All of this means that mineral economics factors have a crucial role in the lack of reporting of critical mineral and element 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 minerals and elements 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 refinery). 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. This is despite the fact that they could (and may actually) produce significant amounts of Te and Se although whether these elements are produced or not depends on the approaches used during metal extraction. This is a common case for the majority of the critical elements produced as by-products as discussed above.

The uncertainties and knowledge gaps outlined above have generated a situation where proxies for unreported critical mineral and element resources are needed to assess the global resources (and hence likely future supply) of these minerals and elements. One example of this is the critical metal In, where the geological relationship of global In production from Zn (95%) and Cu (5%) refining ([Schwarz-Schampera, 2014](#); [Werner et al., 2017a-b](#)) combined with available In, Pb-Zn, and Cu resource data ([Mudd et al., 2013, 2017](#)) have been used to estimate a global In resource of some 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), noting that the way the USGS defines reserves differs from that used by the majority of the mining industry. Resource data 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., 2018a). As such, further development of these proxies is certainly warranted, including the incorporation of fundamental geological knowledge such as the department of individual critical minerals or elements within different mineral deposit types. This key knowledge not only informs on the grades of these minerals or elements expected within certain mineral deposit types and the relationship between the concentrations of these minerals and elements with more widely quantified main products, hence allowing robust proxies to be determined, but also provides information on how extractable these minerals and elements are. For example, if a given critical element of interest is present in a deposit but is associated with or is hosted by a mineral that is considered gangue or waste, then it is unlikely that this element may be produced without significantly changing mineral processing approaches, a costly step that may not be justified. Without this information it is difficult to quantify the uncertainties involved in proxy calculations, potentially leading to significant over- or under-estimation of critical mineral or element resources. However, obtaining these data may also be beneficial for individual mines and could lead to economic benefits for a given mine, as is apparently the case for Te extraction at Bingham Canyon (Rio Tinto to build new tellurium plant at Kennecott mine, 2021).

A significant proportion of the uncertainties outlined above also reflect the lack of fundamental understanding of the “life cycle” of critical elements from mining through processing to final product. On the macro-scale, mining is often geographically decoupled from refining in that a country’s annual mined production for a metal does not always equal its refined metal production (e.g., Nansai et al., 2014; Brink et al., 2020). This decoupling can be quantified for main metals, (e.g., Cu and Ni), as well as for some of the minor metals (e.g., Co) that have publicly available data. An analysis of 2016 BGS mined and refined production data for Cu, Ni, Co, and Te demonstrates the global-scale of this decoupling (Figure 5; Table S3). There are very few examples where the mined metal production equaled the refined metal production. These include Cyprus for Cu; Sweden for Te; Myanmar, Colombia, Madagascar, and Poland for Ni; and Morocco, South Africa, and Zimbabwe for Co (Figure 5), all of which are relatively small producers compared to the major centers for the mining and refined production of Cu, Te, Ni, and Co. Figure 5 shows that mined metal concentrates are shipped all over the world for refining and demonstrates that the origins of the refined metal are not easily tracked. The paucity of primary metal concentrate origin data has a trickle-down effect for our understanding of supply risks and opportunities and for the quantification of critical element and mineral resources. For example, China is the world-leading producer of refined Te. However, it remains unclear how much of this Te is derived from domestic (i.e., Chinese) Cu metal concentrates versus how much is derived from concentrates supplied from other countries. This global-scale uncertainty reflects uncertainties surrounding individual mines, smelters, and refineries. For example, the United States has three electrolytic copper refineries, only one of which, the ASARCO Amarillo plant in Texas, is actively recovering 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 third party concentrates, as well as scrap copper metal (ASARCO Amarillo Refinery, 2021). Although the ASARCO Amarillo plant refined ~50 t of Te and ~150 t of Se in 2018 (BGS, 2021), 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-products cannot be reconciled and therefore predictions on the future supply of Te and Se from these mines are very difficult. The uncertainties within these examples of the global- and country-scale dynamics of primary metal concentrate material flows highlight three significant barriers in understanding and quantifying critical element and raw material supply: (1) geological—not all ore deposits contain by-product critical elements; (2) geographical variability in mineralized material—ore deposits are not uniformly distributed across the globe; and (3) geographical variability in processing facilities—smelters and refineries are located in both mining and non-mining countries. In short, these uncertainties reflect the fact that many countries refine third-party ores and concentrates that could essentially have come from anywhere in the world (Figure 5).

This, in turn, leads to challenges in estimating global critical mineral and element 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

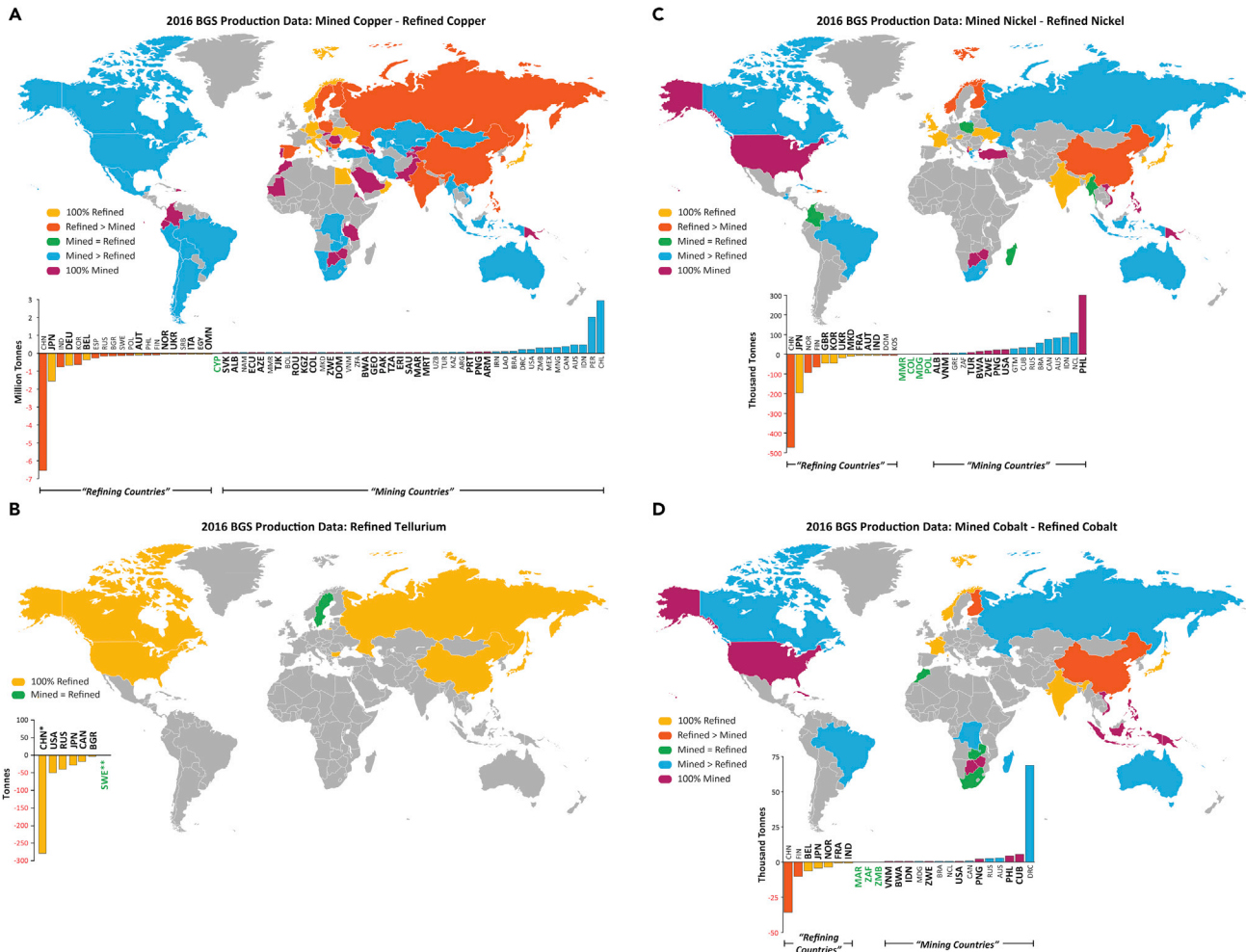


Figure 5. Global analysis of mined and refined main-product Cu (A) and Ni (C) production and their associated critical element by-products Te (B) and Co (D), respectively (data compiled from the BGS, 2021; Table S3)

The graphs show net metal production where country-wide mined production (in terms of contained metal) is subtracted from country-wide refined production of the same metal; countries with negative values refine more than they mine, and vice versa. The lack of mining countries for the Te data shown in B reflects the difficulties involved in both assessing global mined production of this element (barring Sweden, where a single mine, Kankberg, produces all the refined Te) and the flows of this element through smelters to refineries where the metal is produced. Countries in green, bold text are those that mined metal equal to their refined metal output. [Country abbreviations: ALB = Albania; ARG = Argentina; ARM = Armenia; AUS = Australia; AUT = Austria; AZE = Azerbaijan; BEL = Belgium; BGR = Bulgaria; BOL = Bolivia; BRA = Brazil; BWA = Botswana; CAN = Canada; CHL = Chile; CHN = China; DRC = Democratic Republic of Congo; COL = Colombia; CUB = Cuba; CYP = Cyprus; DEU = Germany; DOM = Dominican Republic; ECU = Ecuador; EGY = Egypt; ERI = Eritrea; ESP = Spain; FIN = Finland; FRA = France; GEO = Georgia; GBR = United Kingdom; GRE = Greece; GTM = Guatemala; IDN = Indonesia; IND = India; IRN = Iran; ITA = Italy; JPN = Japan; KAZ = Kazakhstan; KGZ = Kyrgyzstan; KOR = Republic of Korea; KOS = Kosovo; LAO = Laos; MAR = Morocco; MDG = Madagascar; MEX = Mexico; MKD = North Macedonia; MMR = Myanmar; MNG = Mongolia; MRT = Mauritania; NAM = Namibia; NCL = New Caledonia; NOR = Norway; OMN = Oman; PAK = Pakistan; PER = Peru; PHL = Philippines; PNG = Papua New Guinea; POL = Poland; PRT = Portugal; ROU = Romania; RuS = Russia; SAU = Saudi Arabia; SRB = Serbia; SVK = Slovakia; SWE = Sweden; TJK = Tajikistan; TUR = Turkey; TZA = Tanzania; UKR = Ukraine; USA = United States of America; UZB = Uzbekistan; VNM = Vietnam; ZAF = South Africa; ZMB = Zambia; ZWE = Zimbabwe]

lack of mineral resource data for these critical elements, for reasons outlined above, it is also very difficult to estimate 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 Se and Te production. If we assume that Se and Te are equally recovered from Cu concentrates produced only by the Mission, Ray and Silver Bell mines, we can estimate the potential Se and Te 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 150 t/year and 50 t/year, respectively (BGS, 2021), remain unchanged than the United States has ~2,400 t Se and ~800 t Te of potential resources remaining in these current operations. This contrasts with 2021 USGS Mineral Year Book Report, which estimated domestic reserves of 10,000 t Se and 3,500 t Te (USGS, 2021).

This epitomizes the challenge of estimating global critical element resources when there are limited or no data for mineral resources, productions and/or refining of the saleable critical element. In addition to a lack of data, the mining industry is also dynamic. For example, as briefly mentioned above, 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. This will involve the addition of a 20 t/year by-product recovery circuit to its Kennecott smelter, which unlike the ASARCO Amarillo plant only refines Cu concentrate from the Bingham Canyon mine (Rio Tinto to build new tellurium plant at Kennecott mine, 2021), demonstrating the potential economic and critical element production benefits of knowing the deportment of critical elements within the concentrate being smelted or refined. 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. Not only will the new Te production expand US annual production by ~25% and global Te production by ~4% but this new development will also provide an example of the economic and social benefit of recovering this critical element. This also demonstrates that these benefits can only be achieved by understanding the mineralization present within a mineral deposit and the abundances of the critical elements contained therein.

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 produce a negative 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 minerals and elements are by-products of main- and co-product mining and refining (Table 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).

In addition to the lack of resource data there are also challenges and uncertainties in the annual reported production values for these critical by-products 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 2B). The uncertainty in reported annual production values is compounded by a lack of transparency in the source and quantity of metal concentrates processed at smelters and refineries. This particular challenge is exemplified by worldwide Te production. Over ~90% of global 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 makes it impossible to reconcile the origin of the by-product metal from a given smelter or refinery. Without knowing the origin of the Cu concentrate or the amount of Te in the 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 mineral and element accounting, how can we classify something as critical if we don't know how much we have?

Furthermore, the limited economic value for some critical elements has resulted in a lack of research in understanding the mineral department of these elements and the underreporting of these raw materials in mineral deposits. In some cases, without these quantified inputs for by-products that are often classified as critical, production cannot be maximized at the mine, smelter, or refinery levels. In addition, without the communication of this important orebody knowledge, when it happens to be collected, critical element supply will inherently be over or under estimated. As a result, these non-renewable natural resources are reporting to waste rather than a saleable product and industry and government alike are making ill-informed decisions.

These discussed uncertainties could be removed by a combination of research and policy change. Fundamental and applied research in mineral department of the critical minerals and elements 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 department throughout the mineral exploration and mining value chain (e.g., [Nuss and Eckelman, 2014](#); [Frenzel et al., 2017](#)). 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 department research done prior to and/or during mining activities (e.g., [Frenzel et al., 2019](#)). 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-products ([Jowitt et al., 2013](#); [Nedelciu et al., 2020](#)). 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 and element resources with confidence.

CONCLUSIONS

Critical minerals and elements are crucial to modern life, advanced technology, low- and zero-CO₂ power generation and transport, and the defense sector. These minerals and elements 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, namely there is significant unrealized potential for critical element production as a function of a lack of knowledge of the department and processing behavior of these elements. Simply put, we do not know how much of these elements are present within known mineral resources and ore reserves nor accurately and precisely how much of these elements we 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 elements 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. Global reporting codes do not currently allow the outlining of resources of metals and minerals without significant economic value even though a given company may have the data required to outline these resources. Clearer reporting of exactly these data would require policy changes but would also enable not only a more accurate understanding of the global resources of these vital commodities but also allow their tracking through the mining chain and into eventual end-products. All of the changes outlined above will provide the knowledge base for ensuring a more secure supply of these vital commodities, the vast majority of which will most likely be subject to increasing demand driven by efforts to mitigate anthropogenic climate change and CO₂ emissions.

LIMITATIONS OF STUDY

Not applicable for perspectives paper.

SUPPLEMENTAL INFORMATION

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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